Potential of a trap-fishery for the spiny lobster *Palinurus delagoae* off eastern South Africa: has the stock recovered?

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ABSTRACT

An experimental trap fishery for the deep-water lobster spiny lobster *Palinurus delagoae* commenced in 2004, and was run until 2006. Data collected by on-board scientific observers were used to explore fishing effort, catches and catch per unit effort. The recent data were compared with those for a previous experiment conducted in 1994-1997, which apparently contributed to the collapse of the stock, to determine whether the stock had recovered and could sustain a trap fishery. There was a demonstrable recovery of the *P. delagoae* stock after the previous stock collapse, according to the catch rates and the size composition of catches between 2004-2006. However, catches of *P. delagoae* declined between 2004-2006. This was related to decreases in effort and in catch per unit effort over the three years. This, and a simultaneous decline in the bycatch of *P. delagoae* in the prawn trawl fishery off KwaZulu-Natal, suggests that the *P. delagoae* stock is extremely vulnerable to concomitant trawl and trap fishing. It is recommended that trap fishing should either be permitted at low levels of effort and catch only, or once more be suspended to allow the resource to recover.

INTRODUCTION

The spiny lobster *Palinurus delagoae* is a deep-water species that is endemic to southern Africa (Pollock et al. 2000). It occurs at depths of between 100 and 600 m on rocky or muddy organic substrata (Berry 1971, Groeneveld and Melville-Smith 1995), from the East Coast of South Africa (32°S) to southern Madagascar and northern Mozambique (17°S) (Palha De Sousa 1992, Cockcroft et al. 1995), in temperature ranges between 12-14°C (Berry 1971). *P. delagoae* and its near neighbor *P. gilchristi*, which occurs along the southern Cape coast, were originally thought to be conspecific, but were recognized by Berry and Plante (1973) as being distinct. Both species are heavily fished.

Palinurus delagoae has been exhaustively studied in South Africa, including analyses of its distribution and population size structure (Berry 1971, Cockcroft et al. 1995), relative abundance (Groeneveld et al. 1995, Groeneveld and Cockcroft 1997) reproduction and fecundity (Berry 1973, Kondritskiy 1976, Groeneveld et al. 2005), migration (Groeneveld 2002), fisheries and population growth and mortality parameters (Berry 1972, Groeneveld and Melville-Smith 1995, Groeneveld 2000) and genetic population structure (Gopal et al. 2006), the latter leading to the discover of a previously unrecognised sister species, *Palinurus barbarae* (Groeneveld et al. 2006). All of this information is reviewed in Groeneveld et al. (2006). In brief, *P. delagoae* populations often display a size gradient across depths, with small immature lobsters occurring in the deeper regions of their depth range and the large sexually mature animals being found in the shallower waters. The size at which 50% of the population reaches sexual maturity was previously estimated to be between 65-70mm, and adults moult each year between August and October. Adult lobsters grow very slowly, and their growth rates diminish with age. Females, after reaching sexual maturity, tend to grow even slower than males. The species undertakes numerous migrations during its life-time. As they mature, juveniles migrate from deeper to shallower waters, eventually reaching the depths preferred by adults (150-350m). Sexually mature females migrate in the opposite direction during the winter months, for their eggs to hatch in deeper waters (>300 m) (Kondritskiy 1976). *P. delagoae* is also known to undertake long-distance migrations (Groeneveld 2002), to maintain its distribution in the face of directional larval displacement by the strong Agulhas Current. Other spiny lobster species are also known to undertake seasonal migrations, including *Palinurus gilchristi* that migrates up to 800 km far against the direction of the Agulhas Current (Groeneveld & Branch, 2002) *Panulirus cygnus* (Phillips et al. 2003), *Panulirus versicolor* (Frisch 2007), and *Panulirus ornatus* (MacFarlane & Moore 1986).

Fecundity, the number of eggs a female carries, depends on lobster size and can vary among similar-sized individuals in populations of lobsters of the same species, and between species (Melville-Smith et al. 1995, Groeneveld et al. 2005). *P. delagoae* is less fecund than the South Coast rock lobster *Palinurus gilchristi*, a con-generic (Pollock et al. 2000), but more fecund than *Palinurus elephas* (Groeneveld et al. 2005). Larger eggs improve chances of larval survival because the naupliosoma larvae hatch at a more advanced stage, and the phyllosoma will thus have to drift for a shorter period of time before settling (Kittaka 1997). The eggs of *P. delagoae* are larger than those of *P. gilchristi* (Pollock & Melville-Smith 1993 and Groeneveld et al. 2005) which implies that *P. delagoae* could have stronger larvae, so that they will not disperse as far, which allows the larval population to stay within migration distance of the adult population (Groeneveld et al. 2005). This shorter dispersal phase may be important because *P.*

delagoae discharge their larvae into the strong Agulhas current, which may otherwise over-disperse larvae leading to excessive larval losses and low potential for larval return (Groeneveld et al. 2005).

P. delagoae is an important bycatch of the multispecies crustacean trawl fisheries that have been operating since 1960 off the coasts of South Africa and Mozambique (Pollock et al. 2000). In Mozambican waters, this species was also targeted by a directed trap fishery in 1980–1999. In South Africa, a trap fishery for *P. delagoae* was operated on an experimental basis from 1994-1997 (Groeneveld et al. 2006). However, concurrent trap and trawl fishing apparently resulted in over-exploitation (Groeneveld 2000, Palha de Sousa 2001). Declining catch rates and catches caused the trap fishery in Mozambique to collapse. In South Africa, the annual catches of the experimental fishery declined from 90 to 7.4 tons between 1994 and 1997 (Groeneveld 2000). Simultaneously, the bycatch of *P. delagoae* in the crustacean trawl fishery decreased from 33 to 10 tons (Groeneveld 2000). It was concluded that *P. delagoae* is a vulnerable resource and cannot support both fisheries simultaneously (Groeneveld 2000). Therefore, trap fishing for *P. delagoae* was suspended in the late 1990s, both in South Africa as well as Mozambique after an independent study (Palha de Sousa 2001).

However, interest in a *P. delagoae* trap fishery has not diminished. The appeal of trap fishing is that it permits access to areas that are inaccessible to trawlers, due to the rocky nature of the substrate (Groeneveld and Cockcroft 1997). Therefore, in 2004 a new experimental trap fishery was initiated, to determine whether the stock had recovered from the previous collapse and whether it could be fished on a sustainable basis by a trap fishery. This experiment was performed over a three-year period (2004-2006) and was designed by Marine and Coastal Management (MCM) of South Africa together with the Instituto de Investigação Pesqueira (IIP) of Mozambique.

This study is based on the data collected during the second experimental fishery (2004-2006), and has the following aims:

1. To assess whether and to what extent the *P. delagoae* stock in South Africa has recovered from the previous stock collapse; and

2. To determine the potential for a sustainable *P. delagoae* trap fishery in South Africa.

Towards these objectives, the following were investigated:

1. Trends in the *P. delagoae* catch and catch per unit effort (CPUE) throughout the 2004-2006 experiment;

2. Trends in biological measurements (size composition, sex ratio, size at maturity) during this period; and

3. A comparison of the 2004-2006 results with those of the 1994-1997 experiment.

METHODS

Study area and fishing gear

The study area was situated along the KwaZulu-Natal coast of South Africa, and comprised three regions, the North (26°53'S - 28°S), Central (28°S - 29°S) and South (29°50'S - 30°42'S) regions (Figure 1). These regions were selected on the basis of the known distribution of *P. delagoae* abundance (Groeneveld et al. 1995). To facilitate spatial analyses, each of the regions was stratified according to depth and latitude (6'intervals), with each resulting grid block being given a unique identification. A total of 96 grid blocks were to be sampled among the three regions, with fisheries and biological data to be collected by a scientific observer accompanying the fishing vessel. The North region consisted of 16 grid-blocks (mean area per block: 9.5 km^2, the Central region of 40 (mean area per block: 8.5 km^2), and the South, 28 (mean area per block: 14.8 km^2). Sampling during 2004-2006 was conducted from a single commercial fishing vessel (FV Cape Flower) rigged for long-line trap-fishing. All three regions were sampled each year, with effort being proportional to the number of grid blocks per region. The fishing gear consisted of bottom long-lines, with between 50 and 120 traps attached (average: ~ 115 traps per line). In 2004 and 2005 plastic barrel traps as well as beehive traps were employed, however the catch from the beehive traps were very small in 2006 only plastic traps were used. Traps were baited with hake or snoek heads. The Cape Flower was equipped with seawater tanks for live lobster transport and a freezer for storage of frozen lobster products (i.e. lobster tails and whole frozen lobsters).

Design of Experiment

The experiment was divided into two phases, structured and unstructured sampling. The structured sampling consisted of the setting of two long-lines, each with a soak time of 48-96 hours, within each grid block in each region. Once structured sampling of all the grid blocks in a region was completed, unstructured sampling commenced, without restriction on placement or the soak time of long-lines.

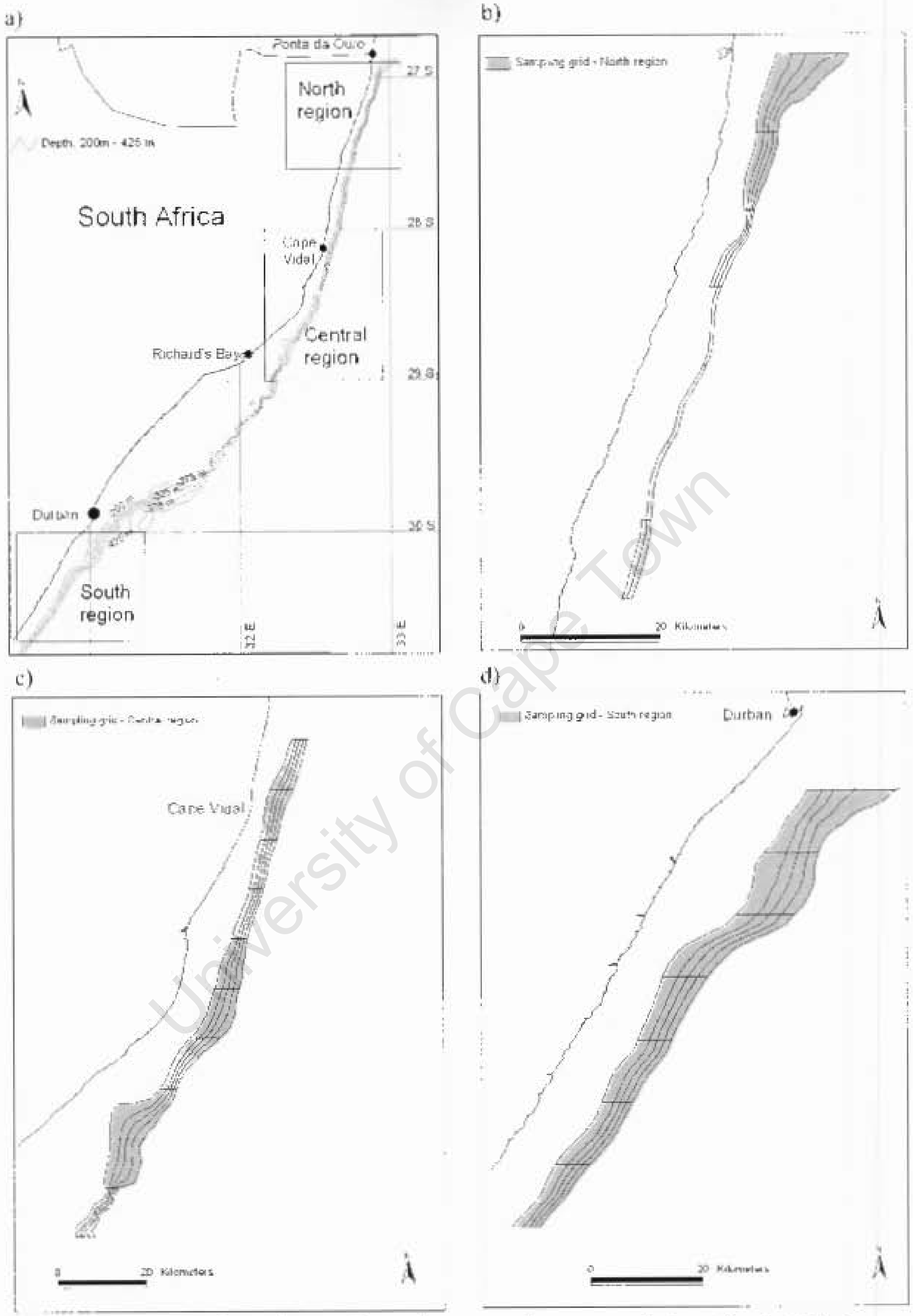

Figure 1. Locations of the three regions where sampling occurred along South Africa's KwaZulu-Natal coast (a), with the grid blocks shown for each region, North (a), Central (c) and South (d).

Data collection

Sampling took place in May-December 2004, July-October in 2005 and May-October 2006. Catch and effort data were recorded by the observer for each long-line that was retrieved. These included data on location (grid-block), depth (m), soak time (hours), number of traps, sea-conditions and the numbers of *P. delagoae* and other species caught. The *P. delagoae* catches of all long-lines retrieved during the structured phase of sampling, and most of the long-lines retrieved during the unstructured phase, were sampled by the observer for biological data. This included the carapace length (CL ± 1 mm) and sex of individuals. In the case of females, the state of maturity, based on the presence or absence of ovigerous setae, was recorded. For each long-line that was sampled, the observer attempted to measure most of the *P. delagoae* brought aboard. In the case of large *P. delagoae* catches (> 100 specimens per line), no less than 100 individuals were sampled. There was no fishing during summer (mid-December to the beginning of May) because of the terms and conditions of the permit.

Data analysis

The data from the observer data sheets were captured into an Access (Microsoft Corp.) database. Excel (Microsoft Corp.) spreadsheets and Arcview GIS 3.3 (Environmental Systems Research Institute, Inc.) were used for the analysis of the data and presentation of the results.

Size at maturity of *P. delagoae* females was estimated using the setal method. The ratio of females with ovigerous setae to the total number of females was calculated per size class using all the females sampled within each 1-mm CL interval. A logistic curve

$$f_m = \frac{1}{1+\exp(a-bCL)}$$

was fitted, where f_m is the frequency of mature females, and a and b are constants, obtained by a non-linear search algorithm with a least squares fitting procedure. The size at maturity was defined as the CL at which 50% of the females had well developed setae.

The CL of sampled lobsters were converted to whole wet mass (WM) using applicable conversions of the form $y = ax^b$ (Table 1).

Table 1. Relationships between carapace size (mm) and wet mass (g) for *P. delagoae* males, females and for the sexes combined (from Groeneveld and Goosen 1996, Kirkman and Groeneveld 2005 & 2006).

y	ax^b
Male	$1.7 \times 10^{-3}CL^{2.78}$
Female	$1.6 \times 10^{-3}CL^{2.80}$
All (unknown sex)	$1.8 \times 10^{-3}CL^{2.77}$

Catch biomass was calculated from the number of lobster caught per line, multiplied by the mean WM for males and females separately. The catch rates, or catch per unit effort (CPUE), was calculated as the mean WM (kg) per trap.

Chi-square tests, with Yates' correction factor for a single degree of freedom (Zar 1984), were used to determine whether the sex ratio of catches was consistent between regions and between years.

General linear models (GLM)

To determine whether the sizes (CL) of lobsters changed over the three years of the experiment (2004-2006), a GLM that also took into account the influences of month (May – December), region (North, Central and South), depth (< 275 m, 275-325 m, 325-375 m, > 375 m) and sex (male or female), was applied to the size composition data.. The dependent variable CL was first transformed to normalize the data, using the natural log (*ln*) transformation. The GLM model was of the form:

$$ln\,(\mathrm{CL}\ \delta) = \alpha + \beta_{\mathrm{year}} + \tau_{\mathrm{month}} + \gamma_{\mathrm{region}} + \lambda_{\mathrm{depth}} + \varsigma_{\mathrm{sex}} + \varepsilon$$

The independent variables were treated as Boolean, taking on a value of either 0 or 1, and the constants α, β, γ, ς, τ, and λ were estimated. The error term (ε) was assumed to follow a normal distribution.

A GLM was also used to determine whether CPUE varied with the years of the experiment (2004-2006), while taking into account the effects of region (North, Central, and South), sampling phase (experimental or commercial), month (May – December) and soak time (< 36 hrs, 36 – 72 hrs, and > 72 hrs). : The model was as follows:

$$ln\,(\mathrm{CPUE} + \delta) = \alpha + \beta_{\mathrm{year}} + \gamma_{\mathrm{region}} + \varsigma_{\mathrm{sampling\ phase}} + \tau_{\mathrm{month}} + \lambda_{\mathrm{soak\ time}} + \varepsilon$$

As above, the independent variables were treated as Boolean, with the constants α, β, γ, ς, τ, and λ estimated by the model. To allow for the occurrence of CPUE values of zero, a constant ($\delta = 0.04$ of the mean CPUE) was added, and the error term (ε), was assumed to follow a normal distribution. The value $\delta = 0.04$ was selected in accordance to the previous GLM of the 1994-1997 data, so that the analyses could be similar.

A standardised CPUE for each year was calculated using the following formula:

$$CPUE_{STD} = (e^{\alpha + \beta\ \text{year} + \gamma\ \text{region} + \varsigma\ \text{sampling phase} + \tau\ \text{month} + \lambda\ \text{soak time}} - \delta)^{*}\text{Area}$$

with the standard conditions chosen as sampling phase (unstructured), month (July) and soak time (36h – 72h). Regional values were area-weighted and summed across areas to yield an annual trend. GLMs were performed using the statistical software programme SAS (Anon 1989).

Comparison with 1994-1997 data

The main difference between the 1994-1997 and 2004-2006 experiments was that up to three vessels were used at a time during the previous experiment, but only one vessel was employed throughout the latter experiment. In 1994-1997 plastic barrel traps were used, as in the 2004-2006 experiment, though in 2004 and 2005 beehive traps were also deployed. In 2004-2006 four additional grid blocks were added to the North sampling region (Figure 1b), which increased the area sampled by 60 km^2. In 2004 the sampling time extended to December, and to October in 2005 and 2006, whereas in 1994-1997 sampling stopped in September. Differences do not prevent comparisons between the experiments because the data were standardised and the experiments were very similar in other respects: sampling was conducted in the same three regions, using the same stratification, and both experiments consisted of phases of structured and unstructured sampling. Furthermore, the collection of biological data was done in an identical fashion between the two experiments. Unfortunately, the raw data of the previous experiment were not available. This precluded statistical comparison between the data of the two experiments. Instead, the results are compared visually, using appropriate figures and tables.

RESULTS

Sampling effort

Sampling at sea stretched from May to December in 2004 (116 days at sea), July to October in 2005 (70 days) and May to October in 2006 (85 days). Between 95% and 100% of the 84 grid blocks were sampled each year during 2004-2006. Table 2 shows that sampling effort was highest in 2004, and lowest in 2005, and that effort was greatest during the unstructured phase in each of the three years. During the structured phase the catches from each long-line were sampled by the observer, but the large numbers of long-lines that were retrieved during the unstructured phase necessitated sub-sampling, with the observer coverage ranging from 62% to100% of long-lines.

Table 2: Sampling effort, in terms of the number of sampling days and of long-lines and traps retrieved, per sampling phase each year.

Year	**All phases**		**Structured phase**		**Unstructured phase**	
	Lines	Traps	Lines	Traps	Lines	Traps
2004	906	105 829	207	24 585	699	81 244
2005	616	70 510	175	20 125	441	50 385
2006	731	84 065	193	22 195	538	61 870

Catches

The catches of *P. delagoae* in the North and Central regions were highest in 2004, but in the South the highest catch was highest in 2005 (Figure 2). The total catches of *P. delagoae* per year were 26 t (2004), 15.5 t (2005) and 13.6 t (2006) (Figure 2).

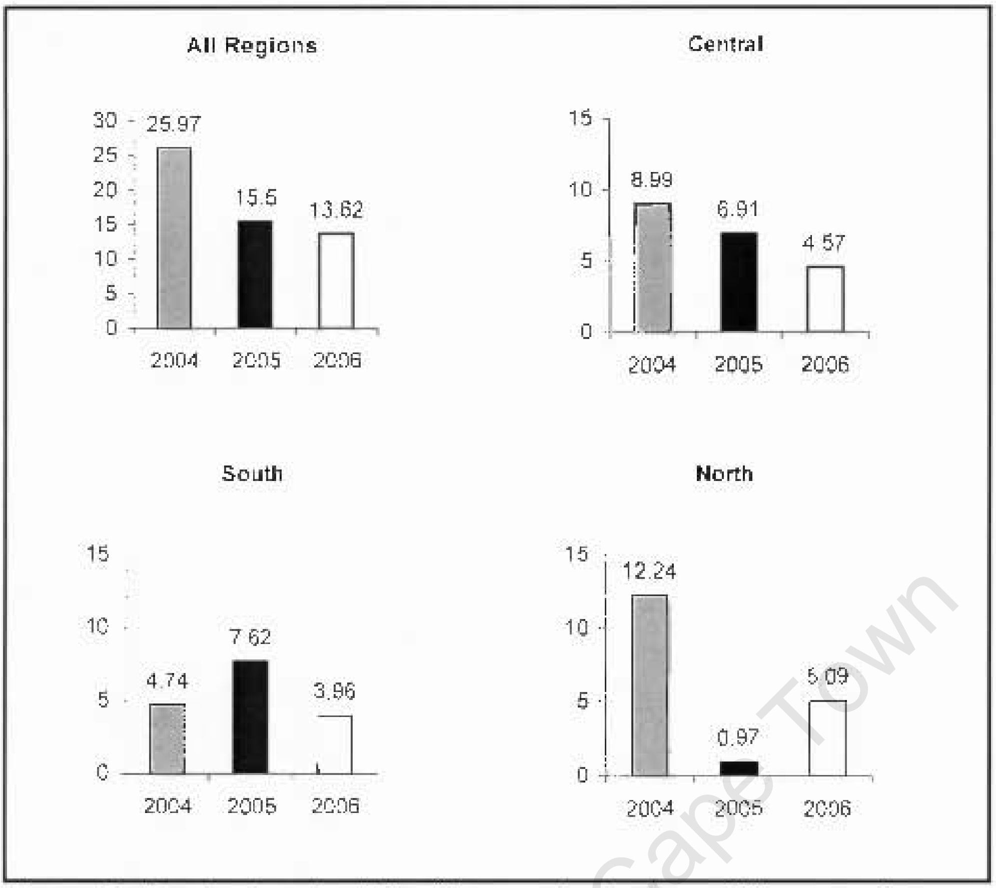

Figure 2. Catches (tons) of *P. delagoae* in the three different regions, as well as all regions combined, during 2004-2006.

The decrease in catch over the time series was not consistent with the amount of sampling effort per year (in terms of number of traps set) (Figure 3). The sampling effort in 2005 was lower than in 2004 and 2006. This is not reflected in catch (t) which showed a steady decrease over the three years. Figure 4 shows comparative catches for the 1994-1997 period, derived from Groeneveld & Cockcroft (1997) and Groeneveld (1997) and compared with the 2004-2006 data in the Discussion below.

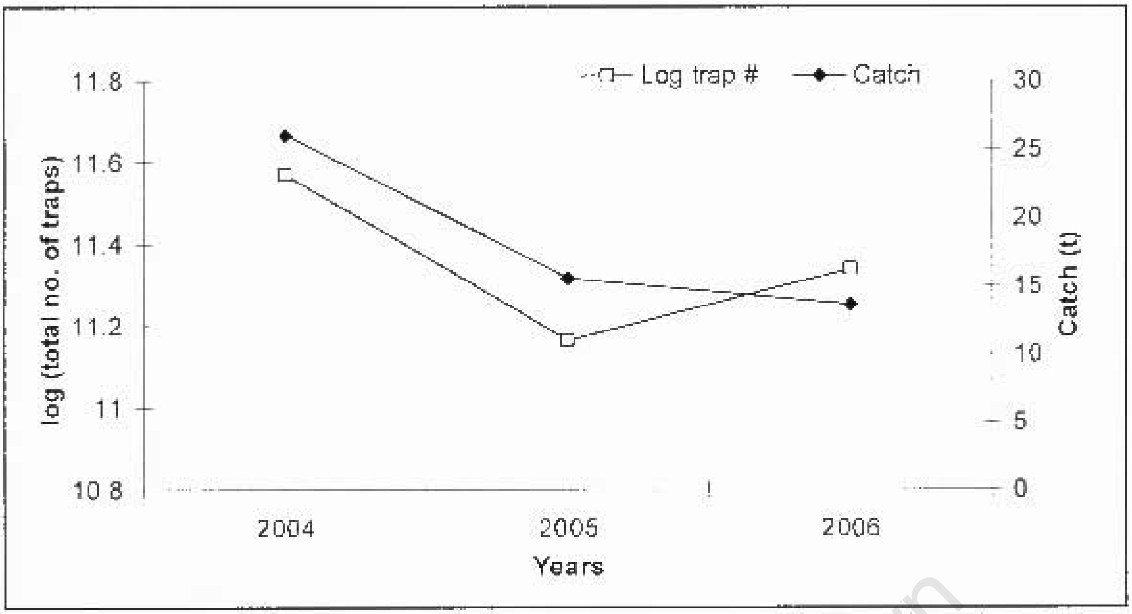

Figure 3. The combined catch (t) compared to the sampling effort (total number of traps) per year between 2004-2006.

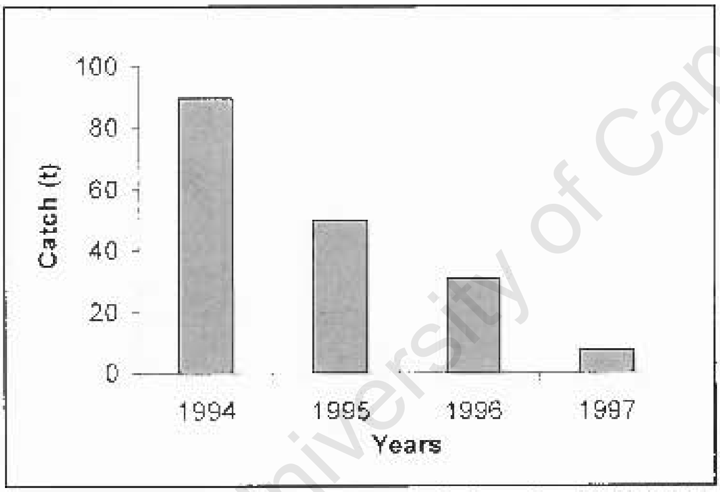

Figure 4. The catch (t) per year during the 1994-1997 period (Groeneveld & Cockcroft 1997 and Groeneveld 1997).

Female size at maturity

There was little difference in the estimated size of females at maturity between the three – 70.2 ± 0.4 (Figure 5).

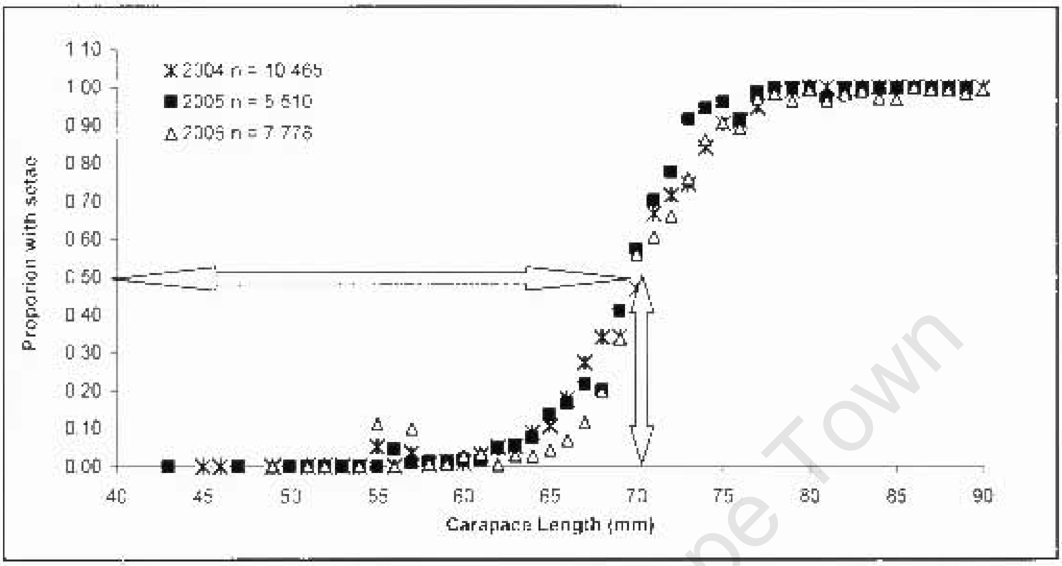

Figure 5. Estimated size of *P. delagoae* females at maturity, each year from 2004-2006, as estimated from the presence of ovigerous setae.

Size and sex composition of catches

According to the results of Chi-square tests, the sex ratio of catches did not differ from unity, within any year or region (Table 3, Figure 6 and 7).

Table 3. X^2 values for the tests comparing the sex ratios of catches (per region each year), with equal sex ratios. The critical X^2 at the 5% significance level, was 3.84 (1 d.f., with Yate's correction factor).

	2004		2005		2006	
Region	n	X^2	n	X^2	n	X^2
South	11 474	0.65	1 719	0.05	9 125	0.37
Central	7 917	0.05	5 932	0.17	7 301	2.57
North	8 002	0.01	10 296	1.01	8 947	0.17
All Regions	33 403	0.17	17 947	0.65	25 373	0.05

The size distribution of the *P. delagoae* catches (sexes combined) was very different between the three regions (South, Central and North) (Figure 6). The size distribution of the lobsters caught in the South was characterised by a prominent recruitment peak between about 55 and 75 mm CL, each year. The mean size of lobsters was greatest in the Central region, where considerably less recruitment occurred than in the South. Differences in the mean size of lobster catches between years were most pronounced in the North region, from 98.5 mm in 2004 to 89.6 mm CL in 2006 (Figure 6). This was due mainly to the progressively greater input of recruits between 65-75 mm CL, over the three years in this region. The mean size of lobsters caught in the other two regions remained more- or less constant between 2004-2006. For comparison, the size frequency distributions of lobster catches of the 1994-1997 experiment are presented in Figure 7.

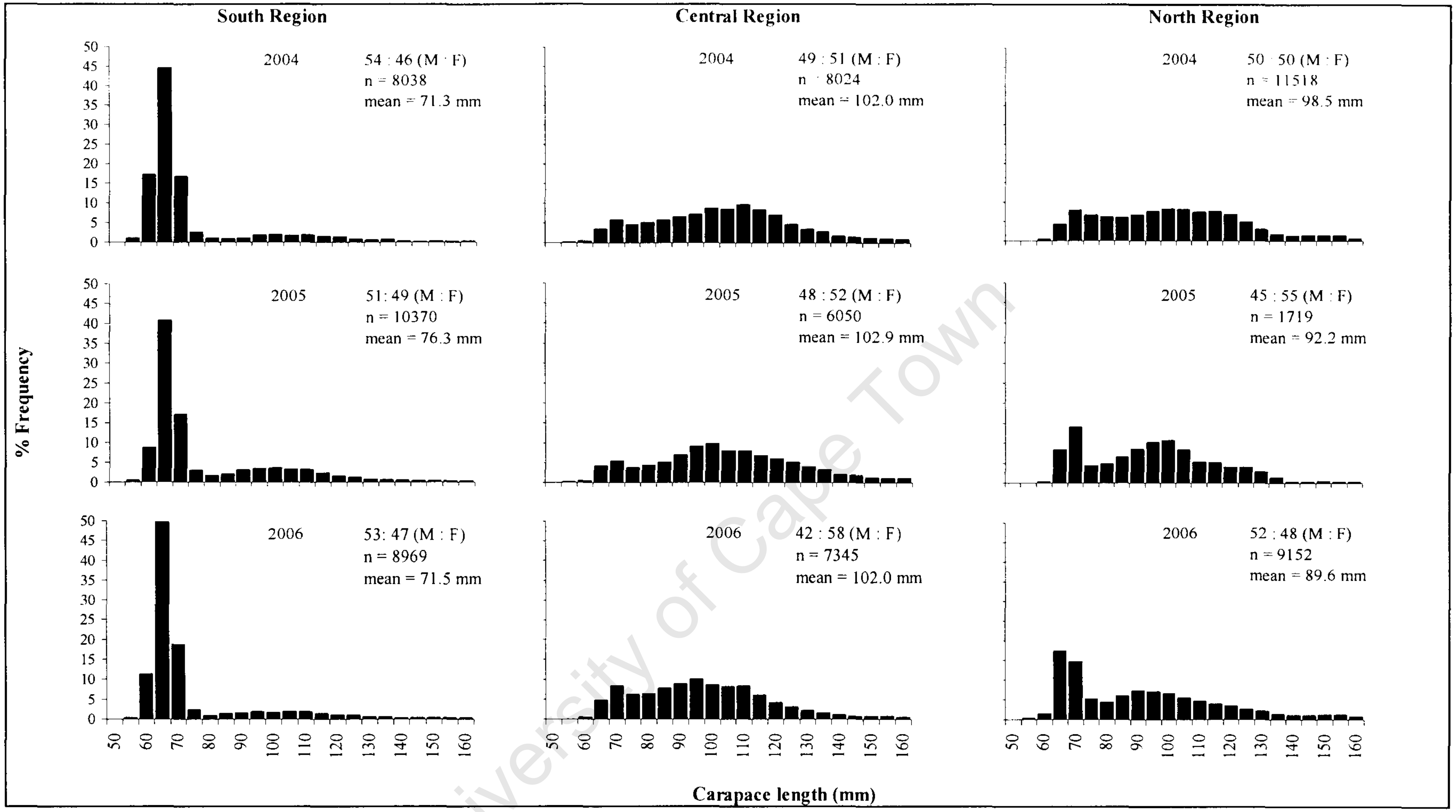

Figure 6: Length-frequency distributions of *P. delagoae* (combined sexes) sampled in South, Central and North regions during 2004-2006 (M:F is the male to female ratio; n represents the number of individuals measured).

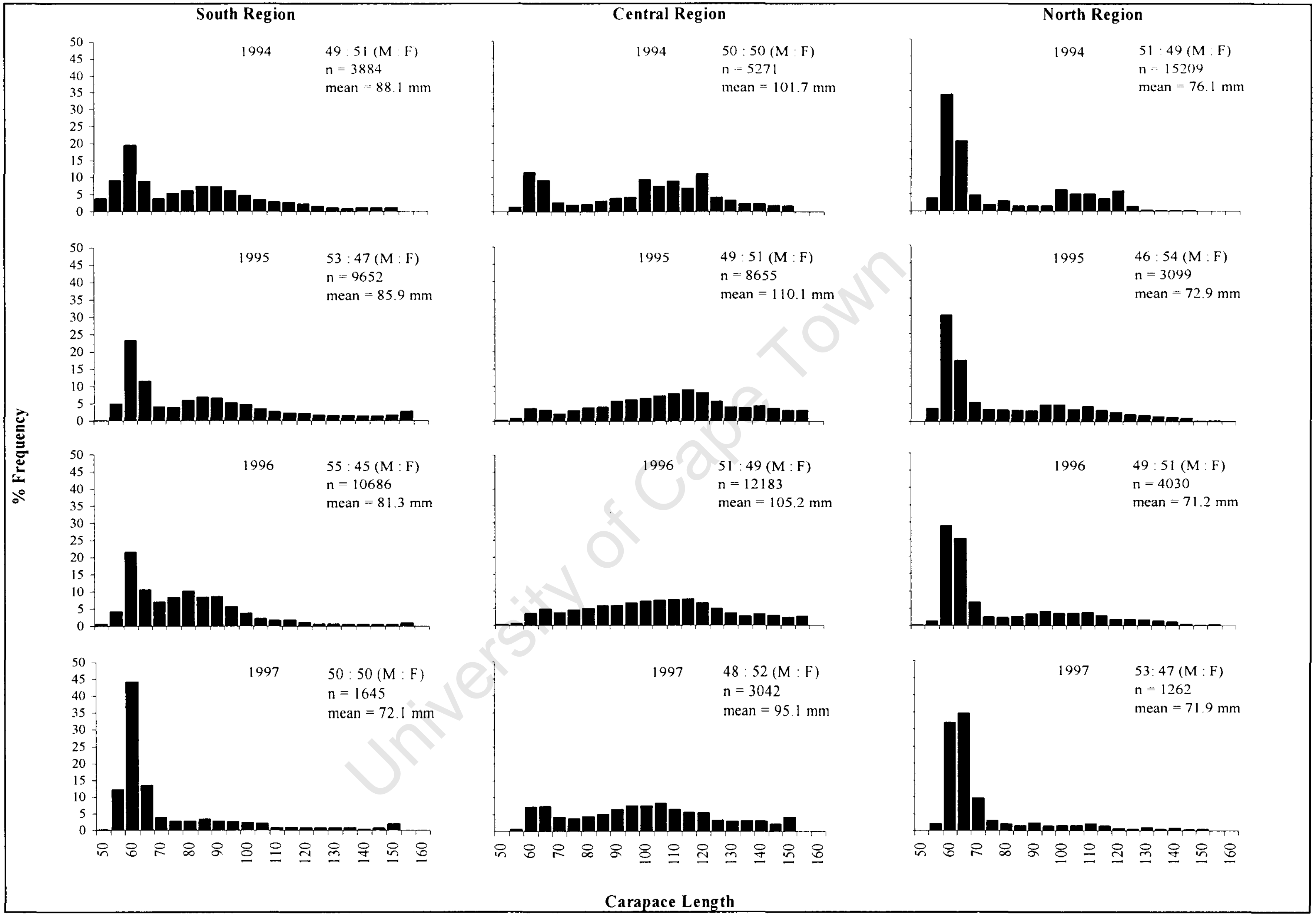

Figure 7: Length-frequency distributions of *P. delagoae* (combined sexes) sampled in South, Central and North regions during the 1994-1997 experiment (M:F is the male to female ratio; *n* represents the number of individuals measured) (Groeneveld & Cockcroft 1997 and Groeneveld 1997).

The residuals of the GLM were normally distributed, and there was no indication of any skewness or bimodality (Figure 8). The results (Table 4) show that the decline in CL declined between 2004 and 2006 was statistically significant. CL also differed significantly between the regions, between depth intervals, months, and by sex. Almost 33% of the variance in CL was explained by this model.

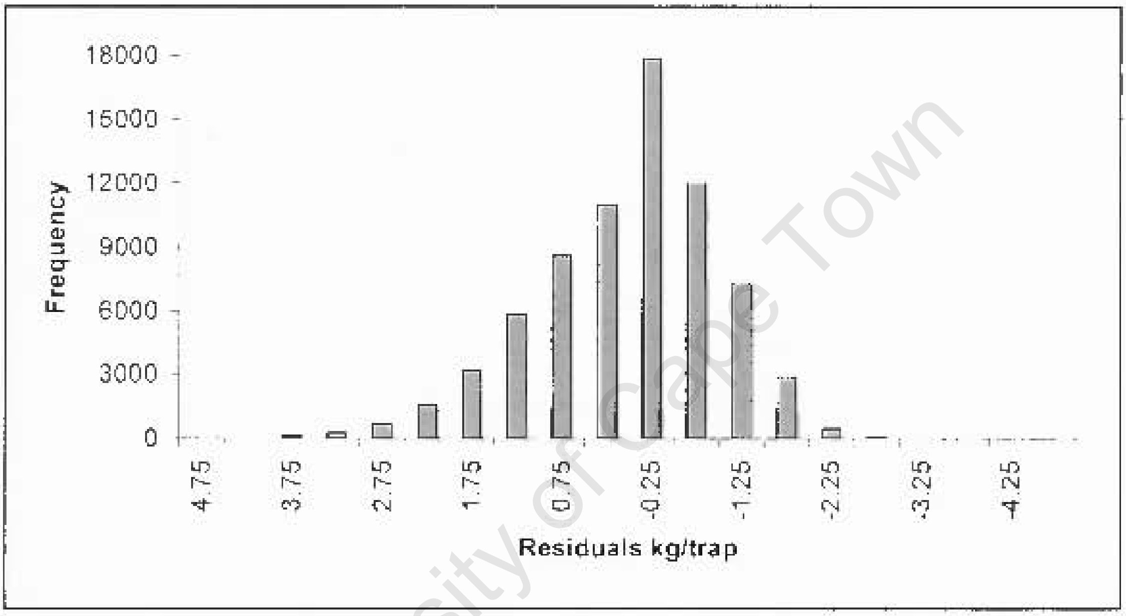

Figure 8. Frequency distribution of the residuals resulting from the fit of the GLM model of CL versus, region, month, year, depth and sex.

Table 4. Estimates of the parameter values of the GLM model used to examine the relationship between the CL and year, region, month, depth and sex. ($R^2 = 0.328$; CV = 5.077; d.f. = 16; $F = 2188.88$; $P = <0.0001$)

Variable	Parameter	Estimate	t	P	s.e.
Intercept	α	4.1139	451.18	< 0.0001	0.0091
Year					
2004	β_1	0.04857	22.96	< 0.0001	0.0021
2005	β_2	0.02633	7.8	< 0.0001	0.0033
Month					
5	τ_1	0.02972	3.32	0.0009	0.0089
6	τ_2	0.07092	8.06	< 0.0001	0.0088
7	τ_3	0.07533	9.45	< 0.0001	0.0079
8	τ_4	0.09783	11.91	< 0.0001	0.0082
9	τ_5	0.13267	16.49	< 0.0001	0.008
10	τ_6	0.10587	12.89	< 0.0001	0.0082
11	τ_7	0.10236	11.19	< 0.0001	0.0091
Region					
Central	γ_1	0.27928	70.24	< 0.0001	0.0039
North	γ_2	0.22666	51.99	< 0.0001	0.0043
Depth					
< 200	λ_1	0.14759	12.56	< 0.0001	0.0117
275-325	λ_2	0.17089	60.98	< 0.0001	0.0028
325-375	λ_3	0.06854	26.24	< 0.0001	0.0026
375-400	λ_4	0.02387	9.19	< 0.0001	0.0025
Sex					
F	ς_1	-0.02139	-12.66	< 0.0001	0.0016

To ensure that large numbers of recruits were not swamping size distribution statistics, the mean sizes (CL) of only the top 5% of lobsters in the size ranges of catches were compared for each region (Figure 9). This also showed a decrease within each region, the greatest decline occurring in the North, which is consistent with the statistics for the entire size range. The overall decline in the mean size of lobsters between years was also consistent with the results of the GLM (see below).

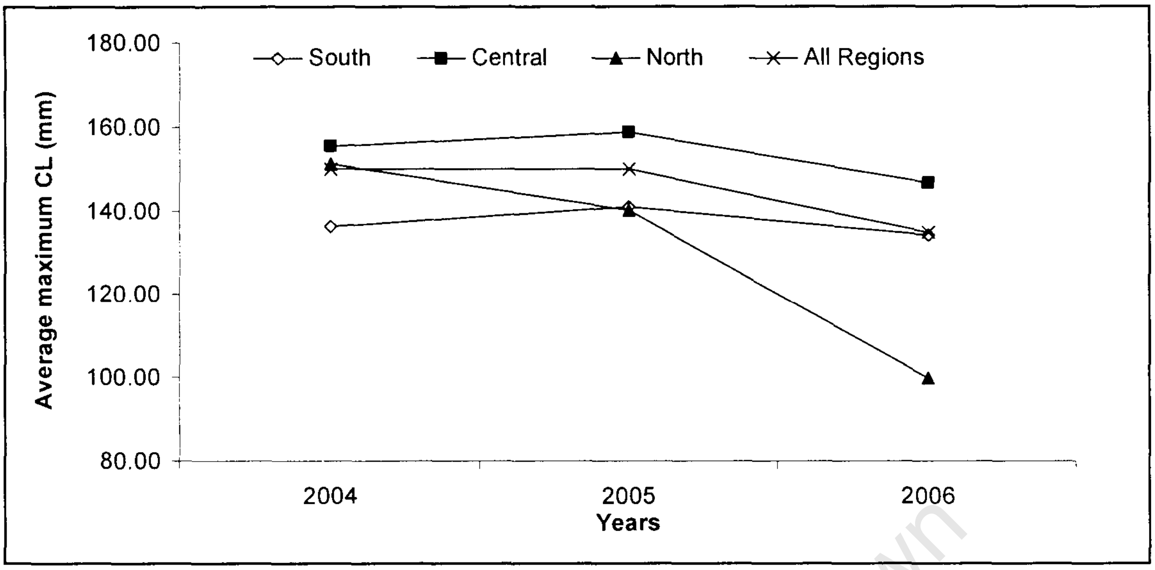

Figure 9. The mean maximum size of the upper 5% of the size distribution for South, Central and North and all regions combined for 2004-2006.

CPUE

The GLM residuals for catch rates per trap (Figure 10) were normally distributed, and there was no indication of any skewness or bimodality. The GLM parameters and statistics are shown in Table 5. The R^2 value shows that 16% of the variance in CPUE was explained by the model. The estimated parameters that were significantly different from zero ($p < 0.001$) were year (2004), month (all except November), region (Central and North), and soak time.

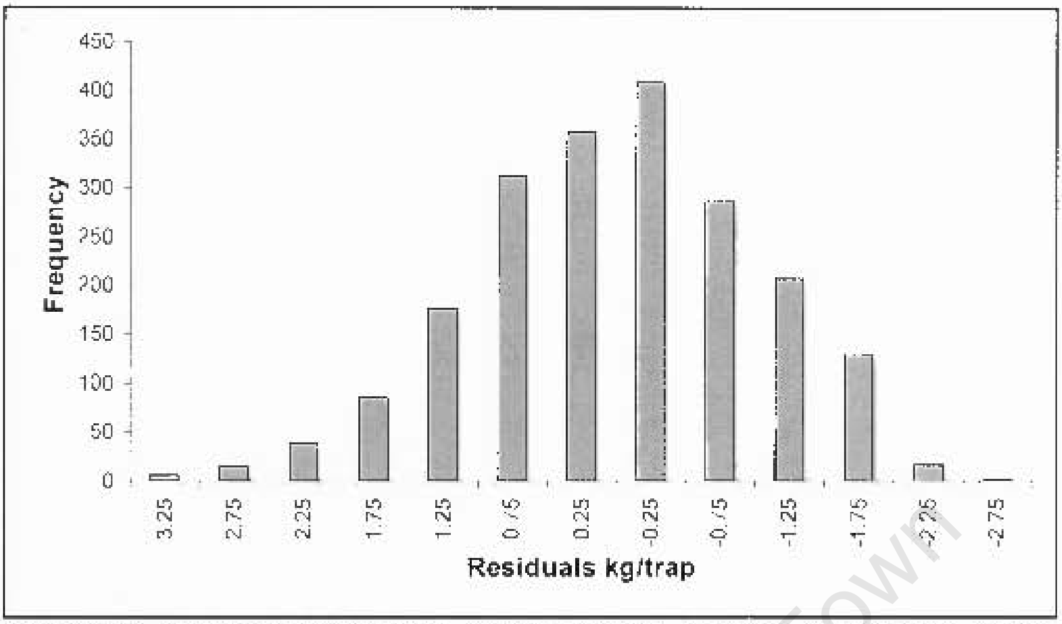

Figure 10: Frequency distribution of the residuals resulting from the fit of the GLM model of CPUE versus, region, month, year, sampling phase and soak time.

Over the three-year period, the GLM showed a decrease in the overall standardised CPUE (Figure 11a), from 0.2 kg/trap to 0.13kg/trap, and similar gradual declines over time were observed for each region separately (Fig. 11b-d). For comparison, Figure 12 shows the CPUE data from Groeneveld and Cockcroft 1997 for the 1994-1997 period.

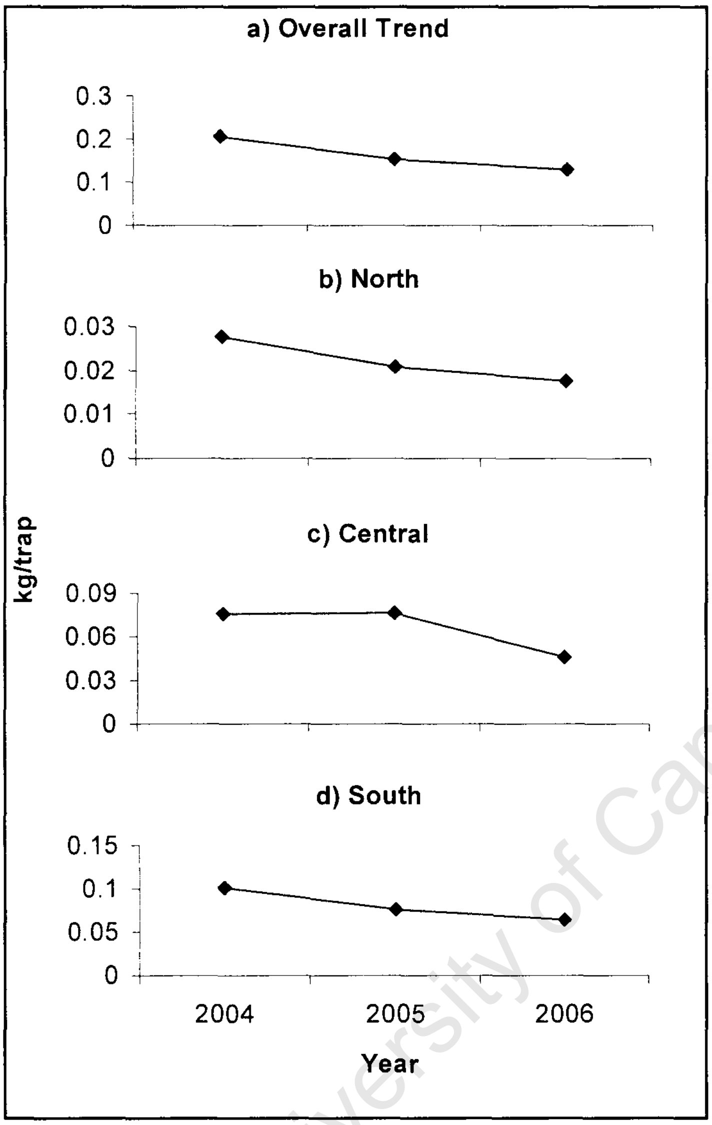

Figure 11: The trends in standardised CPUE, scaled according to month (July), soak time (36 h - 72 h) and sampling phase (unstructured phase) for (a) all three regions combined, and (b) the North, (c) Central and (d) South regions individually (note the differences in scale between the y-axes).

Table 5. Estimates of the parameter values of the GLM model used to examine the 2004-2006 relationships between the CPUE and year, region, sampling phase, month and soak time.
($R^2 = 0.161$; CV = -39.217; d.f. = 14; $F = 27.79$; $P = <0.0001$)

Variable	Parameter	Estimate	t	P	s.e
Intercept	α	-2.9430	-24.69	<0.0001	0.1192
Year					
2004	β_1	0.3762	9.02	<0.0001	0.0417
2005	β_2	0.1348	2.36	0.0818	0.0571
Region					
Central	γ_1	0.4004	5.62	<0.0001	0.0712
North	γ_2	0.4061	5.73	<0.0001	0.0708
Sampling Phase					
Unstructured	ς_1	0.1542	3.76	0.0002	0.0410
Month					
5	τ_1	0.5602	4.74	<0.0001	0.1181
6	τ_2	0.5823	5.37	<0.0001	0.1085
7	τ_3	0.9264	9.79	<0.0001	0.0946
8	τ_4	0.6987	7.03	<0.0001	0.0994
9	τ_5	0.8261	7.97	<0.0001	0.1037
10	τ_6	0.4719	4.66	<0.0001	0.1012
11	τ_7	0.2706	2.41	0.0160	0.1122
Soak					
<36h	λ_1	-0.2785	-4.18	<0.0001	0.0667
36-72h	λ_2	-0.1444	-3.76	0.0002	0.0384

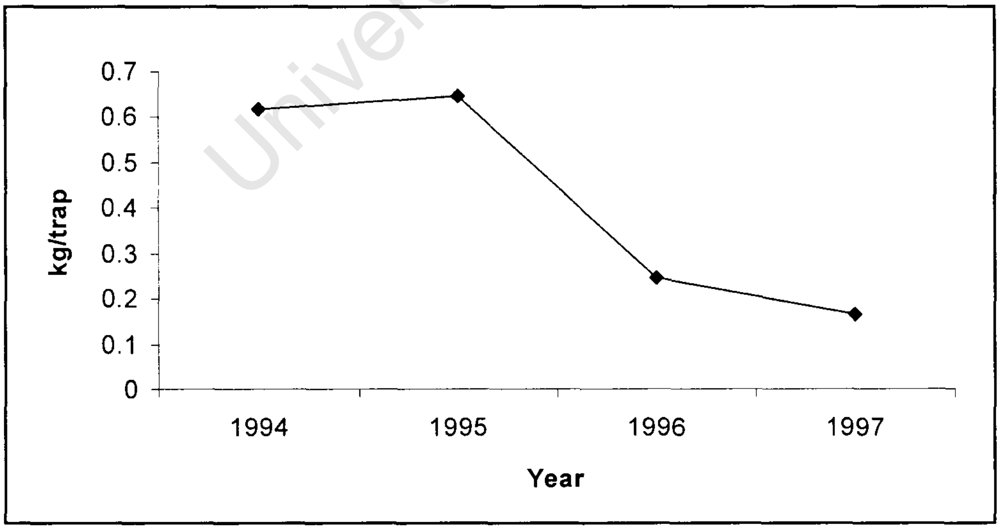

Figure 12. The overall trend in standardised CPUE, scaled according to month (July), soak time (36 h< soak time < 72 h) and sampling phase (unstructured phase) for 1994-1997 (Groeneveld & Cockcroft 1997 and Groeneveld 1997).

DISCUSSION

This study on the potential for a sustainable trap-fishery for the deep-water spiny lobster *Palinurus delagoae* served several purposes: it assessed spatial characteristics of the populations at three sites, traced changes in the population size structure over the three years of exploitation, and recorded catch and effort information. A standardised abundance index was developed to determine the impact of fishing between 2004 and 2006, and the fisheries and population trends seen in this 3-year period could be compared with the results of the preceding 1994-1997 experimental fishery, which used similar methods and analyses.

Catches

The catches of *P. delagoae* decreased over the three years of the project, being lowest in 2006 (Figure 2). The higher catches in 2004 may be explained by the accumulation of biomass over the 6 years in which no fishing occurred after the 1994-1997 trapping experiment. The catch in the 1994-1997 was higher than in 2004-2006, which is expected seeing that a relatively pristine population was fished in 1994-1997, whereas the 2004-2006 experiment involved a recovering population. The catches of *P. delagoae* during 1994-1997 decreased sharply from 89.5 t/y in 1994, to 50 t in 1995, 30.9 t in 1996 and 7.4.t in 1997 (Figure 4). Thus, the decline in the recent experiment was less severe than in 1994-1997, presumably because of the much lower fishing effort (1 vessel) in the 2004-2006 study compared to the earlier study (3 vessels). Nevertheless, the recent decline, even at a lower effort, confirms the findings of Groeneveld (2000) that only a modest yield can be expected from a deep-water trap-fishery for *P. delagoae*.

Size and sex composition of catches

The sex ratio of the catches of *P. delagoae* did not differ from unity in all three regions and years (Table 3). This is consistent with the findings of Brinca and Palha De Sousa (1983) following a study of the biology and availability of *P. delagoae* off the coast of Mozambique. The fact that sampling covered the whole adult depth range of this species (100-450m) (Cockcroft et al. 1995) probably ensured that there was an equal chance of catching males and females. Juveniles generally occur deeper and are fished at depths down to 600 m by trawl gear (Berry 1971, Groeneveld and Melville-Smith 1995). *P. delagoae* females congregate in shallower water (155 – 300 m) in summer but move back into deeper water in autumn and winter after their eggs have hatched (Koyama 1971, Berry 1972, Kondritskiy 1976), and the expectation is that the sex ratio will be female-biased in summer. The overall equality in sex ratios of catches may thus be a seasonal effect – i.e., because no fishing occurred over the summer months when the egg-bearing females tend to aggregate in shallower depths (Groeneveld 2002). In 2004 the sampling extended to November and December, but despite this the sex ratio was never female-biased. This means that the fishers cannot focus on populations predominated by females because they do not fish in summer when females aggregate there. Several other studies have shown that other palinurid species show a seasonal variance in size composition, due to migrations of females whilst in berry, including *Panulirus argus*, *Panulirus ornatus* and *Panulirus versicolor* (Kanciruk 1980, MacFarlane & Moore 1986 and Frisch 2007).

There was no fishing during summer when females congregate in the shallower waters, however, refraining from fishing during breeding and spawning periods does not necessarily benefit the reproductive output of a population, as shown by Arendse et al. (2007) for the limpet *Cymbula granatina*. Their study investigated several situations where fishing might influence the reproductive output of a population. If the population has a tendency to aggregate during breeding, or if it is prone to being disturbed, then fishing during breeding periods can influence the reproduction of the population (Arendse et al. 2007). However, if this is not the case, a closed season may have no effect. Considering that *P. delagoae* egg-bearing females form mass congregations, as well as the fact that the highest occurrence of egg-bearing occurs in late summer to early autumn (Berry 1973), as shown by historic information of trawl catches of up to 5 tons of egg-bearing females in a single trawl (Berry 1972), it is abundantly clear that a closed season over summer is necessary for *P. delagoae*.

The size composition of the *P. delagoae* catches varied considerably between the three regions (South, Central and North) in 2004-2006. Small lobsters dominated the catches taken in the South, with a large recruitment peak in the size distribution of the catches each year. In the Central and North regions, the size distributions of the catches were more evenly distributed over the size ranges each year. The size composition of catches in the North and South regions differed to some extent between the 2004-2006 and the 1994-1997 experiments (Figures 6 and 7). In most years during 1994-1997, the recruitment peak in the South was less pronounced than in 2004-2006, whereas the size distributions of lobsters caught in the North region each year in 1994-1997 were characterised by a pronounced recruitment peak resembling that in the South region in 2004-2006.

Groeneveld and Cockcroft (1997) have suggested that the preponderance of small lobsters in the North region in 1994-1997 could be explained by restrictions on fishing grounds and depth. Fishing in the North region is restricted to a narrow deep strip seaward of a marine reserve, which stretches 3 nm seawards of the shore. On average, therefore fishing in the North region occurred deeper than in the South and Central regions (Groeneveld & Cockcroft 1997). Given the known size gradient of *P. delagoae* over depth, with smaller lobsters tending to occur in deeper water than larger individuals (Cockcroft et al. 1995), the lobsters caught in the North would be expected to be smaller, on average, compared to the other regions.

However, this was not the case in the 2004-2006 experiment where the smallest animals and largest recruitment classes (60-75 mm size range) were in the South, while comparatively fewer small lobsters made up the catches in the North. There can be several explanations for this anomaly, the first being that a larger area with shallower water was available in the North region in 2004-2006 than previously. Indeed, the four additional grid-blocks are situated north of the marine reserve, and in an area where the continental slope does not fall away as steeply as in the rest of the North area. An increased availability of large-sized lobster, as a result of the additional grids, may therefore have contributed to the observed differences in the size distribution in the North region between the two experiments.

A possible explanation for the large recruitment peaks in the South region, especially in 2004-2006 but also in 1994-1997, is downstream larval transport and puerulus settlement driven by the Agulhas Current and its inshore eddies. Such a mechanism was demonstrated for *Palinurus gilchristi* along the Cape southern coast, where larvae are transported south-westwards in the direction of flow of the Agulhas current, settle at the downstream extreme of their distribution range, and then migrate to the easterly region, the juvenile cohorts would then gradually migrate northwards along the coast against the current direction (termed contranatant movements by Meek 1915) over several years (Groeneveld & Branch 2002). This behaviour could also be inferred from a progressive increase in the size structure of populations along the coast. This is possibly what is happening with *P. delagoae,* seeing that small individuals are found in the South, its downstream distribution limit. Having recruited to the South (Groeneveld 2002), the lobsters migrate back towards the Central and North regions, giving rise to more mature populations in these regions.

During the 1994-1997 experiment, the mean size of lobsters caught declined in each of the three regions (Figure 7). The mean sizes of lobsters caught were smallest in the South and largest in the Central region. This low mean size in the South may be due to the fact that there is a large recruitment peak in the South in the 60-75 mm size class, which brings down the mean size of the entire region. The mean maximum size of the upper 5% of the size composition shows a decrease in all three areas, though it is most severe in the

North. In all the areas combined the decrease was significant, which means that the largest lobsters of the population were being removed, and these are the lobsters that will take time to be replaced, as that they grow slowly (Groeneveld 2000).

The mean size of lobsters declined from 1994-1997 in all three regions (Figure 7). The lobsters in the Central region had the largest mean CL, and decreased by 6.6 mm over the four years. The lobsters caught in the North and South regions had smaller mean sizes, though lobsters in the South were larger than the North. Those in the South declined by 16 mm versus 4.2 mm of those in the North. In comparison with the end of the 1994-1997 period, the mean size had increased again by 2004 in the Central and North regions, but not in the South. However, in 2005, mean CL increased in the South as well by 5mm. There was a clear decline in the mean sizes of lobsters over the three year fishing period in the Northern region, but not in the South or Central regions. This species is very slow growing (Groeneveld, 2000) and fishing therefore has the potential to rapidly remove larger lobsters, and smaller individuals will take several years to grow into the larger size-intervals. This was illustrated by the 6-year gap between the two fishing periods, during which the abundance in the larger size-classes recovered - particularly if the size structure seen in 1997 (after 4 years of fishing) is compared with that of 2004 (first catches after 6 years allowed for recovery).

Size at maturity

The estimated size at maturity of *P. delagoae* females during each year of the 2004-2006 experiment, fell within a very narrow range (70 – 70.6 mm CL) (Figure 5), which is consistent with the mean size at maturity found in 1994-1997, i.e. 67.3 mm CL using the setal method and 71.2 mm using the ovigerous method (Groeneveld 2000), but slightly larger than an estimate of 65 mm CL for *P. delagoae* from Mozambique (Brinca & Palha de Sousa 1983). *Palinurus gilchristi* attains sexual maturity between 59 – 71 mm CL, though it varies with region (Groeneveld & Melville-Smith 1995). For other palinurid species the size at sexual maturity also varies over time and spatially, but in general *Panulirus argus* reaches maturity at the largest size between 81-90 mm CL (Tewfik & Béné 2004), *Panulirus interruptus* attains sexual maturity at about 72 mm (Vega 2003), whereas *Panulirus homarus* reaches sexual maturity at about 53-65 mm CL (Jayakody 1989, Kulmiye et al. 2006).

CPUE

The standardised CPUE of *P. delagoae* showed a decline from 0.2 kg/trap to 0.13kg/trap over 2004-2006, i.e. with equivalent effort, fewer lobsters were caught in 2006 than in 2004 (Figure 11). This pattern was evident for each region. The standardised CPUE values between the two experiments are not directly comparable, as they were determined via separate GLMs and have different parameter estimates - the data from the previous experiment were unavailable, preventing the incorporation of both periods in a common GLM. However, the trends in CPUE within each period are comparable. In either experiment, the standardised CPUE showed declines over the years of sampling (Figure 11 and 12). The decline in 2004-2006 was less pronounced than that of the previous experiment, possibly because sampling effort was much lower in the later experiment.

Crustacean trawl fishery

The *P. delagoae* stock has been exploited by the trawl fishery operating off the coast of South Africa since the 1960s (Pollock et al 2000). Interest in a trap-directed fishery for *P. delagoae* stems from the fact that such a fishery can exploit areas with rocky substrate, which are inaccessible to trawlers (Groeneveld & Cockcroft 1997). The trawl fishery that exploits *P. delagoae* as a small incidental catch operates at a different depth range and bottom type than trapping, and thus the fishing grounds do not overlap (Groeneveld & Melville-Smith 1995, Fennessy & Groeneveld 1997). However, it was previously shown that *P. delagoae* is vulnerable to overexploitation when simultaneous trawl and trap fisheries operate (Groeneveld 2000). In the period corresponding to the previous experiment, the bycatch of *P. delagoae* declined from 33 t to 10 t. Bycatch of *P. delagoae* also declined during the period corresponding to the recent experiment (Figure 13), which may have been influenced by the simultaneous trap fishery.

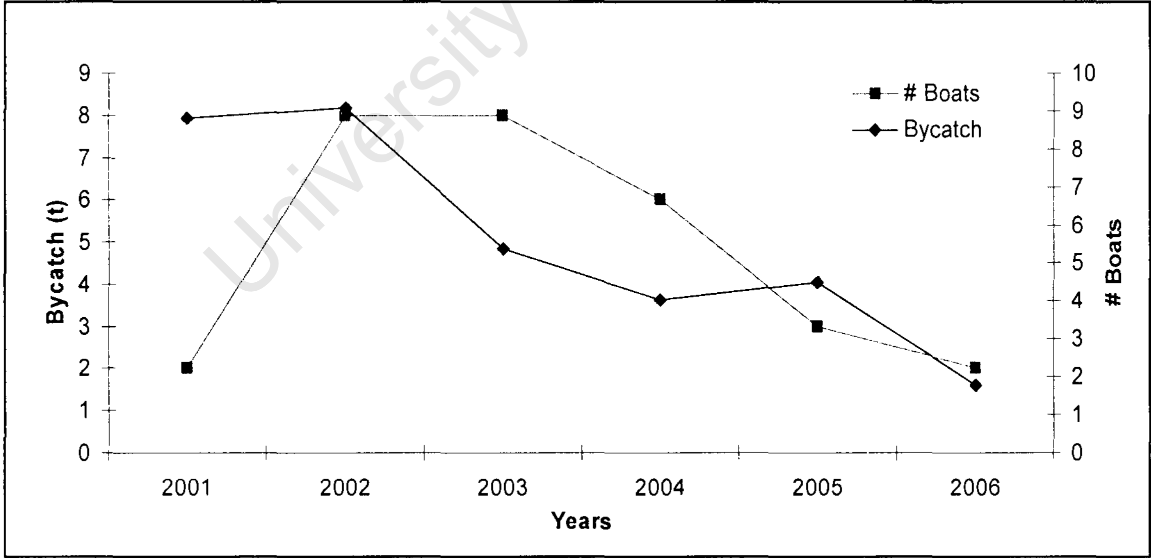

Figure 13. Record of catches (t) of *P. delagoae* caught in the trawl fishery off KwaZulu-Natal from 2001-2006, as well as the effort in terms of number of boats fishing. Data obtained from MCM unpublished data.

Conclusions

This study aimed at assessing the recovery of the *P. delagoae* stock after the previous stock collapse. By comparing the 1997 data with those of 2004, it is clear that there had been a recovery over the resting period. Nevertheless the catches, the mean size of lobsters, and the CPUE all declined over the 2004-2006 period. During the 1994-1997 experiment the situation was similar, and the catch, mean size and CPUE showed even stronger decreases over this period, just before fishing was suspended. The crustacean trawl fishery catches also showed a decline in the amount of *P. delagoae* caught since the trap fishery was reopened in 2004 even at a low effort level. This supports the findings of Groeneveld (2000), who showed that *P. delagoae* is vulnerable to simultaneous trap and trawl fishing, and advised that trawling received precedence, based on several criteria. Firstly, economically, trawling poses less of a risk, seeing that it is well established and targets several species, and has a greater wholesale value. Secondly, in terms of the impact on the population, both types of fishing exploit smaller lobsters, but trapping has a greater impact on the vulnerable adult population, and trawling allows refuge to lobsters living on rocky substrates that trawlers cannot access. Trawling does, however, have a much larger bycatch, and is an environmentally more destructive fishing method. Nevertheless, trawling was found to be the most appropriate method of fishing in this case and, consequently, trapping was suspended after 1997. The findings of this study confirm the vulnerability of *P. delagoae* to trap-fishing in KwaZulu-Natal, and support the proposal that trap fishing should either be permitted only at very low levels of effort and catch, or should once more be suspended to allow the resource to recover. If the fishing is set to continue, a more detailed stock assessment would be necessary to determine the maximum sustainable yield to ensure that this stock does not completely collapse.

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