Research for Management of the Ornate Tropical Rock Lobster, *Panulirus ornatus*, Fishery in Torres Strait:


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This report summarizes research carried out by CSIRO on the ornate rock lobster, *Panulirus ornatus*, fishery in Torres Strait during the 1987–1990 triennium. The program investigated: the importance of the western Torres Strait sea-grass beds as settlement and nursery grounds; the impact of the diver fishery on the lobster population; the effect of the annual breeding emigration on the Torres Strait lobster population; the hypothesis that lobsters die after migrating across the Gulf of Papua and breeding at Yule Island; whether the Yule Island breeding population has the potential to provide recruitment to the Torres Strait fishery; the extent of the breeding population in the Gulf of Papua and far northern Great Barrier Reef; and estimated the abundance of the rock lobster resource in Torres Strait and made an assessment of the potential yield.
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## Executive Summary

### The fishery and past research

The commercial fishery for the Torres Strait tropical rock lobster began in the late 1960's and it has become a major income earner for the Torres Strait Islanders. Effort in the fishery, whether measured by number of fishermen, boats, days worked per year, or hours worked per day, has increased substantially. Current catch per hour is about one third of historic levels, hence the research that CSIRO carries out on this fishery is critical for sound management. Past research has provided basic information on the life history of the tropical rock lobster, particularly the existence of an annual breeding migration out of Torres Strait to the northeast as far as Yule Island at the eastern Gulf of Papua. Lobsters at these breeding grounds are in very poor physiological condition and by the end of the short breeding season they have all disappeared. Recent research has been more directed at assessment of the fishery for management and considerable advances have been made toward the set objectives.

### Western settlement grounds

The extensive seagrass beds of western Torres Strait were surveyed in October 1987 to investigate possible nursery grounds for newly settled rock lobsters that could supply recruits to the fishery farther east. Only 18 lobsters were seen at a rate of 0.35 lobsters per kilometer of bottom surveyed and none of these were newly settled juveniles. The survey indicated that the area was not a significant settlement ground for lobsters nor did it appear to support a significant adult population. Other work has shown that the major settlement occurs in central Torres Strait in the same area as the fishing activity.

### Population changes due to migration

A field program to document the marked changes that occur in lobster population around August each year, as a result of the annual breeding emigration, was concluded in 1988. The movement of larger lobsters out of the fishery began between early August and early September and lasted for 4 to 8 weeks; after which mostly only smaller lobsters remained in Torres Strait. More female than male lobsters emigrated, causing the sex ratio of the catch to be significantly skewed towards males after the emigration. Before lobsters emigrated, they underwent a maturation moult that was evident as one or more large peaks in moulting activity. There was a general lunar rhythm in moulting activity with peak rates of ecdysis around the third quarter of the moon.

### Size-structure and growth

The growth rate and life history of the Torres Strait lobsters were investigated by applying a variety of methods to new and previous data. A growth curve was formulated using tag-recapture, aquarium growth, settlement and hatching data. Size–frequency samples from the Torres Strait population, catch and emigratory population were used to show that the population in Torres Strait consisted mainly of $1^+$ and $2^+$ lobsters, that the catch consisted mostly of $2^+$ lobsters with smaller and variable numbers of $1^+$ lobsters, and that the emigratory population consisted mainly of $2^+$ lobsters with some $3^+$ males. Size-frequencies from different areas of Torres Strait and from different years were used to elucidate temporal and spatial variability in growth.

### Catch monitoring

Catch and effort of Torres Strait lobster fishermen were monitored as part of assessing the impact of the fishery on the stock. Analysis showed that divers using hookah equipment could catch more lobsters per hour than free divers but that continued use of hookah did not appear to impact the catch rate of free-divers. Interannual variability in CPUE appeared to reflect changes in the abundance of the fishable stock which, in turn, reflected variability in recruitment.
The cause of the annual decline of the breeding lobster population on the coastal reefs near Yule Island, PNG, was investigated early 1989, using several complementary methods. The Yule Island fishery followed a typical pattern of punctuated rise and then rapid decline. The decline was not associated with any observed movement of lobsters off the coastal reefs into deeper water. Tag returns indicated that fishing pressure was responsible for >30% of the decline, but the natural mortality rate was even higher (>10-fold greater than for lobsters in Torres Strait), probably as a result of the stress of the migration and breeding. The important implication is that if all breeding populations suffer similar catastrophic mortality then settlement into the fishing grounds each year may depend entirely on the breeding success of the preceding years emigration which should therefore be conserved.

A series of satellite tracked buoys were released in deep water off Yule Island to test whether lobster larvae hatched at Yule Island could potentially be transported to Torres Strait. The buoys moved rapidly eastward to the end of the PNG mainland and then turned south and later southwest toward the north Queensland coast. This pattern of movement indicated the presence of a clockwise gyre in the northern Coral Sea which has the potential to carry larval lobsters from PNG waters back to Torres Strait.

Knowledge of the size of the stock available to be fished facilitates development and management of fisheries. The lobster stock in a 25,000 km² area of Torres Strait was estimated in June 1989, by making visual counts of the number of lobsters in strip transects, after pilot studies in 1988 confirmed the feasibility of a full-scale survey. The main survey took seven weeks and analysis of the transect data provided an estimate of lobster abundance between 11 to 17 million. The surveyed population was sampled concurrently to determine its size structure and provided an estimate of the stock size for the fishery between 2,200-3,350 t tail weight, which is roughly 10-fold greater than the annual catch of about 250 t. This indicates that the current level of exploitation is low and that the fishery is unlikely to be under threat at present and may even support greater effort.

The benthic habitat of central and western Torres Strait was surveyed along with lobsters, in May-June 1989. The distribution and relative abundance of the seagrasses were estimated visually and mapped, as were the distribution of substratum types and epibenthic macrobiota; pearl oyster abundance was also estimated. Seagrasses were seen at most sites and tended to increase from almost zero abundance in the southern and eastern areas of the survey to moderately dense in north-western Torres Strait. The epibenthic macrobiota and substratum type also varied greatly, with the greatest diversity and abundance of biota associated with the harder substrata. The survey area supported an estimated 1.2-2.5 million pearl oysters.

Research had suggested that the number of breeding lobsters at Yule Island could only account for a small proportion of those emigrating from Torres Strait. To search for the remainder, the Gulf of Papua and far northern Great Barrier Reef were surveyed for lobster breeding grounds in depths from 30 to 200 m using a small research submarine. High densities were seen on a number of deep (30–100 m) reef habitats on the edge of the shelf of the far northern GBR; but very few lobsters were found in the GoP or in deep water adjacent to the coastal reefs of the eastern GoP. It is possible that the far northern GBR supports the major breeding population for the Torres Strait fishery. However, it will be necessary to confirm the extent of the far northern GBR breeding

| Breeding lobster mortality | The cause of the annual decline of the breeding lobster population on the coastal reefs near Yule Island, PNG, was investigated early 1989, using several complementary methods. The Yule Island fishery followed a typical pattern of punctuated rise and then rapid decline. The decline was not associated with any observed movement of lobsters off the coastal reefs into deeper water. Tag returns indicated that fishing pressure was responsible for >30% of the decline, but the natural mortality rate was even higher (>10-fold greater than for lobsters in Torres Strait), probably as a result of the stress of the migration and breeding. The important implication is that if all breeding populations suffer similar catastrophic mortality then settlement into the fishing grounds each year may depend entirely on the breeding success of the preceding years emigration which should therefore be conserved. |
| Sources of recruitment | A series of satellite tracked buoys were released in deep water off Yule Island to test whether lobster larvae hatched at Yule Island could potentially be transported to Torres Strait. The buoys moved rapidly eastward to the end of the PNG mainland and then turned south and later southwest toward the north Queensland coast. This pattern of movement indicated the presence of a clockwise gyre in the northern Coral Sea which has the potential to carry larval lobsters from PNG waters back to Torres Strait. |
| Survey of lobster abundance | Knowledge of the size of the stock available to be fished facilitates development and management of fisheries. The lobster stock in a 25,000 km² area of Torres Strait was estimated in June 1989, by making visual counts of the number of lobsters in strip transects, after pilot studies in 1988 confirmed the feasibility of a full-scale survey. The main survey took seven weeks and analysis of the transect data provided an estimate of lobster abundance between 11 to 17 million. The surveyed population was sampled concurrently to determine its size structure and provided an estimate of the stock size for the fishery between 2,200-3,350 t tail weight, which is roughly 10-fold greater than the annual catch of about 250 t. This indicates that the current level of exploitation is low and that the fishery is unlikely to be under threat at present and may even support greater effort. |
| Benthic habitat and pearl shell | The benthic habitat of central and western Torres Strait was surveyed along with lobsters, in May-June 1989. The distribution and relative abundance of the seagrasses were estimated visually and mapped, as were the distribution of substratum types and epibenthic macrobiota; pearl oyster abundance was also estimated. Seagrasses were seen at most sites and tended to increase from almost zero abundance in the southern and eastern areas of the survey to moderately dense in north-western Torres Strait. The epibenthic macrobiota and substratum type also varied greatly, with the greatest diversity and abundance of biota associated with the harder substrata. The survey area supported an estimated 1.2-2.5 million pearl oysters. |
| Breeding grounds survey | Research had suggested that the number of breeding lobsters at Yule Island could only account for a small proportion of those emigrating from Torres Strait. To search for the remainder, the Gulf of Papua and far northern Great Barrier Reef were surveyed for lobster breeding grounds in depths from 30 to 200 m using a small research submarine. High densities were seen on a number of deep (30–100 m) reef habitats on the edge of the shelf of the far northern GBR; but very few lobsters were found in the GoP or in deep water adjacent to the coastal reefs of the eastern GoP. It is possible that the far northern GBR supports the major breeding population for the Torres Strait fishery. However, it will be necessary to confirm the extent of the far northern GBR breeding |
grounds and the abundance of these breeding lobsters, as well as determine whether these lobsters suffer catastrophic mortality after breeding as occurs in the breeding population at Yule Island.

**Microsporidian parasite** "Milky flesh" condition in tropical rock lobsters makes them unsaleable and the causative agent of this condition was investigated using light and electron microscopy. Tail muscle of affected lobsters was found to be infiltrated with millions of microscopic spores (2–4 mm long) of a parasitic microsporidian, probably of the genus *Ameson*. These spores caused the muscle to disintegrate and appear opaque white. The parasite infects <1% of lobsters and, under normal conditions, is not considered a serious threat to the fishery.

**Early larval stages** Recently hatched lobster larvae from Yule Island, PNG, were examined using light and electron microscopy to determine if a previously undescribed naupliosoma stage exists in the life cycle of this lobster. Two stages were identified, the earliest resembling the naupliosoma and a second stage, the phyllosoma I, which has been previously described as the earliest larva of *Panulirus ornatus*. However, it is possible that the suspected naupliosoma stage was released prematurely from the egg, and is normally an embryonic stage.

**Allometric growth** The large front walking legs of male lobsters are considered important for successful mating and the incidence of allometric growth of legs in migrating males was investigated. There was a pronounced elongation of the front legs in larger migrating males (110–120 CL) which may have been associated with the onset of maturity and may be an adaptation to increase the probability of successful mating.

**Stock assessment** To provide outputs of direct utility to management, data collected in the field was synthesized using a variety of stock-assessment methods. Analysis of yield-per-recruit showed that at current levels of fishing mortality, and with a minimum size of 100 mm tail length, yield is only ~20 gm per 1.5 year-old recruit — this is very low compared with other fisheries. The current minimum size restriction does not improve yield and would only become important at very high levels of fishing mortality. This analysis also showed that a proposed closure for October–December would not have the desired effect of increasing yield by preventing growth overfishing, but would probably decrease total catch by as much as 30 t. The stock-assessment was extended to consider the level of escapement — the proportion of the population that escapes fishing to emigrate and breed. With current levels of fishing mortality, escapement is ~93% of the numbers that could emigrate and breed if there was no fishing at all; in comparison with almost all other fisheries, this is a very high escapement rate. A very conservative escapement of 70% would permit a substantial increase in catch as, with a 4-fold increase in fishing mortality, escapement would be about 74% and the projected average yield would be just over 800 tonnes. These considerations suggest that increased effort should be encouraged in the diver fishery.
The commercial fishery for the rock lobster, *Panulirus ornatus*, in Torres Strait began in the late 1960s and is now a major source of income for Torres Strait Islanders. It is a diver spear–fishery because these lobsters will not enter pots. Divers operate from 4–5 m outboard powered dinghies, sometimes using hookah equipment but often simply free–diving with a short spear. Most divers return their catch to island based processors or semi-permanently moored mother vessels. There are, however, about a dozen small mobile freezer boats which each support a team of 2–6 dinghies. Since the fishery began effort has increased substantially, whether measured in terms of number of participants, boats, days worked per year, or hours worked per day. Current catch per hour is about one third of that 15–20 years ago; hence, there is a continuing need for quality assessment and monitoring of the lobster stocks to provide advice to management.

**Fig.1.** Map of Torres Strait and Gulf of Papua showing the main fishing grounds around the central and western reefs and islands (stipled) and the migration pathway (arrows).

Past research has provided basic information on the life history of the rock lobster. Larval development occurs in the open ocean and takes about six months, after that lobsters settle into small holes in the seabed in Torres Strait and grow very quickly, recruiting into the fishery about one year later at ~100 mm tail length. These juvenile lobsters are fished around the reefs and islands of central and western Torres Strait until they are just over 2½ years old. At this time, in August to October each year, most emigrate from Torres Strait and catch rates decline markedly. Tagging studies, carried out in the early 1980s, showed that some of the emigrating lobsters moved north–east into the Gulf of Papua (GoP), undergoing reproductive development at the same time. The tagging studies also showed that lobsters on reefs off the north–east Queensland coast do not participate in the migration across the GoP but in general tended to move to the south–east. Nevertheless, despite the different movement patterns, genetics studies have shown that the Torres Strait and Queensland coast populations are part of the same stock. Prawn trawlers used to target the migrating lobsters and catches up to ~200 t were recorded, but this activity was banned in 1984. Some of the migrating lobsters move as far as the coastal reefs of the eastern GoP.
where there is a breeding ground. This breeding population forms the basis of a seasonal artisanal fishery around Yule Island which lasts only a few months during the summer. This fishery existed in traditional form prior to written history but the origin of the lobsters became known only in the early 1980s. The lobsters on these Papuan coastal reefs are in very poor condition — the muscles are wasted and the blood is very watery. Measurements of the water content of the body tissues showed that the physiological condition of lobsters declines as the migration moves across the GoP and through the breeding season. This lead to the hypothesis that almost all lobsters die after breeding and is why the Papuan artisanal fishery lasts only 2–4 months.

More recently, research has documented the changes that occur in the Torres Strait lobster population due to the emigration and confirmed the catastrophic mortality of the Papuan breeding population. Research then focussed the measurement of parameters such as lobster abundance, fishing and natural mortality, settlement and recruitment, and the extent of the breeding grounds. This information is essential for sustainable development of the fishery through sound stock assessment. The specific objectives of the program during the triennium were:

- Assess the importance of the western Torres Strait sea-grass beds as settlement and nursery grounds.
- Investigate the effect of the annual breeding migration on the Torres Strait lobster population.
- Investigate the impact of the diver fishery on the lobster population in the Torres Strait, including the impact of compressed air diving equipment.
- Test the hypothesis that lobsters die at the end of the breeding emigration to Yule Island.
- Establish whether the Yule Island breeding population has the potential to provide recruitment to the Torres Strait fishery.
- Estimate the abundance of the rock lobster resource in Torres Strait and make an assessment of potential yield.
- Survey the extent of the breeding population in the Gulf of Papua and far northern Great Barrier Reef.

This report is organised into sections that correspond to one or more of the above objectives. However, research related to several of the objectives yielded additional information which is described in additional sections.
Western Torres Strait settlement grounds survey

Little scientific investigation has occurred in the area of Torres Strait west of longitude 142°E (Fig.2). At one time this area included important fishing grounds for pearlshell, *Pinctada maxima*, but little pearling has occurred there recently. The area was of interest as a potential settlement ground for post-larval *Panulirus ornatus*. The extensive, but at the time undescribed, seagrass beds known to exist in the area may have been nursery areas that could supply the fishery to the east with recruiting rock lobsters.

A survey for *P. ornatus* in the western Torres Strait was organised jointly with Mr Jim Prescott from the Papua New Guinea Department of Fisheries and Marine Resources (PNG-DFMR) and carried out during September–October 1987 using the PNG-DFMR research vessel *F.R.V. Kulasi*. Surveys were done by two divers drifting with the current while searching the bottom for juvenile and adult rock lobsters. Survey sites were selected essentially at random but some sites such as reefs and other likely areas were chosen from charts of the area. Information on bottom type, number of lobsters and the distance over which the divers drifted was recorded for each site. Quantitative data on seagrass abundance was also gathered, usually adjacent to an open-water lobster survey site.

Thirty seven sites were surveyed for rock lobsters covering approximately 52 km of seabed (Fig.2). About half (19) of the sites had shelter suitable for large lobsters but only 18 lobsters were seen, and none of these were newly settled juveniles. No lobsters were seen during extensive searching of seagrass beds. Most (13) lobsters were found on Cook Reef and the fringing reef of Deliverance Island with only four lobsters seen in the open water sites. Overall, only 0.35 lobsters were seen per km of seabed surveyed and only 0.086 lobsters km$^{-1}$ in the open water sites. These densities were very low compared with those in the central area of Torres Strait observed during the 1989 lobster survey (see Section 7), i.e. 4.2 lobsters km$^{-1}$ of 4m wide
transects, or an estimated 7.1 lobsters km⁻¹ for transects restricted in width only by underwater visibility.

Seagrass was most abundant in the southern part of the survey area and around the north-eastern islands. Seagrass was sampled to a depth of 33 m in the southern sites, where the water visibility was up to 15 m compared with <1 m in the northern sites. Many of the central to northern sites had rolling sand dunes progressing to mud closer to the PNG coastline.

Conclusions

This survey indicates that the far western Torres Strait area is not a major settlement ground for *P. ornatus*, nor does it appear to support a significant adult population. Information from fishermen and subsequent surveys such as the 1989 abundance survey indicated that in the year of the western Torres Strait survey, large numbers of post-larval lobsters had settled in the area of the fishery to the east.
Population changes caused by migration

During spring each year most $2^+$ year old lobsters, emigrate from the Torres Strait fishing grounds toward the east, where, up until 1984, they were exploited by trawlers (MacFarlane and Moore, 1986; Bell et al., 1987). The timing of trawler catches of emigratory lobsters in Australian waters was variable (Williams, 1985), therefore a field program began in 1985 to identify changes in population parameters that indicated when lobsters were emigrating from the fishery.

Changes in the size frequency, sex ratio and moult activity of the $P.\ ornatus$ population were investigated by measuring the size, sex and moult stage of lobsters in the commercial catch. Catches were monitored from a base camp at Tudu Island in 1985 and 1986 and from Mabuiag and Tudu Islands in 1988. Lobsters measured were caught in the vicinity of these islands. The period of sampling varied but included August and September in all years. Nearly 38 000 lobsters were sampled during the 3 years of the study.

Size frequency

The size frequency distribution of the catch, and the effect of the emigration on it, exhibited two patterns. In 1985 and 1988 the pre-emigratory (July/August) size distributions were bimodal with the fishermen exploiting $2^+$ and larger $1^+$ lobsters, and after the emigration (October), the distributions were almost unimodal with virtually no $2^+$ lobsters present (Fig.3). In 1986, the pre-emigratory size distribution was unimodal with fishermen exploiting only $2^+$ year old lobsters. After the emigration the distribution was still unimodal although there were less larger and more smaller lobsters in the catch causing the distribution (see Fig.3) to move to the left. Note that the 1986 $2^+$ lobsters are smaller than in 1985 or 1988, perhaps because of density dependant effects (see Section 3). In 1986, a very strong $2^+$ year class produced a record catch (Channells et al., 1987) ~50% greater than either 1985 or 1988. The strong 1986 $2^+$ year class dominated the catch before the emigration and was still in high enough densities to dominate the catch after the emigration.

Fig.3. Size-frequency of $P.\ ornatus$ in the Torres Strait catch in 1985, 1986 and 1988 before (August/July) and after (October) the emigration.

The progressive loss of $2^+$ $P.\ ornatus$ from the catch was illustrated by calculating the percentage of the catch made up by lobsters larger than
the midpoint between the $1^+$ and $2^+$ modes found in the pre-emigratory catch size-frequency (there is a small $1^+$ mode in 1986) using the computer program MIX (MacDonald and Pitcher, 1979). The midpoints were calculated separately for each year to take account of variable growth between years. Lobsters larger than this midpoint were assumed to be $2^+$ years old. The two patterns seen in the size frequency distributions were repeated (Fig.4a); while the proportion of large (mainly $2^+$) lobsters in the catch dropped to low levels in 1985 and 1988, it dropped only slightly in 1986 and even showed an apparent recovery. In a year with a strong $2^+$ year class like 1986, percent large lobsters in the catch will not adequately reflect the reduced abundance of $2^+$ lobsters in the fishery caused by the emigration because fishermen preferentially fish large lobsters (CSIRO, unpublished data).

A better indicator of emigratory activity was the proportion of $2^+$ female lobsters in the catch which showed a large and permanent decline due to the emigration in all years (Fig.4b). This was because $2^+$ females make up a majority of the emigratory population and consequently, their numbers in Torres Strait experience proportionally the greatest decline. The decline in the proportion of large female lobsters in the catch occurred during late August and September in 1985, during September in 1986 and during August and September in 1988.

![Fig.4. Proportion $P. ornatus$ in the Torres Strait catch that was: a) $2^+$ year old lobsters and b) $2^+$ year old female lobsters; for 10 day intervals in 1985, 1986 and 1988. Lines show the decline in the proportion of $2^+$ female lobsters in the catch for each year fitted by eye.](image)

![Table 1. Sex ratios of the Torres Strait catch of $P. ornatus$ before (July) and after (October) the emigration. $H_0$: m:f July = m:f October.](table)

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<td>July</td>
<td>1:0.985</td>
<td>260</td>
<td>p&lt;.001</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>1:0.677</td>
<td>446</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>July</td>
<td>1:0.913</td>
<td>4273</td>
<td>p&lt;&lt;.001</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>1:0.420</td>
<td>3662</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>July</td>
<td>1:0.974</td>
<td>9689</td>
<td>p&lt;.001</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>1:0.836</td>
<td>340</td>
<td></td>
</tr>
</tbody>
</table>

**Sex ratio**

The population remaining in Torres Strait becomes significantly biased to males after the emigration (Table 1) because more female lobsters emigrate than males (MacFarlane and Moore, 1986). This effect was greatest in 1986 where the post-emigratory catch was mainly made up of $2^+$ lobsters that did not emigrate which were predominately males. In 1985 and 1988, the change in the sex ratio of the catch was smaller.
because after the emigration, the post-emigratory catch was mainly composed of $1^+$ lobsters which have a sex ratio near to unity. However, sex ratio was not useful as an indicator of migratory activity because it was variable on smaller time scales.

**Moult activity**

Moult activity was defined as the proportion of the lobster sample that showed signs of imminent or recent moult ing. In 1985, microscopic examination of the pleopods was used to identify the moult stage of lobsters; lobsters in pre-moult (stage D2), and postmoult (stages A and B) were classified as moult ing. These moult stages last from approximately 3 d before to 4 d after ecdysis (Turnbull, 1989). In 1986 and 1988 the pliability of the exoskeleton was used to indicate moult stage and lobsters were classified as moult ing if their tails could be squeezed easily by hand. These soft-shelled lobsters included premoult lobsters where reabsorption of the shell had taken place, and postmoult lobsters where the shell had not yet hardened completely.

![Graph](image)

**Fig.5.** Moult activity of *P. ornatus* in the Torres Strait lobster catch (moult stages A, B and D2 in 1985, and soft-shelled in 1986 and 1988) for 5 day intervals in 1985, 1986 and 1988. The third quarter of the moon and the start of the decline in numbers of $2^+$female lobsters is also shown.

The moult ing activity of the catch showed a lunar rhythm. The pattern was clearest in 1988 with peaks in moult ing activity generally occurring about one week after the full moon (third quarter; Fig.5). The lunar rhythm of moult ing observed for *P. ornatus* has not been reported previously for any palinurid and may be a mechanism to reduce predation via a dilution effect, where predators are limited by the rate at
which they can utilize prey during brief peaks in vulnerable moulting activity (Bertram, 1978; Reaka, 1976).

There was a large peak in moulting activity in late August to early September each year (Fig.5). The increase in moulting activity was most evident for 2+ females and to a lesser extent for 2+ males; 1+ lobsters showed no increase in activity above the normal lunar pattern (Fig.6). Although the relative moulting activity of 2+ females may be elevated during more than one moon phase each year, most females moulted during a single moon phase; any subsequent large peaks (such as in 1988) occurred when most 2+ females had emigrated. The timing of the first increase in moulting activity of 2+ female lobsters above the average relative moulting activity for the catch closely preceded the start of the decline in the proportion of 2+ females in the catch (Fig.5).

Crustaceans, generally do not mate prior to a pubertal or maturation moult in which physical and behavioural changes may take place (Sastry, 1983). Female 2+ *P. ornatus* that moulted during August and September 1988 showed a significant increase in the length of the...
pleopod on the second abdominal segment (Fig.7) in relation to carapace length (modified $t$-test comparing points on two regression lines: $p<0.002$; Zar, 1984). The increase in pleopod length is probably related to the use for pleopods to brood eggs and is comparable to the changes in the morphology of female pleopods during the maturation moult and subsequent reproductive moult observed in many other palinurids (Aiken and Waddy, 1980). This change in morphology of the female pleopods and the fact that the synchronous moult was the last moult before initial mating and reproduction among migrating lobsters indicates that it was a maturation moult.

**Conclusions**

Around August and September each year, $2^+$ lobsters, especially $2^+$ females, moult and emigrate out of Torres Strait to begin their breeding migration. This causes changes in the size frequency, sex ratio and moulting activity of the population. The magnitude of these changes, as indicated by the lobsters in the catch, differs among years depending on the relative strength of the $2^+$ year class. The timing of the start of the emigration ranged over 1 month and emigratory activity lasted between 4 and 8 weeks. There was a strong link between moon phase and emigratory behaviour.

The emigration of *P. ornatus* out of Torres Strait is probably comparable to the movement from nursery grounds to adult habitat that occurs in many species of palinurid lobsters (Herrnkind, 1980). For example the two best studied continental shelf palinurids, *P. argus* (Gregory et. al., 1982; Herrnkind and Lipcius, 1989; Davis and Dodrill, 1989) and *P. cynus* (Phillips, 1983).
Growth, size–structure and life history

Growth rate is an important parameter in fisheries science and is a necessary component of most fisheries models; for example, yield per recruit analysis. Further, information on growth parameters, when combined with size-frequency data for various subset populations of the lobster stock (e.g. the catch or the migratory population), can estimate the age composition of these subsets and thus provide life history information.

A growth curve for *Panulirus ornatus* was estimated from a variety of existing data including; tag-recapture data for growth parameters of lobsters 38mm to 125mm CL, aquarium growth data for parameters of early growth, and data on hatching and settlement times for the duration of larval life. The resulting growth curve was then compared to population size-frequency data that was gathered in 1989. Size-frequencies of the catch in 1988 and the catch and emigratory population in 1989 were used to illustrate the composition of those populations.

Growth was estimated from existing tag-recapture records, the majority of which came from extensive lobster tagging studies carried out up to 1985 in Torres Strait and on the east coast of Australia. The details of the tagging techniques and the movements of tagged lobsters were reported by Moore and MacFarlane (1984) and Bell et al (1987). Carapace length (CL) was measured at the time of tagging and field growth rates were determined from the size increase of recaptured lobsters.

A total of 126 tag-recapture records were analysed by using a nonlinear least squares model corresponding to Fabens (1965) equation to fit the von Bertalanffy growth parameters to the tag-recapture data (Kirkwood and Somers, 1984). The size range of the tagged lobsters ranged from 38 mm to 125 mm CL and periods of release varied from one month to three and a half years. Separate growth curves were calculated for each sex (Table 2).

<table>
<thead>
<tr>
<th>Method</th>
<th>Sex</th>
<th>$L_\infty$ (mm)</th>
<th>$K$ (year$^{-1}$)</th>
<th>$t_0$ (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tag-recapture</td>
<td>F</td>
<td>144.23</td>
<td>0.583</td>
<td>0.736</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>162.35</td>
<td>0.447</td>
<td>0.663</td>
</tr>
<tr>
<td>Aquarium growth</td>
<td>F</td>
<td>126.32</td>
<td>0.730</td>
<td>0.787</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>131.85</td>
<td>0.752</td>
<td>0.793</td>
</tr>
</tbody>
</table>

Data from previous aquarium studies of growth, where an initial total of 20 newly settled post-puerulus lobsters were held for up to 3 years, was reanalysed to provide two sets of growth parameters. The first set of parameters were for the period of growth up to 250 days after settlement when size increases roughly exponentially with age, and the second set...
of parameters were for growth after 250 days when growth follows the von Bertalanffy growth curve.

The period of growth from settlement to the inflection at 250 days can be fitted with an exponential equation,

\[ t = a e^{k't} \]  

(Ricker, 1975) using nonlinear least squares (Table 3). Growth in the period after the inflection can be approximated by the von Bertalanffy equation and the growth parameters were calculated using nonlinear least squares (Table 2).

**Table 3. Parameters of the exponential growth equation (1) for *P. ornatus* (sexes combined) between settlement and 250 days old from data on growth in aquaria. The parameter \( t_0 \) was calculated by anchoring the curve at 6.50 mm CL at 0.5 years after hatching.**

<table>
<thead>
<tr>
<th>( a )</th>
<th>( k' )</th>
<th>( t_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm)</td>
<td>(year(^{-1}))</td>
<td>(years)</td>
</tr>
<tr>
<td>6.50</td>
<td>2.33</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Larval life**

Hatching occurs between December and March with January chosen as an average (MacFarlane and Moore, 1986; Bell *et al.*, 1986). The settlement of post-larval rock lobsters on a jetty in Cairns harbour had been monitored between 1982 and 1985. Reanalysis of this data showed that settlement occurred between June and August with July chosen as the average (Fig.8). This indicated a larval life, the time between hatching and settlement, of about 0.5 years.

**Fig.8.** Average number of newly settled (<8 mm CL) *P. ornatus* found on a Cairns jetty per month between 1981 and 1985.

**Growth curves**

The different growth curves for the separate life history stages could be positioned on the age axis using the entire suite of information on larval life, early growth and adult growth. This was done by calculating \( t_0 \) for each of the growth equations. The \( t_0 \) for the early growth equation was equivalent to length of larval life (Table 2). Using the equation for early growth, we estimated that lobsters were 38 mm CL at 1.26 years old. The \( t_0 \) for the von Bertalanffy equations for lobsters >38 mm CL were found by anchoring the curve at 38 mm CL and 1.26 yr, then solving the equation for \( t_0 \) (Table 2). The complete length versus age curves are illustrated in Fig.9.
Fig. 9. Growth curves for male and female P. ornatus. L=larval life, E=early growth, 
V=von Bertalanffy growth (T=tag-recapture data, A=aquarium growth). Also shown is 
the size of the modes of the length frequencies for the four quadrats of the 1989 
population survey (NW=north-west etc.).

A survey of the lobster population in the Torres Strait fishery was 
carried out in June 1989 (see Section 7). As part of that survey, an 
unbiased size-frequency sample of the lobster population was collected 
(Fig.10). Modal analysis of the size-frequency of the sample was carried 
out using the computer program Mix (Macdonald and Pitcher, 1979). 
The results of this analysis showed that the population was composed 
almost entirely of two year classes. Lobsters hatch in January and settle 
in July. Therefore, the two modes were ~17 months (1+ years) and ~29 
months (2+ years) old respectively. Some older males also occurred in 
the population but the absolute proportion that they made up was too 
small for modal analysis to adequately resolve them. This is consistent 
with the results of studies on the emigratory behaviour of lobsters in the 
Torres Strait which show that while almost all 2+ females leave the 
fishery on the emigration, a proportion of 2+ males do not (see Section 
2).

Another feature of the survey results was that when the size-frequency 
sample was split into four quadrats with the central point at 142°34' E 
and 10°11' S, lobsters in the eastern quadrats were smaller than lobsters 
in the western quadrats (Table 4, Fig. 11). When compared with the 
growth curves calculated earlier (Fig.9), the size of the lobsters in the 
eastern quadrats were closest to the calculated growth curves; the 
lobsters in the western quadrats were larger. This is probably because 
the lobsters that made up the tag-recapture data were almost entirely 
from the east coast and the aquarium studies were done even further 
south at Cairns.
Fig. 10. Size-frequency distributions of *P. ornatus* from the catch in 1988 and from the population survey, catch, and emigratory population in 1989.

Table 4. Average size of the modes of the size-frequency distributions of *P. ornatus* sampled during the population survey in 1989, for each quadrat of the sample area; and the size of lobsters at the same age calculated from the von Bertalanffy equation derived from tag-recapture data and aquarium growth.

<table>
<thead>
<tr>
<th>Sex</th>
<th>Sample</th>
<th>CL (mm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.42 yrs</td>
<td>2.42 yrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>old</td>
<td>old</td>
</tr>
<tr>
<td>F</td>
<td>1989 survey</td>
<td>northwest</td>
<td>57.42</td>
<td>99.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>southwest</td>
<td>57.02</td>
<td>96.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>northeast</td>
<td>55.49</td>
<td>93.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>southeast</td>
<td>51.19</td>
<td>85.86</td>
</tr>
<tr>
<td>M</td>
<td>northwest</td>
<td>58.16</td>
<td>107.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>southwest</td>
<td>54.47</td>
<td>112.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>northeast</td>
<td>52.08</td>
<td>99.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>southeast</td>
<td>53.34</td>
<td>96.43</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>tag-recapture</td>
<td>47.45</td>
<td>90.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>aquarium growth</td>
<td>46.74</td>
<td>87.97</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>tag-recapture</td>
<td>46.61</td>
<td>88.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>aquarium growth</td>
<td>49.57</td>
<td>93.06</td>
<td></td>
</tr>
</tbody>
</table>

The tag-recapture growth curve for males (Fig. 9) is slower than expected for two reasons. Firstly, the aquarium growth and field size-
frequency samples indicate that males grow faster than females at all stages, whereas the male tag-recapture growth curve is slower than the female equivalent even at 2+ years old (Table 4). Secondly, the female tag-recapture growth curve and the size of females in the eastern quadrats are closely correlated whereas the male tag-recapture growth curve is lower than the size of males in the eastern quadrats.

Fig. 11. Size-frequency distributions of P. ornatus from the population survey in 1989, with sample area split into 4 quadrats. The results of modal analysis is shown in Table 3.

**Catch composition**

Size-frequency data was collected from the catch during June–July 1988 and 1989 (Fig. 10). This showed that fishermen were exploiting mainly the 2+ lobsters and varying numbers of the larger of 1+ lobsters. The proportion of 1+ lobsters in the catch was probably affected by the abundance of the 2+ year class. Other studies have indicated that 2+ lobsters were less abundant in 1988 than in 1989 (see Section 7). More 1+ lobsters contributed to the catch in 1988 than 1989 (Fig. 10).

The catch size-frequency also showed that there were differences in the size of 2+ lobsters between years: the average size of 2+ lobsters was larger in 1988 than in 1989 (Table 5). This effect could be due to density-dependent processes as 2+ lobsters were less abundant in 1988 than in 1989.

**Table 5.** Average size of the 2+ mode of the size-frequency distributions of P. ornatus sampled from the catch in 1988, and the catch and migratory population in 1989.
<table>
<thead>
<tr>
<th>Sex</th>
<th>Sample</th>
<th>CL (mm) 2.4 yr-olds</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>catch 1988</td>
<td>108.62</td>
</tr>
<tr>
<td></td>
<td>catch 1989</td>
<td>102.46</td>
</tr>
<tr>
<td></td>
<td>migration 1989</td>
<td>104.52</td>
</tr>
<tr>
<td>M</td>
<td>catch 1988</td>
<td>121.72</td>
</tr>
<tr>
<td></td>
<td>catch 1989</td>
<td>113.70</td>
</tr>
<tr>
<td></td>
<td>migration 1989</td>
<td>115.42</td>
</tr>
</tbody>
</table>

**Migratory population**

The migratory population was sampled in November 1989 (Fig.10). Modal analysis and comparison with the population size-frequency showed that the migrating lobsters were mostly $2^+$ lobsters with $3^+$ males making up 10% of the population. This is consistent with the results of studies on the emigratory behaviour of lobsters in the Torres Strait which show that while almost all $2^+$ females leave the fishery on the emigration, a proportion of $2^+$ males do not (see Section 2). Males that do not migrate when they are $2^+$ probably migrate the following year.

**Conclusions**

*P. ornatus* are very fast growing, perhaps the fastest growing of any palinurid studied (Trendall *et al.*, 1988). Growth varies on both spatial and temporal scales: spatial variability is probably the result of environmental factors such as temperature and/or food availability; temporal variability may also be a result of environmental factors and/or density dependant effects. The discrepancies between the calculated growth curves and the actual size of lobsters in the Torres Strait population may be resolved to some extent by more work on ecology of juveniles. In particular, timing of settlement and growth after settlement.

The fishermen exploit each year class for only about 1 year, thus the catch would be susceptible to variations in year class abundance. The relative constancy of the catch is remarkable and is probably due to many factors, not the least of which is that the exploitation rate is low overall ($F > 0.1$; Pitcher *et al.*, 1992a).
Catch monitoring

Information on catch and effort are basic to assessing the impact of any fishery on a stock. In Torres Strait, there are also three categories of fisherman: (1) divers using hookah and based on mobile fishing vessels with freezers; (2) divers using hookah and based on islands; and (3) free-divers based on islands. Differences among these three categories must be understood in order to define an appropriate unit of effort.

The catch and effort of all three categories of fishermen were monitored between June and October 1988; this information was compared with 1986 data to assess changes in the fishery. In subsequent years, only the island based sector (around Mabuiag Island) of the fishery was monitored because it may be more susceptible to overfishing (as it lacks the mobility of the freezer vessel fleet) and it is not covered by the logbook monitoring. The size-frequency distribution of the catch was also measured and this, combined with other sub-projects, contributes to an assessment of the level of exploitation of the stock.

The proportion of divers using hookah increased dramatically from 1986 to 1988: among freezer-vessel divers, the increase was from ~33% to ~100% of diver-days; among island-based divers, the change was from ~0% to ~62%. The use of hookah has continued to remain at virtually 100% among freezer-vessel divers but has declined among island-based divers (1989, ~30%; 1990, ~34%).

The catch-rate differed among the three categories of divers: Islander hookah-divers and vessel hookah-divers caught more kgs per day than Islander free-divers (Fig.12a); vessel hookah-divers caught more kgs per hour than Islander hookah-divers and both caught more kgs per hour than Islander free-divers (Fig.12b). However, during the sampling period in 1988, several island-based divers switched from free-diving to hookah diving, thus enabling a comparison between diving method with the same individual fishermen, controlled by divers that did not switch. The average catch-rate (kg day\(^{-1}\) & kg hr\(^{-1}\)) increased ~2-fold with use of hookah, but the response of individual divers to the switch varied greatly — one caught almost 3-fold more while another caught slightly less when using hookah. Overall the effect of hookah was not significant and depended on the individual.

Fig.12. The catch per unit effort — (a) kgs per day and (b) kgs per hour — of Torres Strait lobster divers belonging to three categories in 1988: Islander free-divers, Islander hookah-divers, or boat hookah-divers. The results of one-factor nested ANOVA and subsequent SNK test (\(a = 0.05\)) are shown.
Continued monitoring of the catch and effort of the Islander fishery based around Mabuiag Island during June of 1989 and 1990 showed significant interannual differences in CPUE. The CPUE of the Islanders in mid-1988 and 1990 was similar (1988 = 1.84 kg hr⁻¹; 1990 = 1.98 kg hr⁻¹; Fig.13), but 1989 was significantly greater (3.15 kg hr⁻¹). The lower catch rate in 1990 was expected from the results of 1989 stock survey (see Section 7) which revealed a relatively small pre-fishery (1⁺) year-class that became the fishable stock in 1990. The catch monitoring in 1989 and 1990 again showed that the catch-rate of hookah-divers was greater than free-divers, although the disparity steadily reduced over the three years of monitoring (Fig.13).

**Fig.13.** Interannual changes in CPUE (kgs/hr) of Torres Strait lobster divers based at Mabuiag Island. The results of ANOVA and subsequent SNK tests (@ 5% level) are shown.

**Conclusions**

The difference in catch rate of free-divers and hookah-divers reduced over the three year period and there is no evidence that continued use of hookah is detrimentally impacting the catch-rate of free divers.

The interannual variations in CPUE correspond with the differences in total catch among years (1988 = 216 t, 1989 = 243 t, 1990 = 183 t) and presumably reflect differences in the abundance of the lobster stock. The lower CPUE and catch in 1990 was expected from the results of the 1989 stock abundance survey (see Section 7) which revealed a relatively small recruiting (1⁺) year-class.

Catch monitoring in conjunction with the stock surveys (Sections 7 and 8) has indicated that the level of exploitation of the lobster stock (i.e. the fishing mortality $F$) is very low compared with other fisheries ($F \approx 0.1$, see Section 14 — Stock Assessment).
**Mortality of breeding lobsters at Yule Island**

The lobsters that emigrate from Torres Strait to breed on reefs around Yule Island are in poor physiological condition (Trendall & Prescott, 1989) and the artisanal fishery based on these breeding lobsters lasts only a few months, after which no lobsters are found. Consequently, it has been suggested that the lobsters invest so much energy in migrating (~500 km) and reproducing that death is inevitable (Moore & MacFarlane, 1986; Trendall & Prescott, 1989). However, the Yule Island population could also decline because of high fishing pressure or lobsters may move into deeper water and become inaccessible to the artisanal fishermen.

To understand the robustness of the lobster stock, and the measures that may be necessary for its conservation, it was important to determine the reason for the disappearance each year of the Yule Island breeding population. In the 1988/89 summer, several complementary research methods were used to distinguish between these alternatives: off-reef tangle netting, catch and effort data, tag-recaptures, and water content of tissue samples. These methods provided information on the numbers of immigrating and emigrating lobsters, natural and fishing mortality rates, and the daily changes in physiological condition of lobsters. This project was carried out in conjunction with Jim Prescott, PNG DFMR.

**Catch and effort**

The catch and effort of the Yule Island fishery were monitored during January through March 1989 to show changes in abundance. The catch followed a typical pattern, with two major peaks in catch before waning through March (Fig.14). The sex ratio of the first peak was close to unity, whereas the second peak comprised almost entirely females (Fig.14).

![Fig.14. Daily catch of the Yule Island P. ornatus fishery from 1 December 1988 to 31 March 1989 and the change in sex ratio from 18 January to 31 March 1989.](image)

Total loss rates were estimated from the exponential decline of the catch per unit of effort (CPUE; kg fisherman⁻¹ day⁻¹) time series and, because of the change in sex ratio with time, separate segments of the CPUE series was used for females and males. The daily instantaneous total
mortality rates ($Z_{\text{day}}$) were estimated to be 0.032 for females and 0.033 for males; equivalent to annual instantaneous total mortality rates ($Z_{\text{ann}}$) of 11.6 and 12.0 respectively. These mortality rates are extremely high and correspond to about 95% mortality during the three month fishing season.

Tangle nets (2' 500 m) were deployed just off the reef edge at Yule Island (~20 m depth) from 18 January to 31 March 1989 to monitor lobster movements, both on and off the reef, during the fishing season. The nets caught mainly female lobsters (67 females:3 males), in two pulses, in synchrony with the January and February full moons (Fig.15). Nearly all of the females had recently shed broods of eggs and several that were tagged from the nets were caught later by fishermen on the reef top. Therefore, catches of female lobsters in the tangle nets were interpreted as short off-reef excursions to hatch eggs coincident with the full moons.

During the period when the catch rate of the fishery was falling rapidly through March, there was no evidence in the tangle net catches of a corresponding emigration from the fishing grounds (Fig.15); only 4 lobsters were caught in the nets during March. On this basis, movement of lobsters to deeper water was rejected as a hypothesis for the cause of the decline in the Yule Island population.

![Fig.15. Daily catch of P. ornatus from the tangle nets at Yule Island (a) contrasted with the daily catch of the fishery (b). The solid horizontal bar indicates the days when tangle nets were used and the open circles correspond to full moons.](image)

A total of 228 lobsters (93 males, 135 females) were captured using hand nets, tagged with plastic cable ties, and then released on the reef edge at Yule Island, between 18 January and 31 January 1989. About one third (0.32; 22 males and 51 females) of the tagged lobsters were recaptured by divers, so the exploitation rate during the fishing season was estimated at 0.32. During the period that recaptures were recorded (31 January to 31 March), divers caught 7638 lobsters; thus the size of the $P. ornatus$ population in the vicinity of Yule Island, estimated by Petersen's single census analysis (from Ricker, 1975 eqn. 3.5) of the tag-recapture and catch data, was $23,900 \pm 20\%$.

The tagging study also provided independent estimates of the daily instantaneous total mortality rate ($Z_{\text{day}}$) and the daily instantaneous fishing mortality rate ($F_{\text{day}}$), by graphical analysis of the recapture rate...
over time (Gulland, 1983; pp. 109–111). $Z_{\text{ann}}$, estimated from the slope of the regression of the natural log of recaptures against time, was 0.028 (Fig. 16) which is equivalent to $Z_{\text{ann}} = 10.2$ and consistent with the very high estimates from the analysis of CPUE data. $F_{\text{day}}$, estimated from the intercept of the regression, was 0.012 which is equivalent to $F_{\text{ann}} = 4.4$. Thus, although fishing mortality was extremely high and was responsible for much of the decline, natural mortality accounted for most of the total mortality ($M = Z - F = 5.8$ or 57% of total), probably because of the stress of migrating and breeding.

**Fig.16.** Linear regression of the natural logarithm of the tag recaptures against time, showing estimation of the total mortality rate of the Yule Island *P. ornatus* population from the slope of the decline.

**Fig.17.** Changes in the water content of the hepatopancreas (HP) of male (l) and female (m) *P. ornatus* from the catch of the Yule Island fishery between 18 January and 31 March 1989. Error bars are ± 1 SE.

*Physiological condition*

The percentage water content of samples of the hepatopancreas was measured to indicate the physiological condition of lobsters (see Trendall and Prescott, 1989). In contrast with the water content for Torres Strait lobsters in good condition (~60%, Trendall and Prescott, 1989), the average water content of lobsters at Yule Island increased from ~70% in mid-January to ~80% by mid-February and then fell slightly through March (Fig. 17). The initial rapid increase to ~80%
indicates a deteriorating physiological condition to a probably fatal state for much of the population (Trendall and Prescott, 1989). The fall in water content through March is probably a result of sampling only the very few surviving lobsters that had lower average water content, rather than an indication of a recovery in the whole population. The apparent recovery in physiological condition was more evident for the males than for females. In males, the timing of the apparent recovery corresponded with the appearance of a higher proportion (though very few in number) of recently moulted individuals (Fig.18) and with a stabilisation of their catch rates at a very low level; these factors suggested that the mortality rate of males had fallen to a much lower rate. It is possible that these very few males could survive the fishing season and become resident on the coastal reefs.

![Graph showing the number and percentage of newly moulted male and female P. ornatus in the catch of the Yule Island fishery between 18 January and 31 March 1989. Open bars and dotted line indicate females, filled bars and continuous line indicate males.](image)

**Fig.18.** Number and percentage of newly moulted male and female *P. ornatus* in the catch of the Yule Island fishery between 18 January and 31 March 1989. Open bars and dotted line indicate females, filled bars and continuous line indicate males.

**Conclusions**

The annual decline in catches of *Panulirus ornatus* by the Yule Island fishery is most likely the result of high natural mortality (~60%) combined with high fishing exploitation (30–40%). It appears that there is little or no emigration off the coastal reefs into deeper water, although females temporarily move off the reef to hatch their eggs during full moons. The cause of the high natural mortality rate may be physiological stress exerted by migrating and breeding, as suggested by Moore and MacFarlane (1984) and Trendall and Prescott (1989).

The important implication from this conclusion is that if all breeding populations suffer similar catastrophic mortality then settlement into the fishing grounds each year may depend entirely on the breeding success of the preceding years emigration which should therefore be conserved; there would be no buffer against poor recruitment that would exist if there were several year-classes of breeding lobsters.
The importance, to the Torres Strait lobster fishery, of the breeding population on the coastal reefs around Yule Island in the eastern GoP depends on whether larvae hatched there could be carried by the currents to later settle back into Torres Strait. To assess this possibility, it was necessary to describe the ocean current patterns in the north-western Coral Sea adjacent to the breeding grounds in the eastern GoP. This project was carried out in conjunction with Jim Prescott of the PNG DFMR.

**Satellite tracked buoys**

Buoys with satellite telemetry electronics and drogues set at 15 m and 80 m were deployed in deep water off the coastal reefs in the eastern GoP in December 1988, and February and March 1989. These buoys were tracked by the French Argos satellite system and their positions were reported every 3-days. The buoys transmitted for up to three months until a cyclone rendered them unserviceable in early April. Initially, all buoys were transported rapidly eastwards — the buoys released in February continued to the eastern limit of PNG territory before being advected back to the southwest (one of these buoys was eventually recovered from the Great Barrier Reef off Port Douglas); the buoys released in March were transported back to the west at the end of March and meandered into the northwestern Coral Sea (Fig.19).

These patterns of movement indicate the presence of a clockwise gyre in the north-western Coral Sea. A similar buoy released by the Australian Institute of Marine Science (D. Burridge, unpubl.), in mid-1988, was carried in a full circuit of this region of the Coral Sea (Fig.19) over a period of about four months.

**Conclusions**

The clockwise gyre in the north-western Coral Sea has the potential return larvae hatched near Yule Island back to Torres Strait and indicates that the breeding grounds around Yule Island are a potential source of recruitment to Torres Strait. In fact, because of this gyre, larvae hatched anywhere along the edge of the Coral Sea from about Cooktown to Port Moresby would probably circulate in the...
northwestern Coral Sea and have the potential to be advected into Torres Strait
Estimation of Lobster Abundance

Orderly managed expansion of the Torres Strait lobster fishery would be facilitated by knowledge of the potential yield, as is the case with any other fishery. The usual method of estimating potential yield, by analysis of catch and effort data, is not suitable for the Torres Strait dive fishery because only part of the effort is monitored and these records began only recently. Consequently, an alternative approach to estimating potential yield from information on absolute stock size was considered. This approach would also provide valuable input for the development of fishery dynamics models.

Of the few attempts to estimate the absolute abundance of spiny lobsters most have used tagging methods (Morgan 1980), which are often subject to serious error problems and biases (Morgan 1974, Gulland 1983). Obviously it was desirable to avoid these problems. As these lobsters are fished by divers, and the depth of Torres Strait in the vicinity of the fishery is rarely greater than 25 m, it was logical for research divers to attempt a direct visual census of the lobsters. This approach has been successful with estimating the stock of the spiny lobster *P. argus* on the Bahama Banks (Smith and van Nierop 1986).

This section describes how research divers estimated the *P. ornatus* stock in Torres Strait by counting lobsters in strip-transects. The area surveyed enclosed approximately 25,000 km² of potential lobster habitat (Fig. 1). This project was carried out in conjunction with Jim Prescott of the PNG DFMR which also provided its research vessel *FRV Kulasi* and crew.

Prior to attempting the full-scale stock survey, it was essential to assess its feasibility and determine the most effective sampling strategy by undertaking pilot studies in the area. These were done during mid-1988 and full details are described in Pitcher *et al.* (1992a).

The pilot study was designed to optimize the sampling unit (transect) because the precision of abundance estimates can be affected by the area and shape of sampling units depending on how a study organism is distributed in its environment (Andrew and Mapstone 1987). The width of transects is also important as cryptic organisms become less visible with distance (Sale and Sharp 1983). Consequently, the effects of total transect area and transect width on the estimates of mean lobster abundance and precision (*p = SE/x*) were examined. This involved surveying 6000 m² of lobster fishing grounds with randomly placed transects of each of 12 combinations of transect area and width. Thus, twelve 500 m², six 1000 m², four 1500 m², and three 2000 m² transects were required for each width (1, 2, and 4 m); totalling 75 transects for one replicate set of estimates of mean and variance for each of the 12 combinations of transect area and width. This procedure was repeated at three other randomly chosen locations within the fishing grounds to give four replicate estimates of abundance and precision for analysis of variance. The time required to lay-out and census the transects of each type was also recorded.

The first pilot study showed that the mean and precision of lobster abundance estimates did not differ significantly with either different areas or widths of transects, though the 1 × 500 m transects tended to underestimate abundance relative to the average over all transects. However, the estimate of the time required for sufficient replicates to attain a particular level of precision (*p=0.10*) differed greatly among transect types. The largest and widest transect type (4 × 500 m) was...
most efficient and could be expected to provide the most precise abundance estimate for a given amount of field time or funds. Thus, $4 \times 500$ m transects were used in all subsequent studies.

The second pilot study was designed to optimize the sampling strategy with respect to allocation of the appropriate replication among a range of spatial scales, because marine organisms are often patchily distributed at multiple spatial scales (Cochran 1977, Underwood 1981, Andrew and Mapstone 1987). This involved assessing the level of variation at larger spatial scales of sampling by counting lobsters in a total of 108 transects: three transects were positioned approximately 0.5 km apart at each of 36 sites; the sites were distributed in groups of three about 2.5 km apart at each of 12 locations; three locations were separated by around 10 km within each of two habitats and two regions of the fishery. For each transect census, a 500 m long line was laid onto the substratum from a dinghy. Two divers then swam down the line carrying a 2 m measuring rod and recording all lobsters within 2 m each side of the line. The times taken to survey each transect, site and location were recorded. The pilot survey data were analysed using a hierarchical ANOVA procedure to estimate the variance in lobster abundance at each spatial scale of sampling (transects, sites, and locations). Cost-benefit procedures (Underwood 1981), that take account of the relative variance and sampling time at each scale, were used to optimize the relative intensity of sampling among transects, sites, and locations. Further, because the relative level of variance within, and the areas of, each habitat differed, it was also important to determine the optimal proportional allocation of the total sampling effort among habitats (Cochran 1977).

The analysis of the second pilot survey showed that sites were not a significant source of variation in lobster abundance, thus sites should be dropped from the sampling strategy. The relative time-cost and variance associated with transects and locations indicated that the most efficient strategy for a full scale study would be to do two transects at each location. This altered sampling strategy required that the variances associated with each habitat be re-calculated for optimal proportional allocation of the total sampling effort to each habitat. The deep habitat covered the largest area and lobster densities in this habitat were the most variable; thus, most of the sampling effort in a full scale study should be allocated to this habitat. Conversely, the reef slope covered the smallest area and, with the least variable lobster densities, should be allocated the least effort. The shoal habitat was intermediate with respect to area and density.

When estimating the abundance of organisms, there is trade-off between the level of confidence of the estimate and the total effort required to obtain it. Based on the level of variance in lobster density observed during the pilot surveys, a suitable compromise was considered to exist when a 95%CI of ±10% of the mean number of lobsters per transect in the pilot stock survey was predicted to be obtained with a total sampling effort of 300 locations. However, the average density of lobsters in a full-scale survey was likely to be less than in the pilot survey, which was undertaken within the main fishing grounds; consequently, it was expected that the 95%CI would be somewhat greater than ±10%. Nevertheless, the surveying of 300 locations was estimated to require at least six weeks of field time, which was a reasonable upper limit to the field commitment. Full details of the survey are described in Pitcher et al. (1992a).
The pilot surveys and optimization of the sampling strategy showed that a full-scale survey was feasible; i.e. a sufficiently precise estimate of lobster abundance was obtainable within budgetary and field-time constraints.

The full scale survey required detailed mapping of the habitats in Torres Strait. Satellite imagery (Landsat MSS data) together with the MicroBRIAN image analysis software were used for detailed mapping and classification of the study area into seven image classes (e.g. Kuchler et al. 1986). This procedure accurately identified the position and determined the areas of the three habitat strata (windward reef slope, shoal areas = submerged coral reef, and areas too deep to subdivide further using this method). In addition, several shallow habitats unsuitable for lobsters (e.g. sand and rubble banks, reef pavement) were identified and eliminated from the survey. The deep stratum actually combined several types of habitat and the density of lobsters varied greatly among them. In order to reduce the overall variance caused by the different habitat types within the deep stratum, an additional five strata within the deep stratum were defined based on habitat data gathered during the survey (i.e., >50% rock, 10–50% rock, <10% rock+rubble, sand, and silt+mud), and these additional strata were included in the analysis.

![Fig.20. Chart of Torres Strait showing survey area; vertical dashed line = eastern boundary of survey area south of Warrior Reef complex; irregular solid lines = coastline of mainland and islands; irregular dotted lines = coral reefs; small filled circles = position of sampled transects; small hollow circles = transects not sampled in northernmost part of study area, near Papua New Guinea coast, due to bad weather.](image)

The positions of all transects were mapped prior to the field phase of the survey to avoid subjective and possibly biased positioning. The entire survey area was divided into 3 × 3 km locations, of which 300 locations were chosen and allocated in close proportion to the known areas and estimated variances of the habitat strata, and at random within each stratum. The coordinates of the beginning of each of the two transects
within each 3 × 3 km location were selected at random from a 0.5 km reference grid. The distribution of these transect pairs is shown in Fig. 20.

The full-scale transect survey of Torres Strait in May-June 1989 took about seven weeks, with three teams of divers, each operating from a dinghy. Two teams counted lobsters while the third team, which included a professional lobster spear-fisherman, sampled the surveyed population for size measurements. The previously mapped starting point of each transect was located by GPS, radar or compass bearings. The 500 m transect line was deployed and paired divers recorded the number of lobsters within the 4 m width of the transect. The amount of seagrass and epibiota, the number of other animals (including pearl shell), and the substratum type were also recorded. Most locations were sampled successfully; however, towards the end of the survey high rainfall over Papua New Guinea increased the flow of turbid water from rivers, and very strong winds mixed seabed sediments into the water column. As visibility was reduced to zero, 29 locations close to the Papua New Guinea coast and the area they represented (~1500 km²) had to be deleted from the survey (Fig. 20).

**Fig. 21.** Chart of Torres Strait showing density of lobsters at sampled locations. Area of filled circles is proportional to density of lobsters; highest density sampled was 90 lobsters ha⁻¹ (largest circle), lowest non-zero density was 2.5 lobsters ha⁻¹ (smallest circles)

Lobsters were observed in 107 of the 271 locations that were sampled and most were found in the southern and western regions of the survey area (Fig. 21). The density estimates of lobsters in locations ranged from 2.5 to 90 lobsters per hectare (Fig. 21). The highest densities of lobsters were associated with the windward reef slope and rocky strata in deeper water. In contrast, the density was virtually zero in the middle part of the northern half of the study area where the substratum was fine sand and silt. Overall, the five additional strata, based on hardness of the
substratum within the deep area, accounted for about 25% of the variance in density of lobsters. The density of the epibenthic macrofauna (sponges, hard, horny, and soft corals) also varied with the hardness of the substratum and division of the deep areas into four strata based on the amount of macrofauna accounted for about 23% of the variance in lobster density. Together, the substratum and macrofauna accounted for about 26% of the variance. The shoal areas, as classified by the image analysis, were shallower than expected and did not include the coralline habitats up to 3 m depth as had been expected. Consequently, much of the latter reef habitat was subsumed into the deep strata, and very low numbers of lobsters were seen in the shoal strata.

The data on lobster numbers per transect were separated into their respective strata and the abundance estimate for the entire study area was calculated as the sum of the products of the mean number of lobsters per transect and the total number of transects within each stratum. This expansion of lobster density estimates per transect for each stratum, yielded a population estimate for the survey area of about 14 million lobsters (Table 6). The variance of each habitat stratum was calculated using nested analysis of variance of the lobster counts in transects at each location. The variance of the overall abundance estimate (actually SE²) was derived from the summation of the products of the variance of each strata and the square of the proportional area of each strata divided by the number of transects (= 2 × n locations) in each strata (Table 1). This variance of the overall abundance estimate was SE² = 0.0185 which corresponded to a 95% CI of ±2.9 million, or ±21% of the lobster population estimate. The precision of the estimate (p: SE/\(\bar{x}\) = 0.105) was relatively high for a large scale ecological study.

### Table 6
Calculation of *P. ornatus* population size and variance estimates for the Torres Strait study area from analysis of variance of the transect survey data; and estimation of the stock biomass and 95% CI from the number and mean weight of legal-sized tails in the population. Wh: proportional area of strata; Nh: total number of possible transects in each stratum; nh: number of locations per stratum; \(\bar{x}h\): stratum mean; \(s^2\): sample variance; \(s_{\text{strat}}\): standard error of overall stratified mean.

<table>
<thead>
<tr>
<th>Strata</th>
<th>Area</th>
<th>Wh</th>
<th>Nh</th>
<th>nh</th>
<th>(\bar{x})h</th>
<th>(s^2)h</th>
<th>N_{h}\ (\bar{x})h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>228</td>
<td>0.0105</td>
<td>114,000</td>
<td>5</td>
<td>3.80</td>
<td>12.65</td>
<td>0.0001</td>
</tr>
<tr>
<td>Shoal</td>
<td>1,009</td>
<td>0.0463</td>
<td>504,500</td>
<td>10</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0000</td>
</tr>
<tr>
<td>&lt;50% Rock</td>
<td>884</td>
<td>0.0405</td>
<td>442,000</td>
<td>11</td>
<td>3.73</td>
<td>14.84</td>
<td>0.0011</td>
</tr>
<tr>
<td>10–50% Rock</td>
<td>2,892</td>
<td>0.1326</td>
<td>1,446,000</td>
<td>36</td>
<td>3.82</td>
<td>34.75</td>
<td>0.0085</td>
</tr>
<tr>
<td>&lt;10% Rock</td>
<td>7,150</td>
<td>0.3279</td>
<td>3,575,000</td>
<td>89</td>
<td>1.46</td>
<td>9.43</td>
<td>0.0057</td>
</tr>
<tr>
<td>Sand</td>
<td>8,195</td>
<td>0.3759</td>
<td>4,097,000</td>
<td>102</td>
<td>0.30</td>
<td>4.43</td>
<td>0.0031</td>
</tr>
<tr>
<td>Silt+Mud</td>
<td>1,446</td>
<td>0.0663</td>
<td>723,000</td>
<td>18</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>21,804</td>
<td>1.0000</td>
<td>10,902,000</td>
<td>271</td>
<td></td>
<td></td>
<td>0.0185</td>
</tr>
</tbody>
</table>

Standard Error: \(s_{\text{strat}} = \sqrt{0.0185} = 0.1359\)

95% C.I.: \(\pm t_{0.05, N_{h}}\) \(s_{\text{strat}}\) = \(\pm 1.964 \times 10,902,000 \times 0.1359 = \pm 2,910,000\)

Population Estimate: \(X = 14,000,000 \pm 20.7\%\)

Stock Estimate: \((\bar{x} \times \text{tail weight}=346 \text{ g}) = 2,776 \text{ t}\)

Confidence Interval: 2,200 - 3,350 t

The abundance estimate from the survey could be converted to an estimate of the fishable stock by weight because the professional lobster
spearfisherman speared all lobsters as they were encountered and these samples from each location were measured, sexed and weighed. The size-frequency distribution of the surveyed population (Fig.22) showed two distinct modes which were separated using "Mix analysis" (Macdonald and Pitcher 1979): the left mode comprised the 1+ year-class and made up 41% of the population, the right mode comprised the 2+ and 3+ year-classes, which made up 57% and ~2% of the population respectively. Lobsters less than the legal size, (i.e. 100 mm tail length, or about 52 mm tail width) would have been almost entirely from the 1+ year-class and made up 43% of the population. Lobsters greater than the legal size accounted for 57% and their average tail weight was 346 g. Thus, the estimate of the fishable (legal-sized) stock in the study area was 6.4–9.7 million lobsters, or between 2,200 and 3,350 t tail weight.

Several thousand lobsters from the commercial catch in June 1989 were measured to compare with the surveyed population and the size-frequency distribution of the commercial catch differed greatly from that of the survey (Fig.22). The 1+ year-class was absent from the fishery sample because, in June, almost all 1+ lobsters were less than the legal size. Nevertheless, the fishermen also target larger lobsters from the 2+ and 3+ year-classes, such that, in the year of the survey, lobsters <70 mm tail width were not fully recruited to the fishery; in other years, this size could vary as growth rates vary among years. The average weight of lobster tails brought to processors in June was 410 g, though it would be about 10% less over the whole year, and the annual catch averaged over the last five years was 250 t of tails; thus, approximately 700,000 lobsters are caught each year. The total number of lobsters in each size class of the catch, when compared with the estimated numbers in the population (Fig.22), gives an estimate of the fishing mortality coefficient ($F$) for each size-class. The $F$ is practically zero for lobsters <52 mm tail width, and although $F$ increases with size >52 mm, until it reaches a maximum and levels off at >70 mm, it is clear that $F$ is small for all size classes (overall $F$>0.1).

![Fig.22. Approximate total numbers of lobsters in each size class of the size-frequency distribution of the surveyed population (open area) contrasted with the numbers and size-distribution in annual catch of fishery (filled area)](image)

**Conclusions**

This survey demonstrated the value of visual transect sampling, a method not used often in fisheries research, for estimating the abundance of a commercially important species. The value of doing pilot surveys to optimize the sampling design was also clear — considerable gains in efficiency were made by calculating the time required to achieve a given level of precision with different types of transect and re-organising the levels of replication at various spatial scales and among the different habitats.
This survey was more than adequate as a baseline for detecting any future dramatic decline in stock numbers (e.g. to << 1500 t); in fact it was sufficiently precise to detect a 20% decrease in abundance (i.e. to < about 2200 t). In contrast, many estimates of stock size have very wide confidence intervals, especially those derived from tagging studies (Gulland 1983), partly as a result of the magnitude of the problem. Using similar transect methods, Smith and van Nierop (1986) estimated the abundance of \textit{P. argus} on the 60,000 km² area of the Bahama Banks with 95%CIs of 80-120%.

Potential sources of bias with transect methods include the cryptic behaviour of lobsters, underwater visibility, ruggedness of the substratum, and differences in the divers' abilities to detect lobsters. However, we consider that the accuracy of the census was likely to be high for four main reasons. First, the divers searched a narrow path intensively, using 2 m measures to delimit the width accurately, so that counts in even cavernous habitat or turbid water should not have seriously underestimated abundance. Second, the substratum of scattered small rocks, rubble and sand that supported about 97% of the population did not provide cavernous dens; consequently, lobsters were not well concealed — their antennae and carapace generally being clearly visible. Third, the rugged coral reef slope habitat, where the chances of under-counting would be highest, comprised only about 1% of the survey area; even if divers undercounted by as much as 50% in this habitat the final stock estimate would be in error by only <1.5%. Fourth, different divers' counts, adjusted for differences among strata, did not differ significantly (MS\textsubscript{div}=2.59, F=1.03 [7,1036], P=0.41). If there was any bias, the stock would have been underestimated only slightly, which is preferable to being overestimated.

The standing stock per unit area of legal-sized \textit{P. ornatus} in Torres Strait (approx. 375 kg/ km\textsuperscript{-2} whole weight) is comparable to the range of estimates made by many workers for \textit{P. argus} in the tropical Western Atlantic (83-583 kg km\textsuperscript{-2}; references cited in Smith and van Nierop 1986). The wide range of estimates for \textit{P. argus} may result partly from different workers sampling different subsets of a wide range of habitats that support the species. For example, if we had sampled only the habitat in the main fishing grounds in Torres Strait, our stock per unit area estimate would have been about 1100 kg km\textsuperscript{-2} whole weight.

The current annual catch of \textit{P. ornatus} (~250 t tail weight, or ~700,000 lobsters) is only about 10% of the estimated stock and indicates that fishing mortality ($F$) is low (~0.1) — relative to other lobster fisheries, this level of exploitation is very low and suggests that the fishery is unlikely to be under threat at present and may even support greater effort. Future research will be directed to producing reliable estimates of sustainable levels of exploitation and will build on the rigorous estimate of lobster abundance provided by the visual transect method and sampling optimization reported here.
Annual population survey

Introduction

In June 1990, the year after the major stock abundance survey (and in subsequent years), a smaller survey of the lobster population was continued at 100 of the 600 sites used in 1989, to determine the relative abundance of both year-classes and provide an index of stock abundance relative to 1989. This survey required a rigorous sampling strategy: the sites were relocated exactly using GPS and all lobsters seen during the fixed-duration dive at each site were sampled and later measured. This data also provides information on the strength of the recruiting year-class and, growth and mortality rates.

Two size-modes (the 1+ and 2+ year-classes) were apparent from the 1990 survey (Fig.23), whereas only the larger mode (2+) was present in the 1990 fishery catch. In the 1989 survey, the 1+ abundance was less than the 2+ (Fig.23) but in 1990, the 1+ (recruiting) year-class was relatively more abundant than the 2+. However, this does not indicate that recruitment to the fishery in 1991 would be greater because the total abundance of lobsters in 1990 was only about 70–85% of that in 1989. Scaling of Fig.23 by the CPUE of the fishery and the survey respectively indicate the likely interannual differences in absolute abundance — the 1990 fishable stock (>legal size, mostly 2+) was only about half that in 1989; the 1990 recruiting year-class was about the same size as in 1989.

Relative abundance and recruitment

This annual population survey indicated that the 1990 fishable year-class was less abundant than in 1989, which corresponds with the lower CPUE in 1990 (see Section 4). This survey also showed that the 1990 recruiting year-class was of a similar size to that in 1989 and indicated that the 1991 fishable stock, and perhaps total catch also, would be about the same size as in 1990. This annual monitoring survey is intended to be an ongoing project which will also provide information valuable for estimating growth and mortality rates.

Conclusions

Fig.23. The size-frequency distribution of the lobster catch landed at Mabuiag Island in June 1988, 1989 and 1990 contrasted with the size-frequency distribution of the Torres Strait lobster population surveyed by research divers.
Distribution of habitat types

While the tropical rock lobster is the Islanders' most valuable economic resource, other resources are also important: for example, fin-fishes form a major part of their diet; dugong and turtle are of great cultural significance; and pearl shell have the potential to regain their historical importance (Haines et al. 1986). All of these resources depend on the conservation of the benthic habitat, but to date there is little published information on the benthic environment of Torres Strait.

In this section, we report information on seagrasses, substratum types, epibenthic macrobiota and pearl oysters that was recorded during the survey of the lobster stock in Torres Strait (Section 7). As the survey was designed specifically to estimate lobster abundance, the information gathered for other resources relied on rapid visual assessment and is therefore subjective and only semi-quantitative. The information is not intended to be definitive and indeed, many of the original pearling grounds (Yamashita 1986) are outside the lobster study area and the seagrasses were not usually identified to species. Nevertheless, this information is valuable as it augments the developing database on the benthic environment of Torres Strait, an area about which little is known, and is complementary to other research on these resources (pearl oysters by K. Colgan; seagrasses by I. Poiner and B. Long) as we surveyed areas not previously studied.

The survey covered an area of about 25,000 km² (Fig. 20) and was undertaken in May-June 1989. The epibenthos was recorded in a total of 542 transects (each 4 × 500 m) distributed in pairs at 271 locations. Transect starting points were located with satellite, radar, or compass fixes. To census each transect, a 500 m line was deployed onto the substratum parallel to the current from a dinghy, and two divers carrying a 2 m measure then swam down the line counting lobsters and pearlshell, and making semi-quantitative visual assessments of the abundance of epibenthic flora and fauna within 2 m each side of the line (for a full description of sampling strategy see Pitcher et al. 1992a).

Two species-groups of seagrass — *Halophila* species (e.g. *H. spinulosa*, *H. ovalis*) and strap-like forms (e.g. *Cymodocea serrulata*, *C. rotunda*, *Halodule uninervis*, *Thalassia hemprichii*, *Enhalus acaroides*) — and four semi-quantitative density categories of each group were recognised. The density categories were: (i) "very dense": uniformly thick mat of shoots and leaves that obscured the substratum; (ii) "dense": fairly uniform distribution of shoots and leaves but not thick enough to cover the substratum completely; (iii) "sparse": shoots often patchy and underlying substratum obvious; (iv) "very sparse": shoots patchy and scattered over substratum. The amount of seagrass per unit area varied by roughly a factor of four between successive categories of seagrass density. The proportion of each transect covered by seagrass of each density category was estimated visually. A logarithmic abundance index was constructed where each additional unit represented slightly more than a doubling of the amount of seagrass (see Pitcher et al. 1992b for details). A three-dimensional contour surface of seagrass distribution and relative abundance was fitted to these index values.

Seagrasses were seen in most locations in both shallow and deeper water, though they were usually very sparse and patchy. Extensive, very dense, seagrass beds were seen in only a few locations. The dense beds tended to be monospecific, dominated by either *Halophila spinulosa* or one of the strap-form species. The contours of the three-dimensional...
surfaces fitted to the total index values at each location provide a broad
description of the distribution and relative abundance of seagrass in
Torres Strait (Fig.24). The pattern of distribution of the two species-
groups is similar: both reach their greatest abundance (index values up
to 5-6) in the north-western area of the survey and lowest abundance
(index ~ 0) in the eastern and southern areas. The major differences
between the groups were that strap-form species were often abundant in
the shallow lagoons of some of the reefs, most noticeably in the north-
eastern area, and the Halophila's were relatively more abundant than
strap-forms near the central area. The seagrass maps give the impression
of gradual changes in seagrass abundances and do not show fine scale
detail, in the order of 10s to 100s of metres, because of the contouring
and only two samples (transects) were taken every 8-10 km on average.
In reality, seagrasses are patchily distributed and density can vary
greatly over short distances (1-100 m). Nevertheless, the maps do show
the large scale (kms-10s km) patterns of distribution and abundance.

Fig.24. The distribution of seagrasses mapped from densities at locations sampled in
Torres Strait: (a) Halophila species; (b) strap-like forms. The contour intervals are not
linear but represent a continuous logarithmic series where, for example 1 = 10% cover
of very sparse seagrass, and 5 = 80% cover of sparse seagrass or equivalent (e.g. 20%
dense, 5% very dense). The dashed lines show the eastern boundary of the survey area
to the south of the Warrior Reef complex.

Substratum Types

The topography and abiotic composition of the seabed, particularly the
relative amounts of rock, rubble, sand and silt, in both transects at all
locations were assessed visually. The substratum at each location within
the deep stratum was classified into one of five broad categories: (i)
">50% rock": hard seabed having >50% exposed rocks interspersed
with rubble and sand; (ii) "10-50% rock": hard seabed having 10-50%
exposed rocks interspersed with rubble and sand; (iii) "rubble":
scattered rubble with sand and <10% exposed rocks; (iv) "sand": sand
of various grades from mobile, coarse dunes to stable, fine sand flats;
(v) "silt": fine silt and mud. The position of locations in each category
were then mapped to indicate the distribution of substratum types in
Torres Strait.

The composition of the substratum varied greatly across Torres Strait,
from thick layers of soft mud through to rocky and hard pavement. The
distribution of locations with the different substratum types is mapped
in Fig.25. The area of fine silt in the north-eastern sector may have
resulted from sediment input from Papua New Guinea rivers (Harris 1988) together with reduced tidal currents due to the blocking effect of the long Warrior Reef complex. In contrast, the bedrock and rubble (>50% rock, 10-50% rock) were often exposed in areas between reefs and islands, probably because the sediment has been scoured from the seabed by tidal currents (Harris 1988), which flow very rapidly through these constricted passages and channels (Wolanski 1986). In many locations adjacent to these channels there were sand banks and mobile dunes up to 10 m high; it is likely that these sediments were deposited where currents weaken outside the constricted areas (Harris 1988). In the central area, the substratum was generally flat sand bound by algae and seagrass; here current speeds are slower and sediment movement would be less. Seabed of scattered rubble was distributed over much of the southern and western parts of the survey area.

Fig. 25. Charts of Torres Strait showing the distribution of substratum types at sampled locations. (a) Rock cover >50%, and rock cover 10-50%; (b) rubble; (c) sand; and (d) silt and mud. See text for full descriptions of the classifications.

**Epibenthic macrofauna**

Macroscopic animals and algae found along each transect were recorded along with a comment on their relative abundance. The epibenthic fauna at each location within the deep stratum was classified into one of four groups according to the subjective visual estimates of the density of small hard corals (foliose, tabulate, encrusting and massive forms), gorgonians and seawhips, soft corals and sponges (massive, vase, foliose, branching and fans) in both transects at each
location. The four categories of this assemblage of epibenthic fauna were: (i) "dense fauna": assemblages that included many hard corals, with similar taxa separated by only a few metres or less, covering >50% of the transect; (ii) "sparse fauna": assemblages having few hard corals, with similar taxa separated by more than a few metres, covering 10-50% of the transect and; (iii) "very sparse fauna": assemblages with no hard corals, typically in patches separated by several 10s-100s of metres and covering <10% of the transect; and (iv) "no fauna": virtually no epibenthic fauna present. Locations in each category were then mapped to indicate the distribution and relative abundance of epibenthic fauna in Torres Strait.

*Fig.26.* Charts of Torres Strait showing the distribution of epibenthic fauna at sampled locations. (a) Dense fauna; (b) sparse fauna; (c) very sparse fauna; and (d) virtually no fauna. See text for full descriptions of the classifications.

The epibenthic fauna in many deeper locations was extremely diverse, with a great variety of sponge forms, and hard, horny and soft corals (dense and sparse fauna; Fig.26). In contrast, many other locations were almost devoid of macrofauna (no fauna; Fig.26). The distribution and abundance of the epibenthic fauna reflect closely the rockiness of the substratum (cf. Fig.26 and Fig.25) and there was a significant association between the two habitat features (Pearson $c^2=355$, df=12, $P<0.001$).
The abundance of each of the three common genera of algae — *Halimeda* (primarily *H. cylindracea*, *H. macroloba*, *H. opuntia* and *H. discoides*), *Caulerpa* (primarily *C. racemosa*, *C. mexicana*, *C. sertularioide* and *C. brachypus*) and *Sargassum* (species unknown) — in each transect was estimated visually. Where the genus was absent, an index value of zero was assigned; where the genus was recorded merely as present, a value of one was assigned; and where the genus was dense, such that flattened plants would be in contact, over more than about 10% of the transect, a value of four was assigned. The index values of the two transects within each location were added to give an incidence index (with possible values of 0, 1, 2, 4, 5, 8) at the location level which was used to map the distribution and relative abundance of each genus.

Though many macroalgae were present in the survey area, *Halimeda*, *Caulerpa*, and *Sargassum* were the most abundant, sometimes forming dense fields. The distribution of locations where these genera were recorded is mapped in Fig.27. The *Halimeda* genus was found on most sub-stratum types shown in Fig.25 as the different species have different habitat requirements. The *Halimeda* species may also contribute substantially to sediment carbonate, as their skeletons were very abundant in many locations. The *Caulerpa* species exhibited a similar distribution to the strap-form seagrasses and were uncommon in the south-east quarter of the survey area. The *Caulerpa* group showed no
particular requirement for any of the five deep substrata though it
tended not to grow in very rocky or muddy areas. The distribution of
the *Sargassum* species was similar to that of the epibenthic fauna,
though it was even more restricted to hard substrata because it requires
a solid attachment for the holdfast.

Pearl oyster shells (*Pinctada maxima*), with a diameter greater than
~100 mm, in the transects were also counted. The counts of pearl
oysters in the two transects at each location were averaged, converted to
density per hectare, and mapped to indicate patterns of distribution and
abundance. An estimate of pearl oyster abundance in the study area and
the corresponding confidence interval was calculated using the same
procedure as was used to estimate lobster abundance (see Section 7, and
Pitcher *et al.* 1992a for details).

Table 7. Calculation of *Pinctada maxima* population size and confidence interval for
the Torres Strait study area from analysis of variance of the transect survey data; \( W_h \):
proportional area of strata; \( N_h \): total number of possible transects in each stratum; \( n_h \):
number of locations per stratum; \( \bar{x}_h \): stratum mean; \( s^2 \): sample variance; \( s_{\bar{x}_{strat}} \): standard
error of overall stratified mean.

<table>
<thead>
<tr>
<th>Strata</th>
<th>Area</th>
<th>( W_h )</th>
<th>( N_h )</th>
<th>( n_h )</th>
<th>( \bar{x}_h )</th>
<th>( s^2 )</th>
<th>( W_h s^2/2n_h )</th>
<th>( N_h \bar{x}_h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>228</td>
<td>0.0105</td>
<td>114,000</td>
<td>5</td>
<td>1.500</td>
<td>10.250</td>
<td>0.000113</td>
<td>171,000</td>
</tr>
<tr>
<td>Shoal</td>
<td>1,009</td>
<td>0.0463</td>
<td>504,500</td>
<td>10</td>
<td>0.050</td>
<td>0.050</td>
<td>0.000005</td>
<td>25,225</td>
</tr>
<tr>
<td>&lt;50% Rock</td>
<td>884</td>
<td>0.0405</td>
<td>442,000</td>
<td>11</td>
<td>0.546</td>
<td>1.246</td>
<td>0.000093</td>
<td>241,111</td>
</tr>
<tr>
<td>10–50% Rock</td>
<td>2,892</td>
<td>0.1326</td>
<td>1,446,000</td>
<td>36</td>
<td>0.278</td>
<td>0.613</td>
<td>0.000149</td>
<td>401,554</td>
</tr>
<tr>
<td>&lt;10% Rock</td>
<td>7,150</td>
<td>0.3279</td>
<td>3,575,000</td>
<td>89</td>
<td>0.169</td>
<td>0.477</td>
<td>0.000288</td>
<td>602,388</td>
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<tr>
<td>Sand</td>
<td>8,195</td>
<td>0.3759</td>
<td>4,097,000</td>
<td>102</td>
<td>0.093</td>
<td>0.344</td>
<td>0.000238</td>
<td>381,477</td>
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<tr>
<td>Silt+Mud</td>
<td>1,446</td>
<td>0.0663</td>
<td>723,000</td>
<td>18</td>
<td>0.056</td>
<td>0.052</td>
<td>0.000006</td>
<td>40,199</td>
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<tr>
<td></td>
<td>21,804</td>
<td>1.0000</td>
<td>10,902,000</td>
<td>271</td>
<td></td>
<td></td>
<td>0.000893</td>
<td>1,862,954</td>
</tr>
</tbody>
</table>

Standard Error: \( s_{\bar{x}_{strat}} = \sqrt{0.0000893} = 0.0299 \)

95% C.I.: \( \pm 1.964 \times (10,902,000 \times 0.0299) = \pm 639,950 \)

Population Estimate: \( \bar{X} = 1.860,000 \pm 34.4\% \)

Confidence Interval: 1.2 - 2.5 million pearl oysters

Pearls were seen in low densities (around 2-3 per hectare) in many
locations throughout the Torres Strait study area (Fig.28), though up to
25-30 per hectare were observed in some places. Greater numbers of
pearl oysters were seen where the epibenthic fauna was more dense
\( (MS_{fauna} = 17.248, F=3.202 [3,241], P=0.024) \) but substratum type
appeared not to influence oyster density \( (MS_{sub}=2.314, F=0.430
\ [4,241], P=0.787) \). However, because of the strong association between
the epibenthic fauna and the substratum type, it was not possible to
separate the effect of the two habitat factors on pearl oyster density.
Neither habitat feature was a very good predictor of pearl oyster
abundance, and together, they accounted for only about 12% of the
variation in the density of shell. The total number of pearl oysters in the
study area was 1.9 million \( \pm 35\% \) (Table 7). Through the 1980s, annual
catches of live oysters from Torres Strait, including fishing grounds
outside the study area, averaged only a few thousand oysters (Colgan
1988) and would appear to be a low level of fishing intensity.
Nevertheless, the pearl stocks are reduced substantially from about 20
years ago (Yamashita 1986), when about 400,000 live oysters were
collected each year, or from the boom period (mid-1800s to mid-1900s)
when mother-of-pearl production reached about 1000 tonnes per annum
(Colgan 1988), which is equivalent to perhaps one million or more pearl shells.

Fig. 28. Chart of Torres Strait showing the density of pearl oysters at sampled locations. The area of the circles is proportional to the density of oysters: the smallest circles = 2.5 oysters per hectare, the largest = 27.5 oysters per hectare.

Conclusions

This study has provided information on the distribution and abundance of seagrasses, substratum types, epibenthic fauna, macro-algae, and pearl oysters that will expand the database on the benthic habitat of Torres Strait and assist in ground-truthing satellite data for large scale mapping and monitoring techniques that are currently being developed for the Torres Strait region. The information on the pearl oyster, *P. maxima*, has provided the first quantitative estimate of pearl abundance and distribution within the survey area and will complement qualitative surveys of the formerly productive fishing grounds for this species (Colgan and Reicheldt 1991).
Breeding grounds survey

Until recently, the coastal reefs of the eastern GoP were the major known breeding grounds. Yet perhaps as few as 1% of the several million lobsters which emigrate from Torres Strait arrive on these reefs each year. It was suspected that most lobsters moved to the continental shelf edge of the Gulf of Papua (GoP) and the far northern Great Barrier Reef (GBR). Previous methods used for sampling migrating lobsters were inadequate for the proposed survey of this area. Because of strong currents and the necessity to search rugged bottom habitat, the most suitable method for the study was a manned submersible. The research submersible DELTA, which carries a pilot and one observer and various camera and sampling equipment, was contracted as the vehicle for the survey. The survey was a collaborative project between J. Prescott (cruise leader) of the PNG Department of Fisheries and Marine Resources, and CSIRO.

Submarine survey

The study area was divided into 15 sectors, each 15 nautical miles wide along the edge of the continental shelf and within each sector, two survey transit lines were selected at random (Fig.29). Bottom topography and benthic habitats along each transit line were recorded by the ship’s echo sounder. Observers in DELTA searched for and counted lobsters in transects 0.5 nm long at the shelf edge, at two random points along the transit line on the shelf, and at other sites where the echo sounder indicated the habitat might be suitable for lobsters. During each transect, substratum type and biota were recorded on video and still cameras. The effective search path width was estimated by the observer. Where shallow reef areas were present adjacent to the submersible dive-sites, divers using hookah estimated lobster densities in the shallow habitat.

A total of 132 dives were made in the DELTA submersible during the survey. Eighty-eight of the dives were along measured transects, which traversed 78 km of seabed. The total area surveyed on these measured submersible dives was estimated to be 342,000 m².

In the GoP, but outside the known breeding grounds around Yule Island, 84 submersible dives were made and a total of only 10 lobsters were counted during only five of the dives (Fig.29). Seven lobsters were observed on an isolated deep (60 m) mid-shelf reef at the top of the GoP, two on the shelf edge (~120m deep) and one in a fish excavation on soft substrate (60 m). Lobsters were seen on three of four submersible dives made within the known breeding area.

In the southwestern part of the study area, encompassing the outer reefs of the far northern Great Barrier Reef and shelf edge beyond the outer reef slope 44 submersible dives were made. On seven of those 44 dives, 79 lobsters were counted (Fig.29) of which 72 were seen during three of the dives. Most of the lobsters were females and many were ovigerous. Habitats supporting high lobster densities were characterised by certain physical characteristics: high relief, strong currents, close proximity to the edge of the continental shelf and depths ranging from 40 to 120 metres. The depths at which the majority of lobsters in breeding condition were observed, was significantly deeper than in previously known breeding areas (e.g. Yule Island). The overall density of lobsters in the far northern Great Barrier Reef area of the survey was roughly seven per hectare of seabed surveyed, which compares with a density of about three lobsters per hectare (excluding the pre-recruit year class) in the area where the fishery operates in central Torres Strait. Thirty-seven
lobsters, some of which were in breeding condition, were observed by
divers on shallow reefs near the outer far northern Great Barrier Reef.
The average density of these lobsters was roughly one lobster per
hectare.

![Chart of the Gulf of Papua and far northern Great Barrier Reef showing the area surveyed. Dive sites at the seaward end of the transit lines coincide with the edge of the continental shelf](image)

**Conclusions**

Because very few lobsters were found in the Gulf of Papua, it is
considered that the mortality of lobsters migrating into the Gulf of
Papua could be extremely high. This survey also indicated that the shelf
edge outside the far northern Great Barrier Reef may support the major
breeding population for the Torres Strait fishery. However, it will be
necessary to confirm the extent of the far northern GBR breeding
grounds and the abundance of these breeding lobsters, as well as
determine whether these lobsters suffer catastrophic mortality after
breeding as occurs in the breeding population of the eastern GoP.
Parasitic infection of lobsters

Tropical rock lobsters in Torres Strait are relatively free of parasitic infections which might affect their marketability; indeed, very few lobsters in the catch are rejected by the processors because of parasitic infections. This parasite-free state of the population is probably due to the annual one-way breeding emigration (Moore & MacFarlane, 1984) of most legal-sized lobsters (about 2.5 years old) out of Torres Strait; thus most infected lobsters would be removed each year. However, some lobster fishermen in Torres Strait reported that a few lobsters in their catch had "milky" flesh. These lobsters were not accepted by processing companies and fishermen often discarded them at sea or kept them to eat. Some lobsters with the "milky" flesh condition were sampled in 1989 and 1990 for further examination.

The abdominal muscle from infected specimens was examined and indicated that the "milky" flesh condition was due to infection by microsporidian spores. Microsporidians are extremely small (2-5 mm long) intracellular parasites. They are ubiquitous parasites, infecting numerous species of freshwater and marine crustaceans as well as fish, amphibians, insects and mammals and even other parasites.

Mature spores and less commonly, reproductive stages, were distributed throughout the abdominal muscle of infected lobsters (Fig. 30a), causing the muscle to appear opaque white. Only tails were examined but the parasite probably infects all striated muscles. The parasites were aggregated in pockets between the muscle blocks and this pattern of infection is consistent with microsporidiosis in other crustaceans (e.g. Parsons & Khan, 1986). The musculature of infected lobsters had deteriorated and filled much less of the abdominal cavity. In parasitised muscle, the contractile muscle fibres (myofibrils) had separated and disintegrated; only fragments of intact groups of myofibrils remained. In general, microsporidian infection causes extensive localised tissue necrosis of lobster striated muscle.

Several important diagnostic features were observed in the mature spores: the ovoid spore, measured 2.0–2.4 mm by 1.4–1.8 mm
(Fig.30b). The polar filament (through which the infective germ (sporoplasm) exits) was isofilar, singly coiled, with a total of 9–11 turns on the long axis. Many microvilli extended from the exospore (~0.1 mm thick) into the host tissue. The endospore was about twice as thick as the exospore. The polaroplast consisted of four to six tubular elements and a granular posterior portion. Each spore contained a single posteriorly located nucleus. No posterior vacuole was observed. The combined features of the parasite characterise the genus *Ameson*.

Estimated prevalence of "milky" flesh in *P. ornatus* was very low in 1990 (0.07%; ~4 in 5000) and are consistent with prevalences of microsporidian infections in other host crustaceans (e.g. Olson & Lannan, 1984; Parsons & Khan, 1986; Owens & Glazebrook, 1988). The prevalence in *P. ornatus* is likely to be much higher than estimated here because only grossly infected lobsters were returned by fishermen and those animals with sub-clinical infections would not have been detected. The ratio of sub-clinical to gross infections in *P. ornatus* is unknown and there is no comparative literature on this ratio in other marine crustaceans.

**Conclusions**

"Milky" flesh condition of lobsters in Torres Strait is caused by an infection by a microsporidian parasite (probably of the genus *Ameson*). Muscular function of infected lobsters is probably greatly impaired; in particular, the characteristic "tail flicking" escape response would be affected; thus increasing the probability of predation on infected lobsters. Prevalence of grossly infected lobsters in Torres Strait is low (<0.1%) and the "milky" flesh condition apparently has little effect on the production of the fishery. However, it could be a serious problem if lobster mariculture becomes a viable practice — production in many prawn farms has been seriously affected by microsporidiosis causing the death of stock (Bergin, 1986).
Section 12

Introduction

A naupliosoma larva in lobster life-history?

Development of the early larval stages of spiny lobsters has been documented (e.g. Prasad and Tampi, 1957; Silberbauer, 1971; Dexter, 1972; Lesser, 1974). The first stage to emerge from the eggs of most spiny lobsters is the phyllosoma. However, in some species earlier stages (naupliosoma, pre-naupliosoma) have been identified (Batham, 1967; Silberbauer, 1971; Lesser, 1974). While the validity of the pre-naupliosoma stage is questioned (Silberbauer, 1971), the naupliosoma stage has been observed in the plankton (MacDiarmid, 1985). The naupliosoma is short lived, lasting <24 hours before moulting into the first phyllosoma, and its presumed function is to swim rapidly towards the ocean surface. The stage 1 phyllosoma is the earliest reported larval stage of *Panulirus ornatus*, but it is recognised that an earlier stage may exist (Prasad and Tampi, 1967). In this section, the larval stages, hatched from berried female lobsters collected at Yule Island, are described.

Naupliosoma larvae

Eight berried *P. ornatus* were caught at Yule Island, Papua New Guinea in January 1990, and kept alive in seawater tanks onboard a research vessel. When hatching began, samples of larvae were taken at regular intervals for microscopic examination. Some newly hatched larvae resembled the naupliosoma stage described by Gilchrist (1916). The suspected naupliosoma (Fig.31) differed from the stage 1 phyllosoma, described by Prasad & Tampi (1957) and that observed in this study (see below), by the folded condition of body and appendages, the presence of a median eye, an apparent lack of setae, a thick cuticle covering the body and a smaller overall length (1.1 mm cf. 1.4 mm). Recently hatched naupliosomas were tightly folded, appearing almost as a sphere, with the eyes pressed against the cephalic shield. The later stage naupliosomas had unfolded, except for the eyes and two pairs of antennae.

![Possible naupliosoma larval stage of *P. ornatus*](image)

Stage 1 Phyllosoma

Naupliosomas moulted into stage 1 phyllosomas within 8 hours of hatching from eggs. The stage 1 phyllosomas (Fig.32a) observed in this study were consistent with the description given by Prasad & Tampi (1957). Previously undescribed fine structure of the mouthparts (Fig.32b) was observed and photographed using scanning electron microscopy.
Phyllosoma larval stage I of *P. ornatus* (a) and detail of the mouthparts (b)

**Conclusions**

A new, formerly undescribed, naupliosoma stage has been tentatively identified for *P. ornatus*. However, it is possible that these naupliosomas are normally an embryonic stage and were released during this study by premature rupturing of the eggs due to abnormal conditions in the shipboard tanks — the eggs of *P. argus*, which "normally" hatch as first-stage phyllosomas, may hatch as pre-naupliosomas when placed in seawater of low salinity (Sims, 1965). Conclusive evidence of the existence of a free-living naupliosoma stage would be its presence in wild-caught plankton samples.
The mating success of male spiny lobsters (Palinuridae) is reported to depend on their physical size (Berry, 1970). In particular, the length of the front walking legs may be important, because they are used to manipulate the female prior to copulation, and there is a pronounced elongation of the front walking legs in large males of most species of spiny lobsters. This positive allometric growth of the front walking legs of males has been documented for several spiny lobsters (e.g. *Panulirus japonicus*, Kubo, 1938; *Panulirus homarus*, Berry, 1970; *Panulirus versicolor*, George & Morgan, 1979) and it has been suggested that this character could be used to estimate size of maturity for males. Two previous studies allude to elongation of the front walking legs in large male *P. ornatus* (Gordon, 1960; MacFarlane & Moore, 1986), but in this study allometric growth of legs of lobsters from a migratory breeding population was formally documented.

The lengths were measured of the second leg (carpus + propodus) and carapace of migrating male and female lobsters, captured by trawling in the Gulf of Papua, in November, 1989. Leg-length was plotted against carapace-length for evidence of allometric elongation of the front legs of males. For males there was a pronounced elongation of the front legs at carapace length (CL) 110–120 mm (Fig.33). The relationship was approximately linear below 110 mm CL and above 120 mm CL and regressions calculated for these segments were significantly different (t = 3.08, p<0.01). In contrast, for females the leg-length to carapace-length ratio was relatively constant for all sizes.

The size at which leg-elongation occurred in males coincided with the mode of the migrating population (Fig.33) and 30–50% of the males,
especially those <110 mm CL, did not have elongated legs even though they were sampled from a migrating population that showed evidence of intense reproductive activity.

**Conclusions**

Elongated front legs of large male lobsters has been shown to be important during mating — if elongated front legs are necessary for male *P. ornatus* to mate successfully, then part of the male population (i.e. those <110 mm CL, ~40% of total) sampled in this study may not have contributed to the reproductive output of the group. This raises the evolutionary question of why males should migrate if they are unable to participate in reproduction; however, this is unlikely since males <110 mm CL have been observed mating successfully (Prescott, pers. comm.). Possibly, it is the relative size of males that is more important to the success of mating (i.e. males may simply need to be larger than their partners).
Stock assessment

Data collected in the field research projects was synthesized to provide outputs relevant to management. During 1989-90, information became available for a preliminary analysis of yield-per-recruit (YPR) which assists the prevention of growth overfishing by indicating the minimum sizes \( l_s \) that maximize yield for a range of fishing mortality \( F \). The YPR model was extended to assess the potential impact of a proposed closed season and to assess the potential long term yield of the lobster stock through consideration of escapement.

The YPR analysis takes into account the changes in the biomass of a year-class with growth and mortality and estimates the yield from each year-class (per recruit) for a range of \( F \) and \( l_s \). The analysis showed that at current levels of effort \( (F>0.1) \), as presently distributed over the seasons, and with natural mortality \( (M) \) estimated at about 0.5 and minimum size at 100 mm tail length, the calculated YPR is about 20 gms, which is very low compared with other lobster fisheries. The contours of the yield-per-recruit surface (Fig.34) indicate that slightly greater yields may be obtained at smaller minimum-sizes; i.e. current minimum-size restrictions do not improve yields to the fishery at sustainable levels of effort (ie. \( F < M \)). However, small grade AA tails are more difficult to market and bring a lower price, whereas size A, B and C tails are in demand and bring the highest price; demand for the largest sizes is lower and this is reflected in their lower value. Therefore, even though the annual catch may be slightly greater if AA sizes were fished, the low value of lobsters considerably smaller than the current minimum-size negates this gain.

Fig.34. Yield-per-recruit surfaces for a range of minimum sizes (mm tail length) and values of fishing mortality (F), with natural mortality set at M=0.5. The contours show lines of constant yield per recruit (grams).

Closed season

The YPR analysis, which combined information about the current seasonal pattern of fishing effort, also showed that a closed season proposed for October to December each year would not have the intended effect of increasing yield by allowing sub-legal sized juvenile lobsters to grow larger before harvest. If, in the model, the fishing effort prevented by a closed season was not redistributed to other months the catch of the fishery would be reduced; if all of the fishing effort that
presently occurs in October and December was redistributed among the other months then a small increase in yield (of <5%) could be expected. In most years, most of the recruiting (1+) year-class of lobsters have reached the legal size and most valuable size grades A (or even B & C) by October and in some years there are also many larger lobsters on the grounds during the months of the proposed closed season.

**Escapement**

The yield of the lobster fishery would increase with greater fishing pressure, and at very high $F$ (probably unsustainable) a minimum size eventually becomes important (Fig.34). However, care must be taken to avoid recruitment–overfishing. Exactly how much fishing is appropriate is probably the most important question for managers. In the absence of good stock–recruitment data, one method of estimating potential yield involves consideration of the proportion of the population that escapes fishing to emigrate and breed. At present, the average annual catch of the fishery is around 240 t, fishing mortality is about $F \approx 0.1$, and natural mortality is probably about $M \approx 0.5$; thus, on average about 7 million lobsters emigrate from the Torres Strait fishing grounds each year. This is about 93% of the numbers that could emigrate and breed if there was no fishing at all; in comparison with almost all other fisheries, this is a very high escapement rate. Theoretical fisheries yield models predict that production is maximized when the breeding stock is reduced to half (50%) of unfished levels, though empirical studies suggest that this level may lead to overfishing. For many stocks, a 30% reduction may be more appropriate (this is very conservative compared with the situation for western rock lobster where the exploitation rate is about 60% per annum). Even so, an escapement of 70% in the tropical rock lobster fishery would permit a substantial increase in catch as, at $F = 0.4$ escapement would be about 74% and the projected yield would be about 800 tonnes on average.

![Fig.35. Abundance, monthly catch, and percent escapement of a cohort of tropical lobsters following average recruitment at age 18 months for three levels of fishing mortality.](image)

**Conclusions**

The YPR analysis showed there is no biological reason to have minimum size restrictions and prior to the introduction of the minimum-tail length, size-distributions of the catch indicated that fishermen tended to avoid spearing lobsters smaller than the current minimum-size anyway. Consequently, the necessity to enforce the minimum-size in legislation (which has a substantial cost) should be re-assessed — it may be sufficient for the processors to refrain from buying small lobsters which they have difficulty marketing.
It is highly likely that the fishing effort prevented by a closed season could not be regained in other months; consequently a closed season would likely reduce the catch of the fishery. Over the last five years, the average catch during the proposed closure has been 33.5 tonnes (>10% of total) and this is may indicate the average drop in catch each year should a closed season be introduced.

In the tropical rock lobster fishery, fishing mortality could be increased as much as 4-fold and escapement would remain conservative at 74%; in this case, the projected yield would be over 800 tonnes on average. The projected yield would vary from year to year, because of recruitment fluctuations, but could be assessed each year by the research program. These considerations suggest that increased effort should be encouraged in the diver fishery.
The lobster population will be sampled in the middle of each year to provide an annual index of the relative abundance of all year-class in the Torres Strait population, an index of the strength of the recruiting year-class, and growth and mortality estimates.

Islander catch will be monitored in the middle of each year to provide catch and effort information, and the size–frequency distribution of the catch.

Studies of the ecology of newly settled juvenile lobsters will document the distribution of puerulus settling sites, micro-habitat use by post puerulus, early growth and mortality, and assess the potential impact of trawling on settlement grounds.

Devices intended to collect the last larval stage, or puerulus, will be trialled. The settlement of the puerulus stage is the earliest that recruitment to the fishery can be assessed. In future, these devices could be deployed widely and sampled regularly to provide an index of settlement, the first feedback of changes in the fishery, catch forecasting, and the timing of settlement.

The breeding lobster population in the far northern Great Barrier Reef will be sampled with the primary aim of obtaining length–frequency data to estimate mortality rates. An assessment will be made of a range of methods to solve other important problems such as the size and extent of the breeding population and development of an index of the breeding stock for stock–recruitment analysis.

The information arising from field research will continue to be analysed using fisheries dynamics techniques and outputs from these analyses will provide information of value for management.


References


