Fisheries Research and Development Corporation

Final Report (Project #92/102): A study of the biological parameters associated with yield optimisation of Moreton Bay Bugs, *Thenus* spp.

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Executive Summary

- This FRDC/QDPI funded project resulted in development of a substantial database quantifying growth, movements and mortality rates of Scyllarid lobsters of the genus *Thenus*. Over 12,000+ lobsters were tagged and released on the central and southern Queensland coasts between May 1993 and October 1995. Several important population parameters were quantified.

- The genus *Thenus* (as represented by specimens collected within Australian waters) is composed of two species, *Thenus indicus* and *Thenus orientalis*. mtDNA and morphometric analyses confirmed that the proposed new species represented by the morph *Thenus* sp. nov is a member of *Thenus indicus* and cannot be considered a separate species.

- Growth rates for both *T. orientalis* and *T. indicus* were determined, for both sexes. A first estimate of the instantaneous rate of natural mortality was obtained for *T. orientalis* (M = 0.918 year^{-1}).

- Minimum legal sizes (MLSs) were simulated for both species and sexes for a range of possible sizes and exploitation rates. Currently there is no MLS for the lobsters in Queensland. Alternative management measures, including temporal-spatial closures and changes to mesh size are not appropriate due to the fact that the lobsters are a by-product of prawn and scallop trawling. It would be impractical for fishers and difficult to police if more than one MLS was introduced.

- *T. orientalis* is the larger and more valuable of two species. A MLS of 80 mm carapace width (CW) would result in a value per recruit which approximates the maximum for the species. Under this MLS, female *T. orientalis* would produce about 20% ($F_{20\%}$) of their virgin stock egg production. It is unknown whether this level of egg production would maintain recruitment over the long term. Adopting a MLS less than 80 mm CW is not recommended.

- A larger, more conservative MLS of 91.6 mm CW would effectively double egg production ($F_{40\%}$) compared with a MLS of 80 mm CW, but this would incur a loss in value per recruit of about 20% compared with the maximum obtainable for the species.

- There is greater uncertainty associated with *T. indicus* because its population parameter estimates are less robust than those of *T. orientalis.* For the range of parameters considered and the estimate of the exploitation rate U = 0.5 used, the simulations indicate that a value per recruit very close to the maximum would be obtained for female *T. orientalis* with a MLS of 80 mm CW. This would result in female *T. indicus* producing about 52% virgin stock egg production.

- A MLS of 91.6 mm CW would result in female *T. indicus* producing about 77% of virgin stock egg production. However, this would incur a reduction of about 37% of the maximum value per recruit.

- Male *T. indicus* are the smallest and fastest growing of the groups considered. Their value per recruit would be maximised at a MLS of 66 mm CW. Increasing the size at first capture to 80 mm CW would incur a loss in value per recruit of about 46%. Increasing the MLS further to 91.6 mm CW would effectively prevent harvesting of male *T. indicus*, because of the small size they attain.

- Returning undersized lobsters is likely to incur some additional mortality, probably due to predation near the surface. This additional source of mortality has not been quantified or factored into any of the simulations.

- Another objective of the study was to address the issue of scrubbing egg-bearing female bugs (in order to market them). We have addressed this issue through microscopic and macroscopic studies of scrubbed bugs and publication of "A Guide to Identifying Scrubbed Bugs". Over 100 copies of this field guide have been disseminated to Queensland Boating and Fisheries Patrol Officers, and fisheries enforcement officers in New South Wales. Copies were also forwarded to FRDC.

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Section 1. mtDNA and morphometric analyses of Scyllarid lobsters (*Thenus* spp.): How many species of Moreton Bay Bugs are there?

1.1 Introduction

Relatively little research has been carried out on the biology of, and fishery for, Scyllarid lobsters of the genus *Thenus* (also known as shovel-nose lobsters or Moreton Bay Bugs). The genus is of considerable value as by-product of prawn and scallop trawling in Australia's tropical and sub-tropical coastal waters. Some targeting of the lobsters is also likely to occur, particularly when catch rates of the principle target species are low. Queensland logbook data obtained over the last 8 years indicate 400-650 tonnes of lobsters, with a wharfside value of $5.2-8.5 million, are landed annually. These estimates are likely to be conservative because it is unlikely all fishers include by-product in their logbook records.

Currently, the only management measure pertaining to Moreton Bay Bugs in Queensland is the prohibition on the capture of egg-bearing females. This regulation is abused by some unscrupulous fishers who scrub the egg mass off in order to market the females. (This problem has also been addressed in this project and resulted in a field guide for Queensland Boating and Fisheries Patrol Officers and others, that assists in identifying scrubbed lobsters and prosecuting fishers.) The range of additional possible management alternatives for Moreton Bay Bugs is limited, due to the fact that they are by-product. Management measures in the form of changes in mesh size, seasonal and spatial closures, and limitations on fishing effort are not applicable because they would affect landings of the target species. A minimum legal size (MLS) appears to be the only practical alternative for sustaining the resource and is the principle objective of this project.

Current knowledge of stock structure, genetic and morphometric variation within and between stocks of Moreton bay Bugs is limited. Independent work by two researchers on *Thenus* in Australia led them to recognise that within what had been considered as the single species *Thenus orientalis*, a distinct second morph existed. This second morph is currently being given specific status as *Thenus indicus* (Burton and Davie in prep.). This relatively recent discovery - that there are two species of Moreton Bay Bugs - complicates the introduction of any additional management measures, particularly a (single) MLS.

The preferred habitat of *T. indicus* (referred to as the 'mud bug' in eastern Australia), is shallower muddy inshore waters (up to 20 metres deep) while *T. orientalis* (the sand bug) inhabits the deeper and more rocky areas (Jones 1988). The fact that differentiation between these two species went unnoticed until recently, has cast some doubt as to the identity of the type species of the genus. The neo-type specimens of *T. orientalis* held in Copenhagen are in such poor condition that their true identity cannot be ascertained (Mr. P. Davie pers. comm.). A comprehensive taxonomic evaluation of the *Theninnae* is further complicated due to its wide distribution throughout the Indo-West Pacific

oceans. Geographically isolated regions such as the Arabian Gulf, Red Sea, the Maldives, Mauritius and Christmas Island may over time have given rise to population differences and possibly new species, some of whose morphological characteristics may appear so similar that species differentiation may only be detected by genetic means. Further morphometric comparisons of body weight/carapace length between *T. orientalis* from eastern Australia and from the Arabian Gulf have indicated a significant morphometric variation between those two populations.

A third morph (*Thenus* sp. nov) of the genus *Thenus* in Queensland coastal waters was identified during tagging studies south of Mackay during the course of the present project (in 1993). This raised further complications concerning the relationship between this putative third species, and the other two species within the genus. A third species might also complicate the introduction of a minimum legal size, particularly if it comprised a significant component of landings and displayed markedly different population parameters from the other species. As a consequence, additional funding from FRDC was sought to determine if this third morph was a separate species, and to determine and understand the taxonomic status of *Thenus* within Australian waters.

1.2 Materials and Methods

Traditional descriptive taxonomy of decapods utilises morphological characters, including morphometrics, descriptions of mouth parts, limb structure, gamete variation, colour patterns etc. These methods have historically proven sufficient for between-species determinations, but often are unable to identify a cryptic species or resolve population differences within a species. The relationship between the two putative species within the *Theninnae* and the morph *T.* sp. nov found in waters south of Mackay was investigated using methodologies including pteropod markings, fecundity, morphometrics, comparative spermiomorphism and acrosomal development. The latter two methods were without success while genetic investigations using mtDNA sequencing analysis combined with morphometric methodology determined the status of the genus *Thenus*.

The use of mtDNA in sequencing analysis.

The choice of mtDNA (mitochondrial DNA) analysis as a suitable means of phylogenetic construction and species determination was based on certain unique genetic properties, namely - inherited maternally, effectively haploid, low rate of sequence arrangement and high evolutionary rates (Hillis and Moritz 1996).

Inherited maternally: - nuclear DNA from a sexually inseminated diploid female generally carries four copies of each nuclear gene but only one mtDNA genome. Although some instances of low frequency biparential inheritance have been reported (Kondo *et al*. 1990, 1992; Walter *et al*. 1991 and Zouros *et al.* 1992), inheritance can be considered to be essentially maternal.

Effectively haploid: - mitochondrial inheritance is clonal in nature as the molecule behaves as a haploid gene (Moritz *et al*. 1987).

Low rate of sequence rearrangement: - most animal mtDNA sequence rearrangements are stable, whereas plant and fungal mtDNA are less so which in turn may lead to overestimates of sequence diversity (Palmer and Herbon 1988; Bruns and Palmer 1989).

High evolutionary rates: - the evolutionary rate of mtDNA varies both among and within phyla (Martin and Palumbi 1993; Wayne *et al*. 1990). Generally however, mtDNA has been shown to evolve at a rate 5-10 times faster than nDNA (Brown *et al*. 1982; Vawter and Brown 1986).

The structure of mtDNA.

The use of mtDNA sequencing methodology is widespread and has been applied to various genetic studies including bio-geography, evolutionary biology, phylogenetics and population genetics. As there have been numerous reviews of the structure of mtDNA and its application in the field of mtDNA sequencing (Wilson *et al*. 1985; Ovenden 1990, Avise 1991;), a brief summary only is presented here in addition to the general methodology employed in direct sequencing. The structure of mtDNA is that of a covalent, circular molecule with a size ranging from 16 to >30 kb. The gene content is generally well conserved throughout the animal kingdom with gene evolution being generally slower in the vertebrates than in the invertebrates. Gene evolution rates however, may vary within the sub-kingdoms (Wayne *et al*. 1990; Martin and Palumbi 1993). Among the invertebrates, whose mtDNA is of a higher evolutionary rate, gene variation occurs among the phyla but appears to be uniform within phyla (Clary and Wolstenholme 1985; Batuecas *et al.* 1988; Hoffman *et al*. 1992). Two genes were selected for sequencing on the basis of their genetic properties: 1) the 16s RNA (16s) gene is non-coding and usually conservative to evolutionary change and 2) the cytochrome oxidase 1 (CO1) gene, which is a coding gene, is more susceptible to evolutionary change and proved to be the more variant of the two.

Sequencing methodology.

To resolve the problems described above, the first requirement was to determine the degree of within-species (population) genetic variation which could be determined using the 16s gene fragment. In order to facilitate this investigation, *T. indicus* and *T. orientalis* were assumed to be separate species, and mtDNA sequences from sympatric specimens (mixed populations) of both species from two locations (Hervey Bay and the Gulf of Carpentaria) were compared. Specimens of the third possible species (*T.* sp. nov) were also included.

Initial mtDNA sequencing of the 16s gene fragment recorded a comparative ambiguity of 0.8% for *T. indicus/T.* sp. nov and 0.0% for *T. orientalis*. Such a low sequence dissimilarity between geographically distant populations indicated that mtDNA 16s sequence comparisons between specimens from different geographical locations could be conducted using as few as two specimens from each location. This procedure was repeated for the CO1 gene fragment. The same specimens were sequenced and the amount of within-species variation recorded (Table 1.1). Gene fragments consisting of 459 bases (153 codons) for 16s and 408 bases (136 codons) for CO1 were compared and aligned manually using the ABI sequence alignment editor SeqEd. Using the specimen 01TiAust as

the standard, within-species and between-species (separate species) ambiguity were determined. Species code name abbreviations and the locations of each are provided in Table 1.2.

Table 1.1 Ratio for within-species and between-species of Australian *Thenus* for the 16s and CO1 gene fragments.

16s	***Ti01***	***To04***	***Base no***	***CO1***	***Ti01***	***Ti04***	***Base no***
Ti01	-	5.1%	454	Ti01	-	12%	407
Ti02	0.0%	-	477	Ti02	0.7%	-	409
Ti03	0.0%	-	469	Ti03	0.7%	-	407
Ti09	0.2%	-	487	Ti09	0.5%	-	341
Ti10	0.0%	-	487	Ti10	0.7%	-	411
Ti11	-	-	-	Ti11	0.7%	-	414
TA07	0.2%	-	512	TA07	0.7%	-	400
TA08	0.2%	-	504	TA08	1%	-	407
TA13	0.4%	-	490	TA13	0.7%	-	416
TA14	0.4%	-	499	TA14	0.7%	-	360
TA15	0.2%	-	499	TA15	-	-	-
To04	-	-	425	To04	-	-	404
To05	-	0.0%	506	To05	-	1.4%	423
To06	-	0.0%	504	To06	-	1%	409
To07	-	0.0%	494	To07	-	1%	412
To12	-	0.0%	494	To12	-	1%	412

Table 1.2. List of all specimens of *Thenus* and outgroups used in mtDNA sequencing analysis.

Id.no.	*Species*	*Location*	*Abbreviation*	*16sar*	*16sbr*	*CO1-B_1*	*CO1-B_2*
1	T. indicus	Australia	01TiAust	y	y	y	y
2	T. indicus	Australia	02TiAust	y	y	y	y
3	T. indicus	Australia	03TiAust	y	y	y	y
4	T. orientalis	Australia	04ToAust	y	y	y	y
5	T. orientalis	Australia	05ToAust	y	y	y	y
6	T. orientalis	Australia	06ToAust	y	y	y	y
7	T. sp.nov.	Australia	07TAAust	y	y	y	y
8	T. sp.nov.	Australia	08TAAust	y	n	y	y
9	T. indicus	Australia	09TiAust	y	y	y	y
10	T. indicus	Australia	10TiAust	y	y	y	y
11	T. indicus	Australia	11TiAust	n	n	y	y
12	T. orientalis	Australia	12ToAust	y	y	y	y
13	T. sp.nov.	Australia	13TAAust	y	y	y	y
14	T. sp.nov.	Australia	14TAAust	y	y	y	y
15	T. sp.nov.	Australia	15TAAust	y	y	n	n
29	I. articrenatus	Newcastle	29IaNewc	y	y	y	y
30	I. peroni	Brisbane	30IABris	y	y	y	y

16sar - forward direction sequence fragment for 16s gene
16sbr - reverse direction sequence fragment for 16s gene
CO1-B_1 - forward direction sequence fragment for CO1 gene
CO1-B_2 - reverse direction sequence fragment for CO1 gene

Sequencing results.

For the allocation of outgroups, specimens of *Ibacus articrenatus* and *I. peroni* (Balmain Bug) were used (*I. articrenatus* specimens were taken from the Newcastle area of New South Wales and *I. peroni* from the adjacent coastal regions of Brisbane). mtDNA sequences were initially analysed using MEGA (Kumar *et al*. 1993). The number of nucleotide substitutions per site (d) using the Jukes-Cantor estimate was $d \geq 0.05$, consequently the Jukes-Cantor distance method was used (Kumar *et al*. 1993) for tree construction of both the 16s and CO1 sequences. After the data were initially analysed, the trees were exported into the programme PAUP for maximum parsimony analysis.

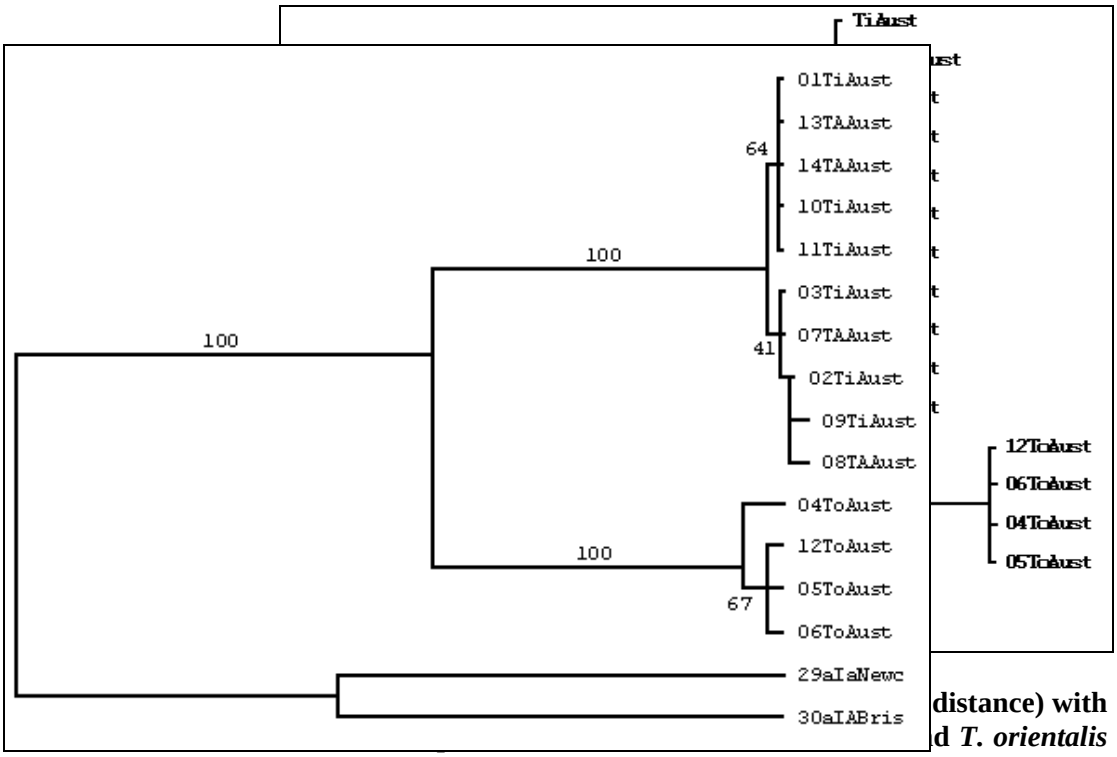
Comparison of tree building results.

Two molecular genetic analytical programmes were used to compare the phylogenetic tree construction method which best suited this particular study. A phylogenetic tree, which is constructed by statistically manipulated data, is limited by the fact that it is based on nucleotide data whose acquisition is itself subject to interpretative error due to stochastic relationships existing between recently evolved species and extinct ancestral polymorphic alleles (Nei 1987; Pamilo & Nei 1988). The tree resulting from a comparison of coding for individual gene fragments is in effect a 'gene tree' and care should be exercised in inferring species and their inter-relationships from it (Kumar *et al*. 1993).

The two primary types of tree construction methods evaluated were distance (MEGA) and discrete-character (PAUP). The distance method involved the comparison between the unweighted pair-group method with arithmetic means (UPGMA) of Sneath and Sokal (1973), and the neighbour-joining (NJ) method of Saiton and Nei (1987). In all cases the trees were rooted using closely related ancestors as outgroups. Theoretical descriptions and explanations of these methodologies are given in Hillis & Morris (1996).

1.3 Results and Discussion

mtDNA sequences of *T. orientalis, T. indicus* and *T*. sp. nov were investigated for the 16s and CO1 fragments. In the case of the 16s gene, both UPGMA an NJ trees were produced using the Jukes-Cantor distance with 100 boot straps (100 boot straps can be easily viewed as a percentage). The within-group and between-group classifications were similar for both methods (Figs 1.1 and 1.2), however, the NJ method (Fig.1.2) was marginally more conservative. **Both methods delineated between *T. orientalis* and *T. indicus* and classified *T*. sp. nov and *T. indicus* as monospecific.**



distance) with
d *T. orientalis*
from Australia.

Figure 1.3. CO1 mtDNA gene sequence NJ tree (J-C distance) with 100 bootstrap confidence level test for *T. indicus* and *T. orientalis* from Australia.

The same procedure was repeated using the CO1 gene fragment. The trees produced by both methods were similar. Again the NJ method was more conservative and the branch distances visually interpreted more readily, which is due to a characteristic of the algorithm of the UPGMA method which produces post species separation branches of equal distance lengths. As both of the tree building methods produced similar results and no advantages of one system over the other were observed, the choice of NJ over UPGMA methodology was purely

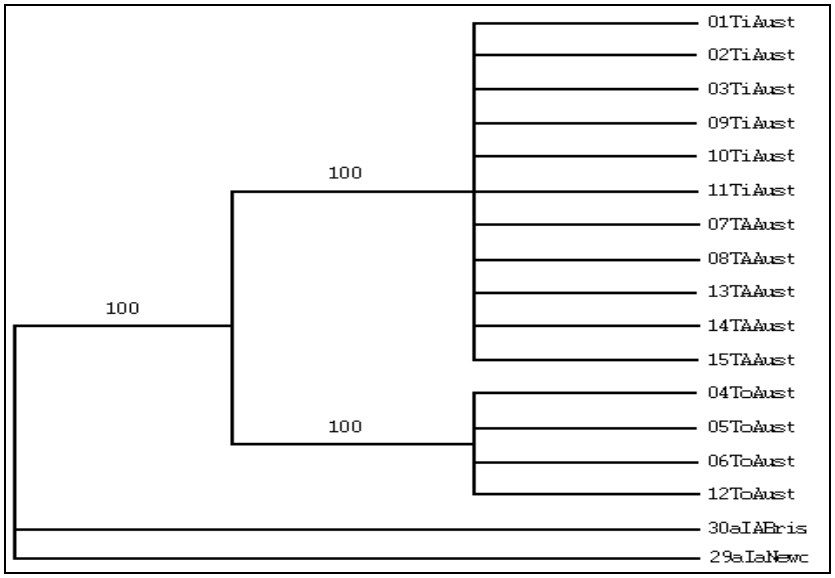


Figure 1.2. 16s mtDNA gene sequence unrooted parsimony tree using a heuristic search with 100 bootstrap replicates. Additional controls were the 50% majority-rule with MULPARS option. Six trees saved but all have the same branching.

subjective and based on visual preference. A final tree-building comparison was made using discrete-character methods (parsimony).

The 16s and CO1 gene sequences were transported into PAUP and MP (maximum parsimony) trees were constructed using the branch-and-bound search and the heuristic search methods. Using discreet-character methodology, the trees produced were to all extents and purposes identical to those or the distance methods (Figs. 1.3 and 1.4).

A general heuristic search with 100 bootstraps produced a tree length of 169 for the 16s gene and 124 for the CO1 gene with a consistency index of 0.876 and 0.976 respectively. A branch and bound search was investigated but discontinued as it was time consuming relative to the information to be gained over the other methodologies.

Summary of phylogenetic analysis for Australian species of Thenus.

A number of conclusions were drawn based on the results of this study:

- *Thenus* sp. from the Australian coastal region is composed of two clades - *Thenus indicus* and *Thenus orientalis*.
- The existence of the morph *Thenus* sp. nov is unfounded. The genetic sequences (16s and CO1) for *T. indicus* and *T.* sp. nov were identical which clearly indicated monospecifity. Additional proof supporting this view was obtained from other investigations involving specimens from Singapore, Karachi and the United Arab Emirates.
- No single type of phylogenetic tree construction method proved to be superior. As the genetic input data was relatively simple, this result was not surprising.

Morphometric analysis.

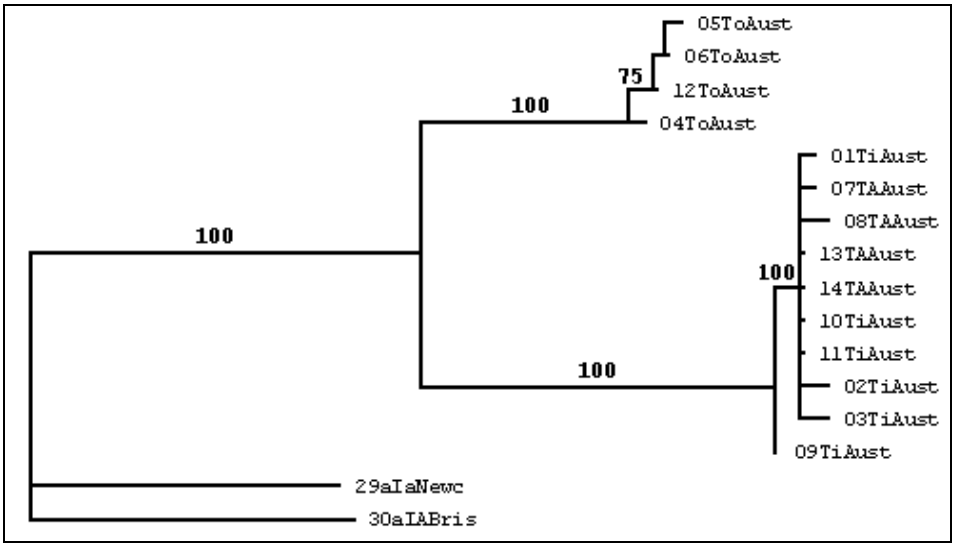


Figure 1.4. CO1 mtDNA unrooted tree using discrete-character methodology (parsimony). A 100 bootstrap heuristic search was used with a 50% majority-rule consensus.

Based on the results of the genetic analysis, a morphometric analysis was conducted to confirm the results. Specimens of *Thenus*, including those used in the mtDNA analysis, were measured and analysed using the programme STATISTICA. Pteropod and body measurements were recorded and analysed using a forward discriminant function analysis and plotted using a canonical analysis scatter plot. The results support the findings of the mtDNA investigation; specimens are divided into the distinct groups, with members of the morph *T.* sp. nov distributed with *T. indicus*.

The genus *Thenus* (as represented by specimens collected within Australian waters) is composed of two species, *Thenus indicus* and *Thenus orientalis*. The proposed new species represented by the morph *Thenus* sp. nov is a member of *Thenus indicus* and cannot be considered a separate species.

Section 2. Effects of tagging on growth, moulting, survival and recapture of Moreton Bay Bugs, *Thenus* spp.

2.1 Introduction

In order to simulate a range of possible MLSs, and hence determine the size associated with maximum yield (or value or egg production), it is necessary to obtain estimates of lobster's growth and mortality rates. Information on size (or age) at recruitment to the exploited phase of the life cycle is also required. In the present study, von Bertalanffy growth curves and mortality rate estimates were derived largely from tag-recapture experiments. Additional population parameter estimates were obtained from length-frequency analyses. A fundamental assumption of such tagging experiments is that any effects of the tag on the individual are negligible, or that they can be quantified and taken into account when deriving the estimates.

Unlike the other two commercially important lobster families (Nephropidae and Palinuridae), there have been few tagging studies on the Scyllaridae. Consequently, the effects of tagging on this particular group are largely unknown. Jones (1988) tagged and released 948 *Thenus* spp. on the Queensland coast (18-19^{o}S). A total of 67 (7%) were recaptured and reported by trawler operators. Spanier and Barshaw (1993) examined the effects of three types of plastic "spaghetti" anchor tags on a total of 30 Mediterranean slipper lobsters, *Scyllarides latus.* The lobsters were tagged, held in aquaria and monitored for 16 months.

The objective of this part of the study was to develop tagging and release methods for *T. orientalis* and *T. indicus* that minimise tagging mortality and maximise recapture rates. Tagging mortality has the potential to bias estimates of the instantaneous rates of total (Z) and fishing (F) mortalities. There is therefore, a need to quantify tagging mortality to obtain unbiased mortality estimates that can be utilised in the MLS simulations (in following sections).

2.2 Materials and Methods

Field tagging studies

Methods used by Jones (1987) were adopted and developed upon, to tag and release Moreton Bay Bugs in the present study. Details on initial capture, tagging, release and recapture for each lobster were recorded in a database and a range of tag-release methods evaluated. Although the main response variable used to assess the methods was recapture rate, effects on growth rate (moulting increment) and moulting frequency of recaptured lobsters could also be examined. Tag-treatments that were evaluated included:

(i) two "spaghetti" anchor tags of different size [Hallprint, Australia; T-bar anchor tags a) TBA-1 (larger tag) and b) TBF-2 (smaller tag)],

(ii) two release methods (a) free surface or b) bottom cage release),

(iii) a tag-wound infection prevention measure (a) application of broad spectrum antibiotic/antifungal cream to the tag wound versus b) no application).

Combinations of these treatment factors were applied in a sequential pattern on each tagging trip. Other factors, such as the species composition (*T. orientalis* or *T. indicus*) of the catch, the sex and size of each lobster, were not controllable. Nevertheless, these details were also recorded in the database and their effects on recapture rates were examined. Other factors suspected of influencing the recapture rate, including; a) the time of day tagged lobsters were released, b) the duration of the initial trawl, prior to tagging, and c) the duration of lobsters on board prior to release were recorded. All lobsters were tagged on their dorsal surface, to one side avoiding the gut and gonads, between the cephalothorax and the abdomen.

Laboratory tagging study

In addition to the field studies, a laboratory experiment was conducted over four months (October 1993 - February 1994) to examine the effects of tag size (TBA-1 and TBF-2), antibiotic/antifungal cream, lobster size and sex on growth increment, moulting frequency and survival of lobsters. Twenty lobsters were held in each of four five-tonne aquaria (total of 80 lobsters). Each aquarium was a) allocated 4 untagged (control) and 16 tagged lobsters, b) aerated and supplied continuously with filtered seawater through a flow-through system, c) provided with sand trays (ca 100 mm deep) to allow lobsters to maintain daily burying and foraging behaviour, and d) covered by a sheet of black polypropylene to minimise incidental light. Lobsters were fed scallop (*Amusium japonicum balloti*) viscera once every 48 hours at dusk. Observations on moulting, survival and tag loss were recorded every morning. A small (< 5mm ϕ) water-proof paper label was glued to the dorsal carapace of each lobster to facilitate individual records and identification of individuals that shed their tags (from the untagged control individuals). Unconsumed food, faeces and dead lobsters were removed with a water vacuum prior to feeding. Clean sand was supplied on three occasions.

Statistical analyses

Chi-square and G-tests were used to determine which treatments (i.e., tag size, release method, etc.) significantly affected recapture rate, moulting frequency, survival and growth increment. Hierarchical general linear interactive modelling (GLIM version 3.77) was deployed to determine whether additional factors (i.e., tag size plus release method) significantly increased the amount of variation explained. Different types of data can be used with GLIM, including continuous, count, proportion and categorical (Payne 1985). The general approach is presented in Figure 2.1.

The model calculates a scaled deviance measure for the null hypothesis (no fitted factors) and factors are then added one at a time. To determine if a factor has a significant effect its scaled deviance is subtracted from that of the null hypothesis. The resulting scaled deviance and degrees of

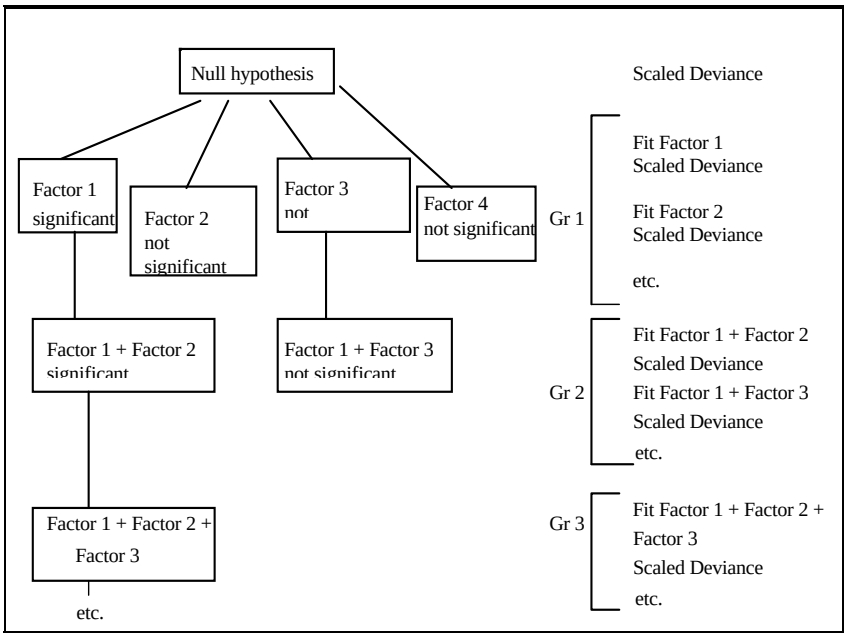


Figure 2.1. Diagrammatic representation of hierarchical general linear interactive model (GLIM). This approach can be used to identify the factors, and their order of influence, affecting growth, survival, moulting and recapture rates of *Thenus* spp in the field and laboratory.

freedom are used to determine whether the factor has a significant effect. Additional factors are "added" to significant factors (Group 1). The scaled deviance for the combined factors (Group 2) is then calculated and subtracted from that of the single factor (Group 1). The influence of triple combined factors (Group 3) is calculated by subtracting their scaled deviance from that of the double factor scaled deviance (Group 2), and so on. In this way, the effects of multiple combinations of factors can be determined.

Following are preliminary results. Until further analyses are undertaken the results should be treated with caution and not cited. GLIM analyses are incomplete. More detailed and rigorous analyses are intended for publication in an appropriate refereed journal.

2.3 Results and Discussion

Field tagging

Twenty-two tagging trips were undertaken on the central and southeast Queensland coasts between May 1993 and October 1995. Eighteen were undertaken to obtain growth rate data, while the remaining four were designed to measure mortality rates. A total of 12,229 (9,888 *T. orientalis* and 2,341 *T. indicus*) lobsters were tagged and released resulting in 1,159 recaptures. A $10.00 reward, in the form of either cash or a scratch lottery ticket, was offered for each recaptured lobster.

Chi-square tests undertaken after the first few months of recaptures revealed that the application of the antibiotic/antifungal cream to the tag wound prior to release significantly increased the probability of recapture for both sexes and both species ($P < 0.001$). Consequently, the cream was applied to all tagged lobsters from March 1994. Application of the cream probably reduces primary and secondary infections associated with tagging, and hence, increases survival and recapture rates.

The size and sex of the lobsters also affected recapture rate. Size and sex are not independent. Females attain larger sizes than males and therefore it is difficult to determine which of the two factors affects recapture rates more than the other. Chi-square tests indicated sex had a highly significant ($P < 0.001$) effect; the observed recapture rates were 10.7% and 8.1% for males and females, respectively. Although speculative, several explanations can be put forward to account for this. The first is that females may have a higher natural mortality rate than males. Secondly, it is likely that some egg-bearing recaptured females were not reported because the fishers were concerned about being prosecuted (possession of egg-bearing females is prohibited). A third possibility is due to the fact that large lobsters (predominantly females) have a higher market value than smaller lobsters (mainly males). There is, therefore, a reduced financial incentive for the fishers to report the recapture of large females. The converse also applies; small tagged lobsters with low market value are more worthwhile to report and claim a reward for than large lobsters that can be sold for higher returns.

Because of this likely under-reporting of female recaptures, male recapture rates are likely to be more reliable for estimating population mortality rates. If males are used to estimate mortality rates then an important assumption is that there are no significant differences between sexes.

Neither tag size (large or small) or species (*T. orientalis* or *T. indicus*) affected recapture rate ($P > 0.05$).

The release method (free surface vs bottom cage) significantly affected the overall recapture rate ($P < 0.001$). However, when the two species were analysed separately, only results for *T. orientalis* were significant. Releasing *T. orientalis* on the surface resulted in an observed recapture rate of 6.0%, while the bottom cage release resulted in a rate of 9.6% - an increase in excess of 50%. Release method did not significantly affect recaptures for *T. indicus* ($P = 0.72$), although recaptures from the bottom cage release were slightly higher. The bottom cage release method is recommended for future tagging studies of *T. orientalis.*

These results will interest opponents of a MLS for Moreton Bay Bugs, and particularly those who argue that returning undersized lobsters has limited long-term benefit. The results strongly suggest that if a MLS is introduced, there will be some additional mortality on undersized lobsters that

are returned to the sea by fishers. Although speculative, the lower recapture rates for surface-released lobsters is likely due (at least in part) to additional mortality by sharks and other predators that associate with trawler discards.

Laboratory results

Tagging the lobsters may affect their growth rates and therefore, growth rates derived from field tagging experiments could be biased. Growth rates are functions of moulting frequency and growth increment. In order to examine the effects of tagging on the incidence of moulting in lobsters held in aquaria, only lobsters that survived the four-month experiment were included in the (moulting) analysis. The reason for this is due to the fact that it is impossible to determine whether lobsters that died during the experiment would have moulted if they had survived.

Effects on survival

Of the 64 tagged lobsters, 19 died over the four-month experimental period. Three of the 16 untagged controls died. Chi-square tests sugested tagging did not significantly affect survival ($P = 0.38$).

Sex and size were found to significantly affect survival ($P < 0.01$), but again, these two factors are not independent and it is difficult to determine which, if either, is the most influential. Large lobsters (> 65 mm CL, dominated by females) had lower survival rates than small lobsters (<= 65 mm CL, mostly males).

Although application of the antibiotic/antifungal cream to the tag wound significantly increased recapture rates *in the field*, the cream did not affect survival of tagged lobsters *in aquaria*. Similarly, tag size had no significant effect on survival under aquarium conditions.

Effects on moulting

The overall incidence of moulting was significantly reduced in tagged lobsters ($P < 0.05$), particularly in small individuals that had been tagged with the large tag. Small tags did not affect moulting.

Instantaneous rate of tag shedding (γ)

Of the 64 tagged lobsters held in the aquaria, a total of 7 lost their tags over the four-month period (119 days). This equates to a loss of 0.109 tags per 119 days. The instantaneous rate of shedding γ = ln (1-proportion tags shed):

$$\gamma = \ln(1-0.109) = 0.115 \text{ (per 119 days) or } 0.354 \text{ year}^{-1}$$

No obvious cause of tag shedding was apparent; shedding was independent of lobster size, sex, tag size and the application of the antibiotic/antifungal cream.

The fact that survival of tagged lobsters maintained in aquaria did not differ significantly from the untagged control group is encouraging. However, tagging may reduce the incidence of moulting and if these results are extrapolated to the field, analyses based on tag-recapture results are likely to underestimate the true growth.

The fact that the application of the cream had no significant effect on survival contrasts with the field data results, which suggested the cream's application increased survival. However, this is not

surprising as the composition of infectious microbes under field and aquarium conditions is likely to be very different.

In summary, a number of conclusions can be made regarding the effects of tagging *Thenus* spp. Firstly, application of an antibiotic/antifungal cream greatly increases the recapture rate of tagged lobsters. The bottom release cage also increases recaptures, particularly for *T. orientalis.* Secondly, large lobsters, (which are usually females) display higher mortality in aquaria and lower recapture rates in the field, than smaller lobsters (usually males). Thirdly, tagging mortality appears to be negligible under aquarium conditions and therefore can probably be ignored when deriving total (Z), fishing (F) and natural (M) mortality rates from the field tag-recapture results. Fourthly, the study facilitated the first estimate of an instantaneous rate of tag shedding rate γ, also required to estimate mortality rates. Estimation of these mortality rates and other critical population parameters is presented in the following section.

Section 3. Quantifying growth and mortality rates in Moreton Bay Bugs, *Thenus* spp.

3.1 Introduction

Estimates of growth and mortality rates are required to simulate the effects of a range of MLSs and hence, identify the most appropriate age or size at first capture. These parameters are poorly understood for *Thenus* spp. Jones (1988) used a combination of methods, including size frequency-modal analysis and progressive plotting to generate von Bertalanffy growth curves for *T. orientalis* and *T. indicus.*

Mortality rates and particularly the natural mortality rate (M) are more difficult to quantify than growth. This is largely because of difficulties in locating, and therefore studying, a population which is not already exploited, and therefore experiencing mortality from multiple (i.e., natural and fishing) sources. Partitioning the overall instantaneous rate of decline (*X*) in an exploited population into its various components, which include natural mortality (*M*), fishing mortality (*F*) and emigration, is problematic. No statistically robust mortality rate estimates have been published for *Thenus* spp. to this time.

The objective of this section of the report is to describe and quantify critical population parameters for Moreton Bay Bugs, specifically growth and instantaneous mortality rates. Other parameters, including fecundity-with-size and market value-with-size also affect utility-per-recruit analyses, and hence the derivation of a MLS. Estimates of these parameters are also presented.

3.2 Materials and Methods

Growth rates

The principle method used to quantify growth rates for *T. indicus* and *T. orientalis* was that of Fabens (1965). This method uses tag-recapture data and a least-squares approach to minimising residuals between observed and expected size-at-recapture to obtain estimates of the von Bertalanffy growth parameters, K and L_∞. The third parameter, t_o required for the von Bertalanffy model cannot be calculated from tag-recapture data. This parameter, t_o, is only required when absolute ages are required. Since absolute age is not considered an essential parameter in subsequent analyses, t_o can be ignored. Male and female lobsters grow at different rates and reach different maximum sizes. Growth rates were therefore estimated separately for each sex, as well as for each species.

Between May 1993 and October 1995, 22 tagging trips were undertaken on the central and southeast Queensland coasts using both research and commercial trawlers. Although the principle objective of the trips was to tag and release lobsters, the size - frequency data obtained over this period can also be used for modal progression analysis to obtain additional, independent estimates of growth rate. Where robust length-frequency data were obtained, they were analysed using the ELEFAN program, within the FAO-ICLARM suite of stock assessment programs FiSAT (Gayanilo *et al.* 1994).

Mortality rates

Mortality rates are more difficult to measure than growth, and yet they generally have a greater impact on per-recruit analyses, and therefore on the derivation of a MLS. Obtaining realistic mortality rate estimates is therefore critical for deriving an MLS.

The exponential decay in the number of recaptures (per unit of fishing effort) over time provides an estimate of the instantaneous rate of decline (*X)* in the *T. orientalis* population and can be used to derive mortality rates. This rate (*X*) is composed of the instantaneous rates of natural (*M*) and fishing (*F*) mortalities, as well as the instantaneous rate of tag shedding (γ), thus:

$$X = F + M + \gamma$$

where *F* is the instantaneous rate of fishing mortality,
M is the instantaneous rate of natural mortality and
γ is the instantaneous rate of tag shedding.

The tag-induced mortality rate (α) and the reporting rate of recaptures (β) also affect overall estimates of recaptures. However, they affect the intercept of the regression (not the slope) and therefore *X* is independent of these parameters (Hilborn and Walters 1992). When estimates of *X*, *M* and γ are known, the instantaneous rate of fishing mortality *F* can be derived using the equation above.

Where size class frequency data were available, additional estimates of total mortality (*Z*) were derived using the length converted linearized catch curve method (Sparre and Venema 1992) available in the FiSAT software. This method also utilises the length frequency data obtained over the two and half years and is independent of the shortfalls associated with tagging, in particular the problems associated with quantifying tag-shedding.

Significant resources were designated to obtaining independent estimates of the instantaneous rate of natural mortality (*M*) for *T. orientalis.* The method used is based on a sequential tag-recapture experiment described by Ricker (1975) and relies on the difference in the recapture rate between two sequential tag-release experiments. The first batch of tagged lobsters were released in May 1994 while the second batch were tagged five months later in October 1994. Negligible fishing effort occurred in the period between the two releases due to a seasonal size restriction on scallops - the main target species in the area. Dredge (1990) deployed this method to obtain estimates of *M* for the red spot king prawn, *Penaeus longistylus.* Using this method, *M* can be estimated thus:

$$M_{T_2 - T_1} = \ln\left(N_1^{'} \Big/ N_1 \right)$$

where:

$N_1^{'} = N_2 Re_1 / Re_2$,

T_1 and T_2 are times at tag releases 1 and 2, respectively,

N_1 and N_2 are the numbers of lobsters tagged and released at times 1 and 2 respectively,
Re_1 *and* Re_2 are the numbers of lobsters recaptured from releases 1 and 2 respectively, and
$N_1^{'}$ is the number of survivors at time T_2.

A fundamental assumption underlying the use of this method is that there is no fishing effort during the closed period, and therefore no mortality due to fishing. An advantage of the method is that, if the instantaneous rate of tagging mortality α and reporting rate β are constant for both batches of releases, these parameters do not need to be considered in the derivation of *M*.

Pauly's (1980) empirical method for the estimation of *M* is a widely used approach for quantifying natural mortality rates and was used here to provide a second independent estimate of *M*. It is based on a multiple regression analysis of 175 fish stocks from a wide range of taxa and habitats and can be expressed thus:

$$\log(M) = -0.0066 - 0.279\log(L_\infty) + 0.6543\log(K) + 0.4634\log(T)$$

where L_∞ and K are the von Bertalanffy growth parameters and T is the mean annual water surface temperature in ^{o}C. The method is deceptively easy to apply and is now widely used worldwide. A re-investigation of the work by Lijam (1990), using a larger data set and correcting some of Pauly's original data, gives encouragingly similar values. Confidence intervals are ±20% over most of the likely range.

Estimating fecundity and value for a range of size classes

Jones (1988) obtained fecundity estimates for a range of sizes for both *T. indicus* and *T. orientalis.* His estimates are deployed herein to simulate the effects of various MLSs on egg production.

Market values for different size classes of lobsters, required to simulate the effects of different MLSs on the value of the catch, were obtained by recent phone interviews with processors located between Cairns and Brisbane.

3.3 Results and Discussion

Growth rates

Logbook data on the distribution of catches for Moreton Bay Bugs, combined with information on the depth of water trawled and the depth-related distribution of the two species indicate that *T. orientalis* forms the bulk of Moreton Bay Bug landings in Queensland. *Thenus orientalis* also grows to a larger size than *T. indicus* and commands higher market prices. For these reasons, emphasis was placed on *T. orientalis.* Tagging data results were generally more robust for *T. orientalis* than for *T. indicus.* A total of 2,341 and 9,888 *T. indicus* and *T. orientalis* were tagged and released, respectively.

Growth rates were estimated for male and female *T. orientalis* that had been at liberty for a minimum of 100 days prior to being recaptured. This period was used in order to maximise the

likelihood of moulting while liberty, and to reduce bias in the results due to inclusion of a large number of individuals that had been at liberty for only a short time that were unlikely to have moulted and grown. Because fewer *T. indicus* were tagged and recaptured, the minimum time at liberty used for estimating growth was reduced to 30 days to increase the number of recaptures for analysis. Table 3.1 contains a summary of the von Bertalanffy growth parameters, K and L_∞ for both species.

Table 3.1. von Bertalanffy growth parameters for *Thenus* spp. obtained using Fabens' (1965) least-squares method for analysing tag-recapture data.

Species and Sex	Minimum days at liberty	Number of recaptures analysed	K day^{-1} (95% C.I.)	L_∞ mm CL (95% C.I.)
Male *T. orientalis*	100	197	0.0014 (0.0013-0.0016)	77.45 (76.45-78.46)
Female *T. orientalis*	100	121	0.0016 (0.0014-0.0018)	89.04 (87.58-90.49)
Male *T. indicus*	30	73	0.0026 (0.0020-0.0031)	61.23 (58.46-64.00)
Female *T. indicus*	30	77	0.0023 (0.0019-0.0027)	72.44 (68.87-76.01)

Growth curves are presented graphically in Figure 3.1. Female *T. orientalis* reached a larger L_∞ and

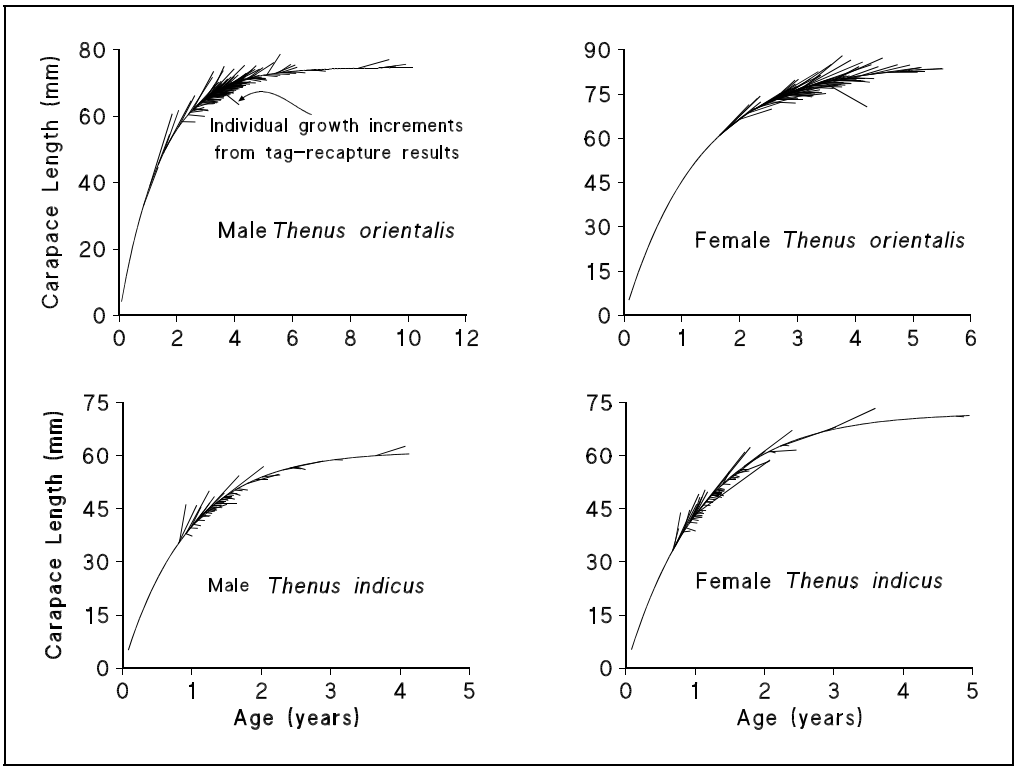


Figure 3.1. von Bertalanffy growth curves for *Thenus* spp., based on Fabens' (1965) method of analysing tag-recapture data.

displayed a slightly higher growth rate (K) than males. Growth rates (K) were higher for *T. indicus* but L_∞'s were lower, particularly for males.

Plots of the residuals (observed minus expected growth) against days at liberty are presented for each species and sex in Figures 3.2. The model fitted the data well for female *T. orientalis*. However, significant deviations occurred for the remaining groups. Clumping of the residuals below expected values is particularly noticeable for male and female *T. indicus*. This is difficult to explain, but possibly due to the inclusion of a relatively large number of recaptured lobsters that had been at liberty for a relatively short time (i.e., > 30 but < 70 days). Many of these individuals probably did not moult and therefore did not grow before being recaptured. The fitted von Bertalanffy model describes continuous growth, and hence it expects growth to take place from the time of release. The fact that that growth in crustaceans is incremental (not continuous) is likely to explain the negative clumping. The analyses could be repeated using individuals that had been at liberty for longer periods, however this is likely to reduce the number of recaptures that would be included for analysis. When length frequency data were examined the growth curve fitting procedure in ELEFAN identified a similar L_∞ (approximately 90mm CL) for female *T. orientalis*, however the K was more than twice that obtained by tagging.

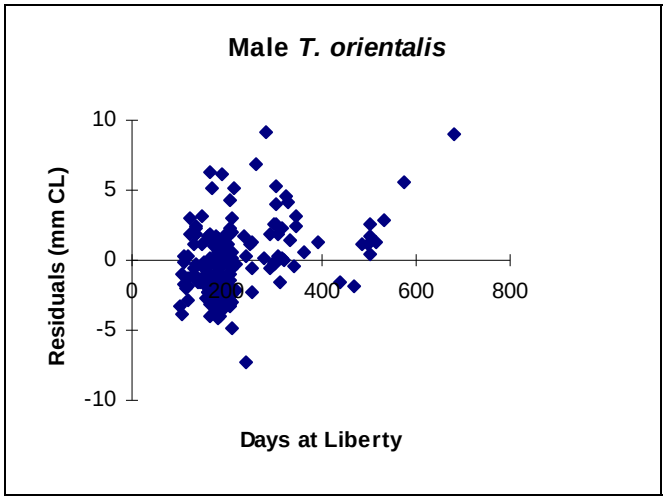


Figure 3.2. Residuals for measured size at recapture versus expected against time at liberty for male *T. orientalis*. Only lobsters at liberty >= 100 days were included.

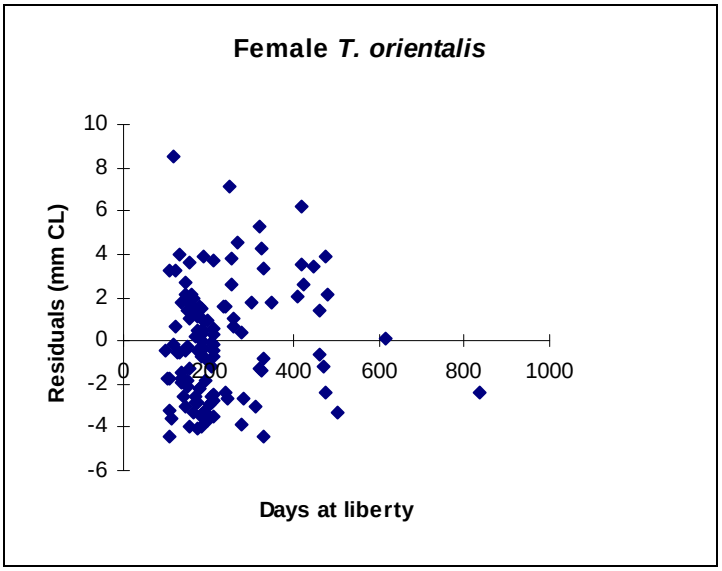


Figure 3.3. Residuals for measured size at recapture versus expected against time at liberty for female *T. orientalis*. Only lobsters at liberty >= 100 days were included.

Growth curves that were based on length frequency analysis generally fitted the frequency distributions poorly. Nevertheless, length frequency analyses offer a second method for quantifying growth which is independent of the effects of tagging. Both length frequency growth analyses and the laboratory aquarium studies suggest that tagging may slow growth by inhibiting moulting. Further comparisons between these two methods need to be undertaken. If tagging reduces the incidence of moulting in the field, growth curves based on tag-recapture data may underestimate the true rate of growth.

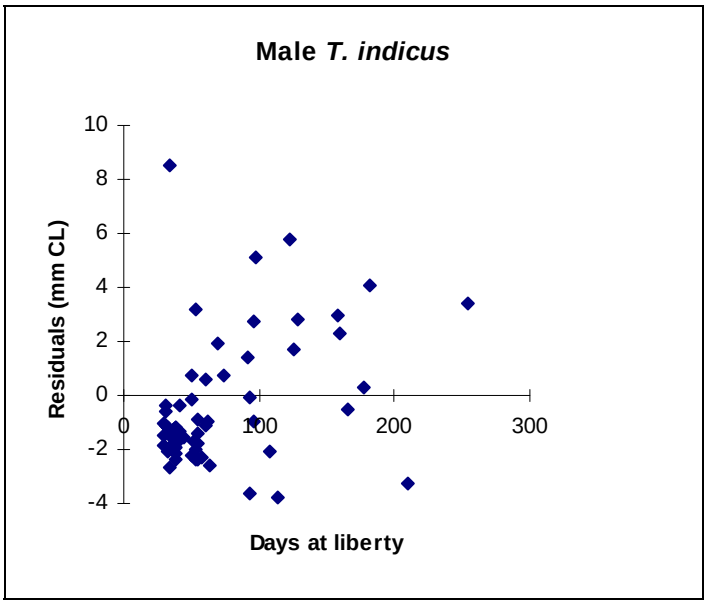


Figure 3.4. Residuals for measured size at recapture versus expected for male *T. indicus*. Only lobsters at liberty >= 30 days were included.

Estimating mortality rates

The instantaneous disappearance rate *X* was estimated from a single large tagging trip which involved two trawlers from 14-22 October 1994. A total of 2,128 *T. orientalis* were tagged and released in the vicinity of Mast Head Reef (23°24'S, 151°30'E). The instantaneous disappearance rate (*X*) is based on the exponential rate of decline in recaptures per unit of fishing effort over the following months.

Tagged lobsters were allowed a few days to recover from tagging and to disperse prior to commencement of the recapture

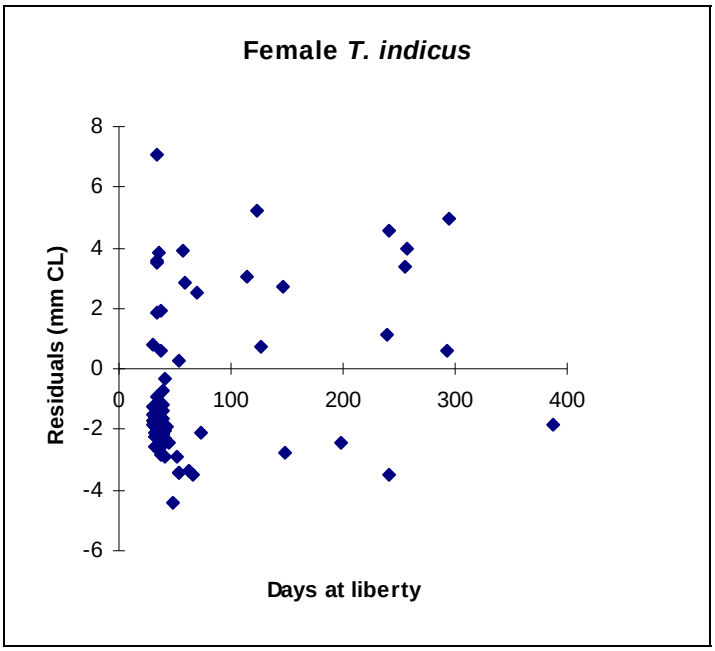


Figure 3.5. Residuals for measured size at recapture versus expected against time at liberty for female *T. indicus*. Only lobsters at liberty >= 30 days were included

phase of the experiment on 31 October 1994. This date coincides with the annual lowering of the size limit on scallops and is characterised by a large pulse increase in fishing effort which provides recaptures from the two releases.

A total of 222 males and 138 females were recaptured over the following 65 weeks. Possible explanations for the difference in recapture rates between sexes were discussed in Section 2. Figure 3.6 shows the exponential rate of decline in recaptures with time for males and females. Instantaneous disappearance rates (*X)* were 0.0378 week^{-1} (1.966 year^{-1}) and 0.0262 week^{-1} (1.362 year^{-1}) for males and females, respectively. Significance tests for the differences between sexes have not yet been undertaken. When sexes were pooled (Figure 3.7) an instantaneous disappearance rate *X* of 1.919 year^{-1} (0.0369 week^{-1}) was obtained. The higher recapture rate for males tend to dominate the estimate.

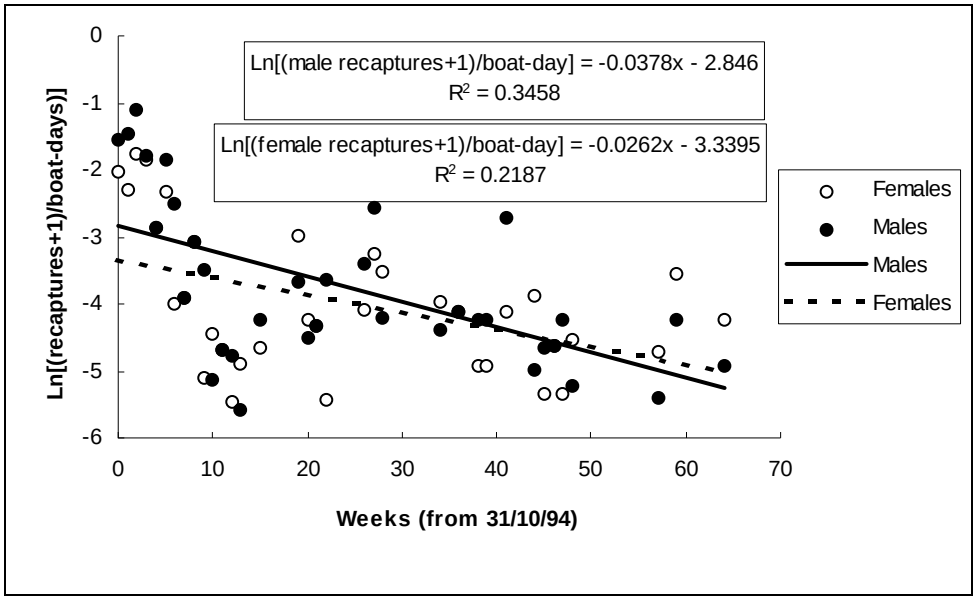


Figure 3.6. Exponential decline in recapture rate of tagged *T. orientalis* per unit of fishing effort. Results are based on a single large tag-recapture experiment. The slope of the regressions provides an estimate of the instantaneous disappearance rate, *X* (week^{-1}) for each sex.

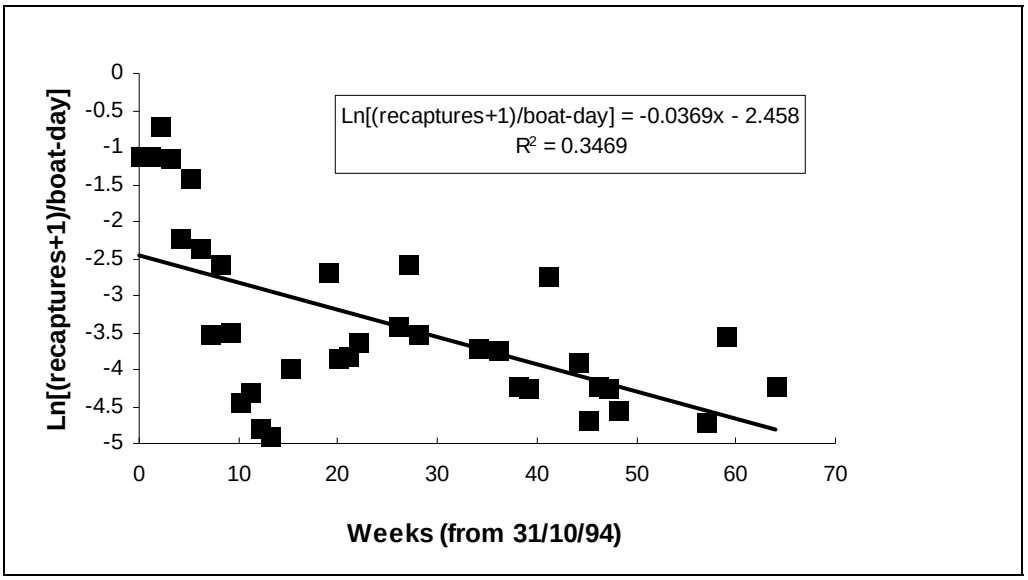


Figure 3.7. Instantaneous disappearance rate for *T. orientalis.* (Sexes pooled.)

Estimating M

The instantaneous rate of natural mortality, obtained using Ricker's (1975) sequential tagging method, was derived from two tagging trips in May and October 1994. The following parameters were obtained: N_1 = 2179, N_2 = 2128, Re_1 = 247 and Re_2 = 362. This facilitated an estimate of $N_1^{'}$ to be made, where $N_1^{'}$ = 1452 and hence an estimate of the instantaneous rate of natural mortality:

$$M_{T2\text{-}T1} = 0.406 \text{ per 23 weeks (duration of the closed period) or } 0.918 \text{ year}^{-1}.$$

This estimate of *M* is likely to be slightly high and includes a small (unquantified) component of fishing mortality, due to the fact that there was some low level fishing effort during the closed period (May-October 1994). This low level fishing effort resulted in a small number of tagged lobsters being caught during the closed period, thus, violating the fundamental assumption underlying the method - that there is no fishing mortality over the closed period. Nevertheless, the level of fishing effort (and therefore fishing mortality) was low and only very few lobsters were caught during the closed period. The estimate of *M* obtained is therefore approximate and likely to be slightly high due to the inclusion of some additional fishing mortality, *F*.

Pauly's (1980) method requires input parameters for the mean surface water temperature and von Bertalanffy *K* values for each species and sex that *M* is estimated for. A value of 23^{o}C was used for the mean water surface temperature. *K* values were based on the results of Faben's (1965) analysis in Table 3.1. A summary of the instantaneous rates of natural mortality are provided in Table 3.2.

Table 3.2. Estimates of the instantaneous rates of natural mortality *M* for *Thenus* spp. based on two different methods.

Sex and Species	Estimate of *M* based on Pauly's (1980) empirical formula. ($year^{-1}$)	Estimate of *M* from Ricker's (1975) sequential tagging method. ($year^{-1}$)
Male *T. orientalis*	0.81	0.92
Female *T. orientalis*	0.85	0.92
Male *T. indicus*	1.29	N/A
Female *T. indicus*	1.23	N/A

Comparison of results for the two methods (Ricker 1975 and Pauly 1980) is encouraging for *T. orientalis.* The estimates are similar, varying between 0.81 and 0.92. It is however noteworthy that Pauly's method results in slightly lower values of *M.* This could be due in part to the fact that the Ricker sequential tagging method resulted in slightly high estimates of *M.*

Estimating F

Given estimates of *X, M* and γ, an estimate of *F* can now be derived thus:

$$F = X - (M + \gamma)$$

$$F = 1.919 - (0.918+0.355) = 0.646 \text{ year}^{-1}$$

The estimate of *M* (0.918 $year^{-1}$) used here to derive *F* was based on the Ricker (1975) sequential tagging method. If this estimate of *M* is slightly high, the resulting derived value of *F* is likely to be slightly low.

Fecundity and value estimates

Jones (1988) described the relationship between fecundity and lobster size for female *T. orientalis* and *T. indicus* thus:

Number of eggs (*1000) = -67049 + 1273.2 * Carapace length (mm) (*T. orientalis*)

Number of eggs (*1000) = -26329 + 658.7 * Carapace length (mm) (*T. indicus*)

Interestingly, Jones also detected a decline in fecundity with incubation period, suggesting that the numbers of eggs that survive through to hatching may be lower than what the above regressions imply. However, he concluded that the results require further confirmation.

The wholesale value of different size classes of lobsters paid to fishers by processors was obtained by phone interviews with processors located in Cairns, Mackay, Gladstone and Brisbane in November 1996. Approximate values for different size classes of *Thenus* spp. are presented in Figure 3.8. It should be noted that the price range, and particularly the ascending slope in the price range (Figure 3.8) greatly influences the value per recruit simulations.

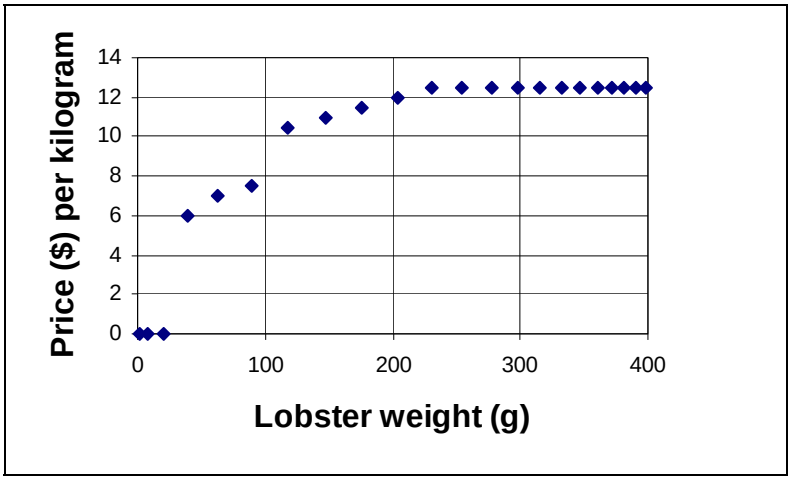


Figure 3.8. Approximate prices paid to fishers by seafood processors for different size classes of *Thenus* spp. (based on phone interviews with processors November 1996).

If a MLS is introduced with the intention of maximising value (rather than egg production), then periodic price surveys should be undertaken and the simulations re-run. The optimal value per recruit will change if the price range changes. No empirical formula was fitted to the data in Figure 3.8 and the scatterplot point positions are partly subjective, although based on interviews with processors. This is partly due to the fact that prices vary between processors and also because there is no succinct minimum size (or weight) at which the lobsters become unmarketable (i.e., at what size is the value zero?)

In summary, this section of the report has focused on quantifying parameters required to simulate the effects of a range of possible MLS on yield, value and egg production for Moreton Bay Bugs. Although the estimates of growth and mortality derived here are currently the most robust reported for the genus, considerable uncertainty associated with these parameters remains. Where possible this uncertainty will be considered in the following section which reports on the simulation results and identifies the most appropriate MLS.

Section 4. Simulating minimum legal sizes (MLSs) on Moreton Bay Bugs, *Thenus* spp.: effects on value and egg production.

4.1 Introduction

Minimum legal sizes (MLSs) are a common fisheries management tool that can be used to optimise various utilities (Die *et al.* 1988, Die 1992). Application and examples of MLS in Australian fisheries were reviewed by Hancock (1992). The utilities may vary and depend on why a MLS is first considered. For example, in a lightly exploited recreational fishery a MLS might be considered in order to increase the number of fish caught per angler. This may not necessarily maximise the weight of the catch. In contrast, in a heavily exploited, overfished industrial fishery, a MLS would most likely be introduced to increase the size/age at first capture in order to increase egg production with the intention of increasing recruitment. Thus, MLSs can be considered for a range of objectives.

For *Thenus* spp. a MLS is being considered to reduce the likelihood of recruitment overfishing occurring (i.e., increase egg production) and to maximise value of the catch. Actual numbers or yield (weight) of lobsters caught is secondary. Other forms of managing the resource, including temporal and spatial closures and altering mesh size, are inappropriate due to the fact that Moreton Bay Bugs are a by-product of prawn and scallop trawling.

The objective of this section of the report is to develop quantitative methods for simulating MLSs and report on their likely effects on value and egg production. An optimum age /size at first capture is identified. This age is then converted to a carapace width (mm CW), for practical implementation and policing. C.W. is perceived as a more practical means of meeasurement, in terms of policing, than C.L.

4.2 Materials and Methods

The empirical methods used for simulating the effects of different MLSs are well established and based on the early yield per recruit approach by Beverton and Holt (1957). Yield per recruit is a standard steady-state model widely used for stock assessment. It can be deployed to determine the level of fishing mortality and size/age at first capture required to maximise and sustain yield. In a steady state fishery, yield per recruit can be estimated by:

$$Y/R = \exp(-M(t_c - t_r)) \sum_{i=t_c}^{i=t_l} \left\{ (F/(F+M)) \exp(-(F+M)(i-t_c)) \left(1 - \exp(-(F+M))\right) W_i \right\}$$

where, Y = steady state yield of the fishery, R = number of recruits, M = instantaneous rate of natural mortality, F = instantaneous rate of fishing mortality, W_i = mean weight of fish aged i, t_r = age at recruitment to fishable stock, t_c = actual age of first capture, t_l = maximum age of fish in stock. Some rigorous assumptions underlie the equilibrium yield per recruit:

(i) recruitment is constant, yet not specified (hence the expression yield per recruit)

(ii) all fish (lobsters in the present study) of a cohort are hatched on the same date

(iii) fishing and natural mortalities are constant over the post-recruitment phase

(iv) fish older than t_l make no contribution to the stock.

The utility function(yield) in the yield per recruit model can be varied. In the present study, the main objective of the simulations is to examine the effects of a MLS on the value and egg production of the lobsters. This is achieved by substituting value-at-size and fecundity-at-size regressions for the length-weight relationship in the Beverton and Holt formula. It should be pointed out that, unlike yield and value, it is virtually impossible to identify "safe" or optimal levels of egg production. This is because the relationship between egg production and recruitment is poorly understood in Moreton Bay Bugs.

In the simulations, vulnerability to fishing mortality was assumed to be knife edged. This assumption is likely to be valid, due to the fact that the lobsters are relatively large (compared with the trawl mesh size) and period over their life span during which selectivity varies, is short. Lobsters younger than the age at first capture (t_c) were assumed to have zero vulnerability, while those equal to or older than t_c were assumed to be 100% vulnerable. For simplicity certain results are expressed in terms of variation with exploitation rate, U, where $U = F/F+M$. All simulations were carried out using spreadsheet (Excel version 7) models based on Beverton and Holt's (1957) empirical formula. All modelling was based on harvesting at different ages. Optimal ages at first capture were identified and converted to carapace width (mm CW) measures, which is likely to be the most practical body-length parameter used to implement a MLS.

Emphasis was placed on *T. orientalis* as logbook catches indicate this species is the more valuable of the two in Queensland. Simulations were also carried out for *T. indicus.* However, results for this species should be considered with caution because of greater uncertainty associated with its mortality rates.

4.3 Results and Discussion

Value per recruit

Figure 4.1 is a surface plot of the value per recruit for female *T. orientalis* for a range of exploitation rates (*U*) and ages at first capture. From the previous sections, estimates of the instantaneous rates of natural and fishing mortalities were 0.918 and 0.646 year^{-1}, respectively, based on the tagging results. The exploitation rate estimate (*F/F+M*) is therefore 0.413. Fishing mortality is likely to vary spatially and temporally. In heavily fished areas, such as Hervey Bay, the exploitation rate is likely to be higher than this value. In other regions that receive less fishing effort, *U* is likely to be less than 0.413. Given the current estimate of exploitation rate *U* to be 0.413, the corresponding ages at first capture that are likely to result in high value per recruit are 1.6-2. years (Figure 4.1). Maximum value occurs at an age of first capture of 1.75 years, but there is very little difference between ages in this range.

Figure 4.2 represents a two-dimensional "slice" through the surface plot at exploitation levels that closely reflect the current fishing effort levels (*U* = 0.4 and 0.5). For female *T. orienatlis*, an age of 1.75 years corresponds to a carapace width (CW) of 80.3 mm (Figure 4.3). It is important to note that while the lobsters are capable of living for 4-7 years, harvesting them at these old (large) sizes will result in sub-optimal value per recruit, due to the effect of natural mortality on the population.

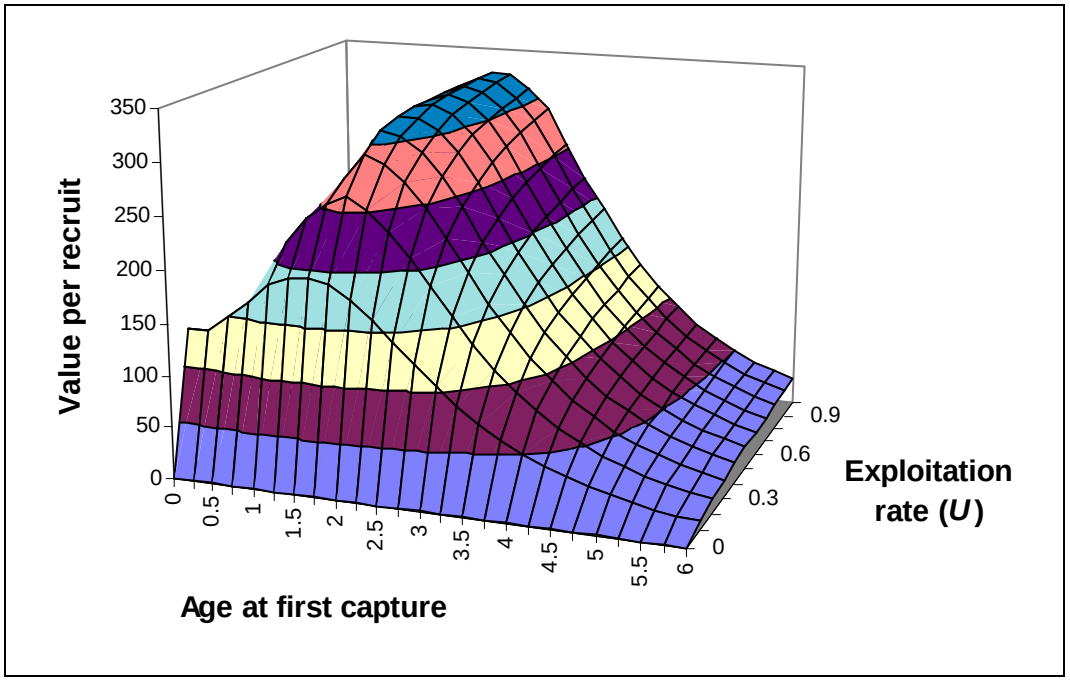


Figure 4.1. The value per recruit surface plot for female *T. orientalis*. Current exploitation rate, *U = 0.413*

Harvesting the lobsters at these older ages a would result in significant annual losses in revenue. Similarly, it would reduce the value of the catch if they were harvested at ages of less than one year, mainly because of the low market value of small size classes.

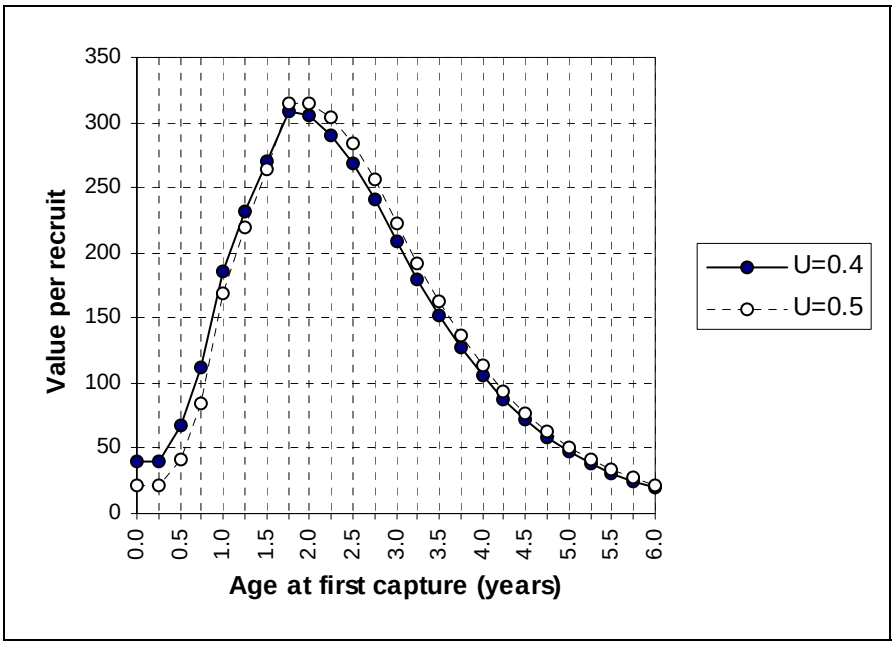


Figure 4.2. Value per recruit "slice" against age at first capture for female *T. orientalis*. Results are presented for the two exploitation levels (*U* = 0.4 and 0.5) that most closely reflect current conditions in the fishery. Maximum value per recruit occurs at an age of 1.75 years.

Value per recruit analyses were also undertaken for male *T. orientalis*. Results for the "slice" through the value per recruit surface plot at the two levels of exploitation (*U* = 0.4 and 0.5) are provided in Figure 4.4. Again, there is little difference in the general shape of the curves for the two exploitation rates. Both indicate maximum value per recruit would be obtained by harvesting at an age of 2.5 years - about 7.5 months older than that for the females. This age (2.5 years) corresponds to a carapace width of 77.3 mm (Figure 4.5). Thus, although the optimum *age* at first capture differs markedly between the sexes, optimal *sizes* are similar (80.3 mm CW for females and 77.3 mm CW for males). For practical reasons on board the vessels, and for enforcement, a single MLS of 80 mm CW could be adopted for *T. orientalis.* Although this

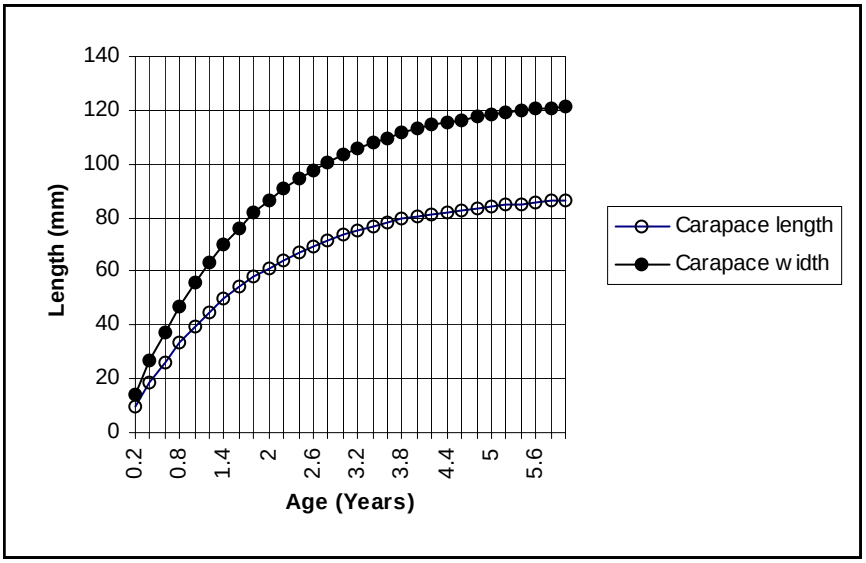


Figure 4.3. Carapace length and carapace width against age for female *T. orientalis*. The carapace is wider than it is long. Carapace width is likely to be the most practical parameter for regulation and policing if a MLS is adopted.

size does not correspond with the absolute maximum for either sexes, deviations from the maximum value per recruit would be negligible.

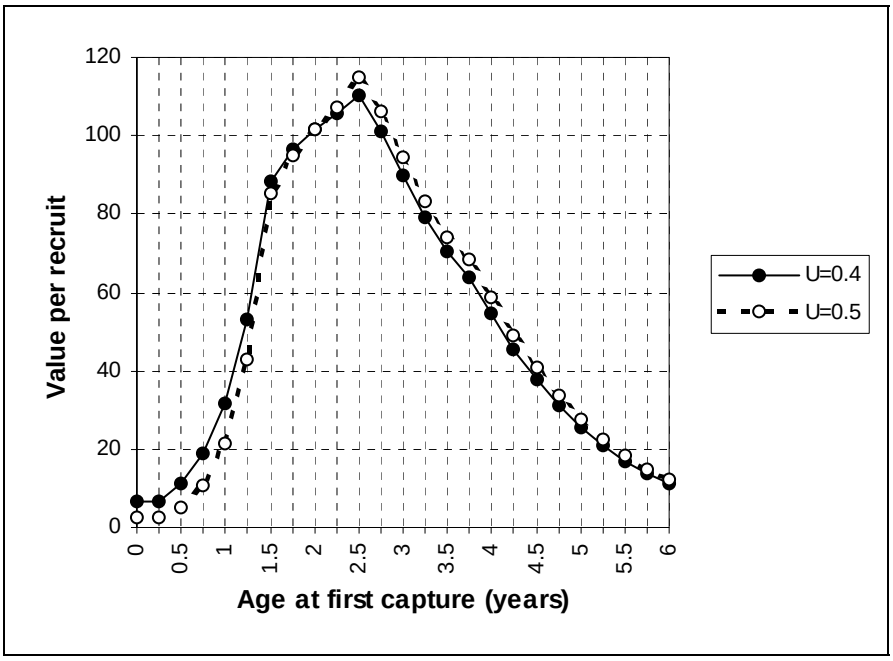


Figure 4.4. Value per recruit "slice" against age at first capture for male *T. orientalis*. The two exploitation levels (*U* = 0.4 and 0.5) reflect current conditions in the fishery. Both indicate an optimum age at first capture of 2.5 years (exact peak not shown).

Effects of a MLS on egg production in female T. orientalis.

The relationship between spawning stock size and recruitment in Moreton Bay Bugs is unknown. Hence, the proportion of virgin stock egg production required to maintain recruitment is also unknown. Any MLS regulation will impact on the size of the spawning stock. It is therefore necessary to examine the effects of the MLS on egg production to ensure an adequate spawning biomass remains in the population and recruitment levels are maintained.

An underlying assumption herein is that recruitment is not independent of egg production. There may be a direct relationship, where by the number of eggs released is directly proportional to the number of recruits. Alternatively, there may be a saturation point where egg production and recruitment increase to a point, at which the environment (food and space) cannot support more recruits. At this point recruitment becomes independent of egg production.

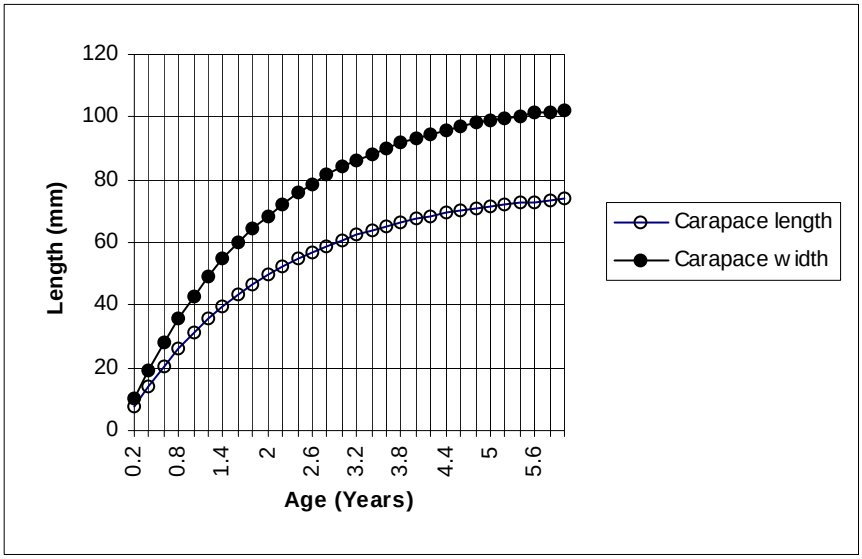


Figure 4.5. Carapace length and carapace width against age for male *T. orientalis*. Optimum age at first capture (2.5 years) corresponds to a carapace width of 77.3 mm.

Harvesting the lobsters at a MLS which maximises value, but greatly reduces egg production is likely to lead to recruitment overfishing in the long term. The lack of information on the spawning stock - recruitment relationship for Moreton Bay Bugs makes it difficult to identify "safe" or optimal levels of egg production. Mace (1994) recommends that when the relationship between spawning stock size and recruitment is unknown, a fishing mortality rate of no more $F_{40\%}$ [a biological reference point (BRP) equivalent to the fishing mortality at which spawning per recruit is 40% of the maximum] should be adopted. Figure 4.6 shows the three-dimensional surface plot of egg production per recruit for female *T. orientalis* for a range of exploitation rates and ages at first capture. The results confirm that maximum egg production occurs under low exploitation and high age at first capture. Egg production also remains high at low exploitation rates (< = 0.1), regardless of the age at first capture. Figure 4.7

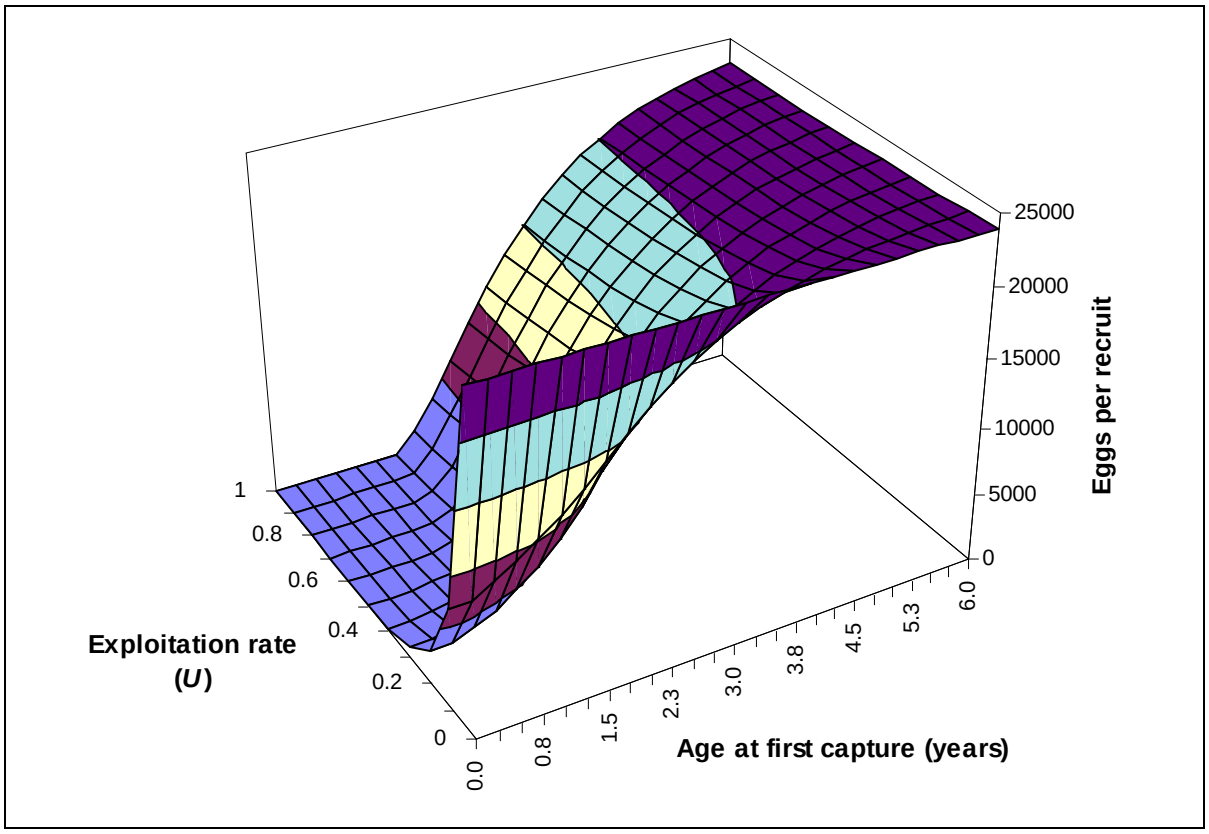


Figure 4.6. Number of eggs produced per recruit for a range of possible ages at first capture and exploitation rates (*U*). Highest egg production occurs under low exploitation levels and a high age at first capture.

shows the relationship between egg production and age at first capture for the "slice" through the surface plot at current exploitation levels (U = 0.4 and 0.5). The results indicate that if a MLS of 80.0 mm CW (approximately 1.75 years of age) is adopted for female *T. orientalis*, egg production will be approximately 20% that of the virgin stock biomass. It is unknown whether this is sufficient to maintain long term recruitment. Mace (1994) warns that the level of fishing mortality which corresponds to 20% of the virgin stock spawning biomass ($F_{20\%}$) exceeds the fishing mortality extinction threshold in some stocks. For these reasons it would be unwise to implement a MLS less 80.0 mm CW for *T. orientalis.*

If Mace's $F_{40\%}$ is adopted, the age at first capture would have to be increased to 2.25 years, which corresponds to a MLS of approximately 91.6 mm CW. This larger MLS would result in a negligible (<2%) loss of value compared with harvesting at the optimum 80.3 mm CW, but it would double the egg production and therefore effectively halve the long term probability of recruitment overfishing.

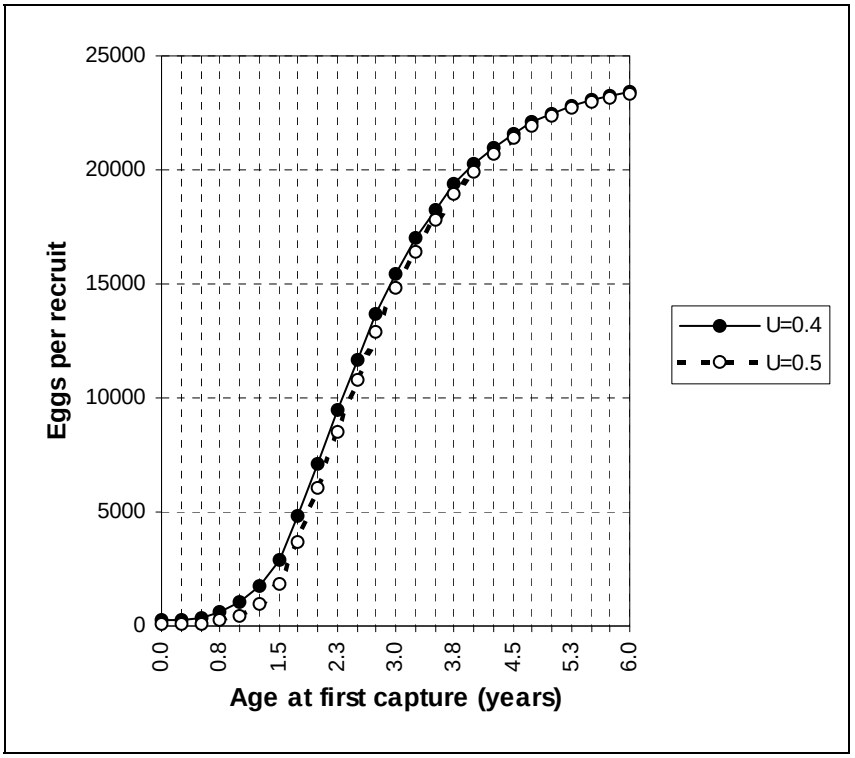


Figure 4.7. Number of eggs per recruit for a range of ages at first capture for female *T. orientalis*.

The effect of Mace's $F_{40\%}$ and the corresponding MLS of 91.6 mm CW would have a greater effect on the value of male *T. orientalis*. This is because males are smaller than females and reach their optimum value at an older age. A MLS of 91.6 mm CW would result in a reduction in the value of males by approximately 40% compared with optimum 77.3 mm CW. Thus, while Mace's $F_{40\%}$ BRP substantially reduces the risk of recruitment overfishing in *T. orientalis*, it would result in a considerable reduction in overall economic value for this species.

Effects on Thenus indicus

No single MLS will optimise the value for both species. Adopting two separate MLS (one for each species) is possible, but likely to be impractical for fishers and very difficult to police. Therefore, the most appropriate single MLS for Moreton Bay Bugs in Queensland will be a compromise for both species (and sexes).

There is greater uncertainty in determining the effects of a MLS on *T. indicus* and therefore results for this species should be considered with caution. This is due to the fact that only one empirical-based estimate of the instantaneous rate of natural mortality *M* was obtained for this species (using Pauly's 1980 method) and because the instantaneous rate of fishing mortality *F* is unknown. A single value of *M* equal to 1.2 year^{-1} was used for both male and female *T. indicus*. In the absence of a quantitative estimate of fishing mortality, *M* and *F* are assumed to be equal. Therefore, the current exploitation rate *U* was assumed to be (*F/F+M*) 0.5. Nevertheless, simulations were carried for a range of exploitation rates (0.1-1.0). The results are presented in Figure 4.8. Under these parameter values and assumptions about exploitation rates, optimum value per recruit for female *T. indicus* occurs at an age of 1.75 years, which corresponds to a carapace width of 80.0 mm.

Egg per recruit simulations indicate that at this size/age at first capture about 52% of virgin stock egg production would be maintained. The more conservative size at first capture of 91.6 mm CW would increase the egg production by female *T. indicus* up to about 77% that of virgin stock production. However, harvesting female *T. indicus* at 91.6 mm CW would also result in a loss of value of approximately 37% of the maximum.

The optimum age at which to harvest male *T. indicus* was 1.5 years, which corresponds to a carapace width of approximately 66 mm. This is quite small and due to the fact that male *T. indicus* are the smallest and fastest growing of the four groups (two species x two sexes) considered. It is therefore expected that the analysis indicated they should be harvested at a relatively small size and young age. If they are harvested at a MLS of 80 mm CW the loss in value per recruit will be equivalent to about 46% of maximum obtainable. If the more conservative 91.6 mm CW is adopted the effect on male *T. indicus* would be dramatic and result in a 100% loss (i.e., zero catch) due to fact that males never reach this large size.

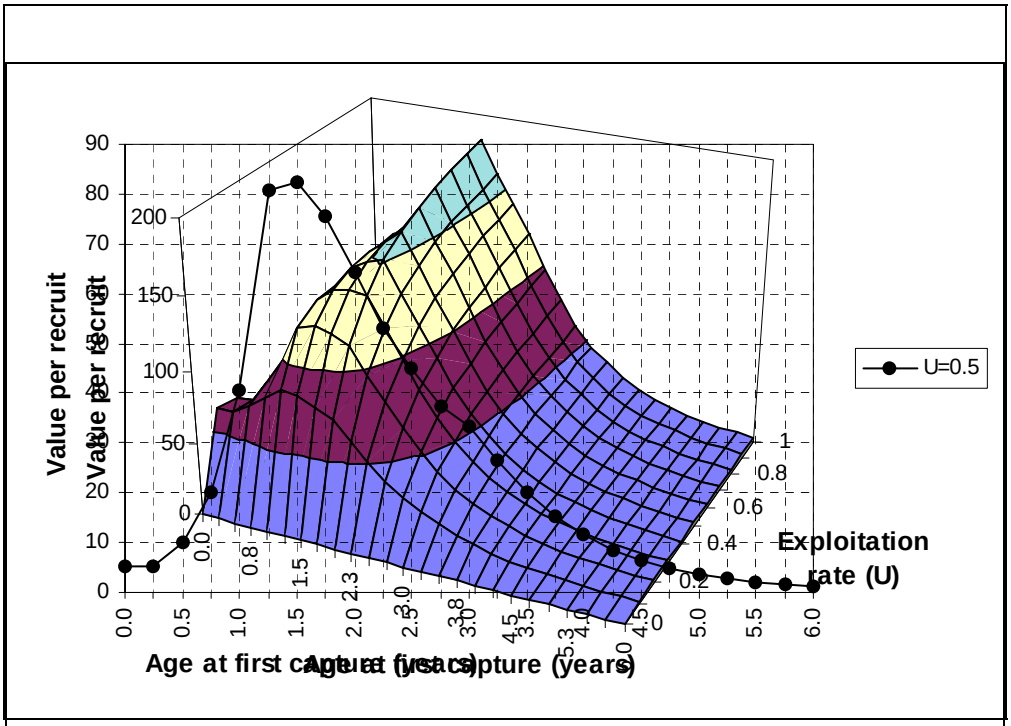


Figure 4.8. Value per recruit for female *T. indicus* for a range of ages at first capture and exploitation rates. The instantaneous rate of fishing mortality *F* is unknown. *M* and *F* were assumed to be equal (1.2 year^{-1}) resulting in a current exploitation rate of 0.5.

Figure 4.9. Value per recruit for male *T. indicus* against age at first capture based on an exploitation rate *U* = 0.5. Maximum value per recruit would be obtained by harvesting at an age of 1.5 years, which corresponds to a carapace width of 66 mm.

4.4 Summary and Conclusions

These results should be treated with caution because

a) they are based on population parameters estimates that are associated with considerable uncertainty;

b) the tagging-based estimate of *M* for *T. orientalis* was derived from a spatially localised population (in the vicinity of Mast Head Reef) and therefore is unlikely to represent all populations throughout Queensland's coastal waters. This estimate of *M* was also likely to be slightly over estimated, due to the fact in incorporates some low level fishing mortality; and

c) apart from Pauly's (1980) empirical method, no mortality rate estimates were obtained for *T. indicus.*

Maximum value per recruit for *T. orientalis* would be obtained by harvesting at a carapace width of 80.3 and 77.3 mm for females and males, respectively. For practical implementation a single MLS of 80 mm CW could be deployed for this species with negligible consequences. At 80 mm CW, female *T. orientalis* would produce approximately 20% of the virgin stock egg production. Its unknown whether this level of egg production would maintain recruitment.

Mace (1994) suggests management measures consistent with 40% ($F_{40\%}$) of virgin stock egg production should be adopted when the stock-recruitment relationship is unknown. This results in a more conservative MLS estimate of 91.6 mm CW and while halving the probability of recruitment failure for *T. orientalis*, it would also incur a considerable loss in value for this species in the order of about 20% (due almost entirely to a loss in male landings). It would also incur a heavy loss in revenue for the smaller *T. indicus.*

There is a greater level of uncertainty associated with the simulations for *T. indicus*. Emphasis was placed on quantifying parameters for the larger and more valuable *T. orientalis.* Assuming an exploitation rate (*U*) of 0.5, simulations indicate maximum value per recruit for female *T. indicus* would be obtained using a size at first capture equal to 80.0 mm CW. At this size, and under the assumptions made about exploitation rate, female *T. indicus* would produce about 52% of the virgin stock egg production. If the more conservative 91.6mm CW was adopted this would reduce the value of female *T. indicus* by 37% compared with the maximum, but increase egg production to 77% that of virgin stock.

Male *T. indicus* are the smallest of the groups considered. Their maximum value would be obtained using a size at first capture of 66 mm CW. Increasing this to 80 mm CW would decrease their value by about 46% that of the maximum value. A MLS of 91.6 mm CW would effectively prevent all harvesting of male *T. indicus*, resulting in a total loss in revenue for this group.

The main problem is in identifying a MLS which facilitates maximum egg production in *T. orientalis*, while minimising losses in revenue from not harvesting the smaller and less valuable *T. indicus.* A MLS of 80 mm CW appears to be a suitable compromise. This MLS will be very close to maximising value per recruit for three of the four groups (male and female *T. orientalis* and female *T. indicus*). However, it will result in a considerable loss in revenue for the smaller male *T. indicus.* A MLS less than 80 mm CW will probably lead to long-term declines in recruitment for *T. orientalis* and therefore should be avoided.

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References

Avise, J. (1991). Ten unorthodox perspective's on evolution prompted by comparative population genetic findings on mtDNA. *Annual review of genetics*. 25:49-69

Batuecas, B., Garesse, R.; Calleja, M; Valverde, J. R.; Marco, R. (1988). Genome organisation of Artemia mitochondrial DNA. *Nucleid Acids Research* 16(14A) 1988: 6515-6529

Beverton, R. J. H. and Holt, S. J. (1957). On the dynamics of exploited fish populations. Fish. Invest. Minist. Agric. Fish. Food. G. B. (2 Sea Fish.), 19: 533 p.

Brown, W. M., Prager, E. M., Wang, A., Wilson, A. C. (1982). Mitochondrial DNA sequences of Primates: tempo and mode of evolution. *Journal of Molecular Evolution* 18(4) 1982: 225-239

Bruns, T. D. and Palmer, J. D. (1989). Evolution of mushroom mitochondrial DNA: Sullius and related genera. *Journal of Molecular Evolution*. 18:225-239

Clary, D.O. and Wolstenholme, D.R. (1985). The mitochondrial DNA molecule of Drosophila Yakuba: nucleotide sequence, gene organisation, and genetic code. *Journal of Molecular Evolution* 22: 252-271

Die D. J., V.R. Restrepo and J.M. Hoenig (1988). Utility per recruit modelling: a neglected concept. *Transactions of American Fisheries Society* 117: 274-281

Die D. J. (1992). Utility per recruit modelling: a forgotten alternative for the evaluation of minimum size regulations. Proceedings of the 1990 ASFB workshops. Commonwealth Bureau of Rural Resources, Canberra (in press)

Dredge, M. C. L. (1990). Movement, growth and natural mortality rate of the red spot king prawn, *Penaeus longistylus* Kubo, from the Great Barrier Reef lagoon. *Australian Journal of Marine and Freshwater Research* **41**(3): 399-410

Fabens A. J. (1965). Properties and fitting of the von Bertalanffy growth curve. *Growth*, 29(3): 265-289

Gayanilo, F.C., Jr.; Sparre, P.; Pauly, D. (1994). The FAO-ICLARM Stock Assessment Tools (FiSAT) User's Guide. FAO Computerised Information Series (Fisheries). No. 7. Rome, FAO. 1994. 124 p.

Hancock, D. A. (Ed.) (1992). Legal sizes and their use in fisheries management. Australian Society for Fish Biology Workshop, Lorne, 24 August 1990. Bureau of Rural Resources Proceedings No. 13. (Australian Government Publishing Service, Canberra)

Hilborn, R. and Walters, C. J. (1992). Quantitative Fisheries Stock Assessment Choice, Dynamics and Uncertainty. (Chapman and Hall, New York) 570 p.

Hillis, D.M. and Moritz, C. (1990). An overview of applications of molecular systematics. Molecular Systematics (Eds. D.M. Hillis and C. Moritz). pp. Sinauer: Sunderland MA.

Hoffmann, R.J., Boore, J.L., and Brown, W.M. (1992). A novel mitochondrial genome organisation of the blue mussel, *Mytilus edulis*. *Genetics* 131: 397-412

Jones C. M. (1988). The biology and behaviour of bay lobsters, *Thenus* spp. (Decapoda: Scyllaridae), in Northern Queensland, Australia. PH.D. Thesis, University of Queensland, Brisbane, Australia

Kondo, R., Matsuura, E.T., and Chigusa, S.I. (1992). Further observation of paternal transmission of Drosophila mitochondrial DNA by PCR selective amplification method. *Genet. Res. Camb*. 59: 81-84

Kondo, R., Satta, Y., Matsuura. E.T., Ishiwa, H., Takahata, N., and Chigusa, S.I. (1990). Incomplete maternal transmission of mitochondrial DNA in Drosophila. *Genetics* 126: 657-663

Kumar, S., Tamura, K. And Nei, M. (1993). MEGA: Molecular evolutionary Genetic Analysis. V-1.1 The Pennsylvania State University: University Park, Pennsylvania

Lijam, N. (1990). Natural mortality estimation from water temperature and growth: confidence limits and scope. MSc thesis, University of Wales, Bangor.

Mace, P. M. (1994). Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. *Canadian Journal of Fisheries and Aquatic Sciences* 51: 110-122.

Martin, A. P. and Palumbi, S. R. (1985). Protein evolution in different cellular environments: cytochrome b in sharks and mammals. *Biological Journal of the Linnean Society* 26(4): 375-400

Martin, A. P. and Palumbi, S. R. (1993). Protein evolution in different cellular environments: cytrochrome *b* in sharks and mammals. *Molecular Biology and Evolution*. 10: 873-891

Moritz, C., Dowling, T. E. and Brown, W. M. (1987). Evolution of animal mitochondrial DNA: Relevance for population biology and systematics. *Annual review of Ecological Systematics* 18:269-292

Nei-M. (1987). Molecular evolutionary genetics. Columbia University Press, New York & Guildford, England. 1987: i-x, 1-512

Ovenden, J. R. (1990). Mitochondrial DNA and marine stock assessment: a review. *Australian Journal of Marine and Freshwater Research* 41(6) 1990: 835-853

Pauly, D. (1980). On the inter-relationships between natural mortality, growth parameters and mean environmental temperature in 175 fish stocks. *J. Cons. Int perm Explor Mer*. 39: 175-92.

Payne, C. D. (1985). The Generalised Linear Interactive Modelling System, release 3.77 Manual. Royal Statistical Society, U.K.

Palmer J. D. and Herbon, L. A. (1988). Plant mitochondrial DNA evolves rapidly in structure, but slowly in sequence. *Journal of Molecular Evolution* 28: 87-97

Pamilo, P. and Nei, M. (1988). Relationships between gene trees and species trees. *Molecular Biology and Evolution* 5(5) 568-583

Ricker, W. E (1975). Computation and interpretation of biological statistics of fish populations *Bulletin of the Fisheries Research Board of Canada* 191

Sparre, P. and Venema, S.C. (1992). Introduction to tropical fish stock assessment. Part 1. Manual. FAO Fish. Tech. Pap. 306/1. Rev. 1. Rome, FAO. 376p.

Saitou, N. and Nei, M. (1987). The neighbor-joining method: a new method for reconstructing phylogenetic trees. *Molecular Biology and Evolution* 4(4) 1987: 406-425

Sneath, P. H. and Sokal, R. R. (1973). Numerical Taxonomy. W.H. Freeman & Co.: San Francisco.

Vawter, L. and Brown, W.M. (1986). Nuclear and mitochondrial DNA comparisons reveal extreme rate variation in the molecular clock. *Science* 234: 194-196

Walter, M. F., Black, B. C., Afshar, G., Kermabon, A.Y., Wright, T. R. F. and Biessmann, H. (1991). Temporal and spatial expression of the yellow gene in correlation with cuticle formation and DOPA decarboxylase activity in Drosophila development. *Developmental Biology* 147(1) 1991: 32-45

Wayne, R. K., van Valkenburgh, B., Fuller, T. K. and Kat, P. W. (1990). Allozyme and morphologic differences among highly divergent mtDNA haplotypes of black-backed jackals. UCLA (University of California Los Angeles*) Symposia on Molecular and Cellular Biology New Series* 122 1990: 161-169

Wilson, A. C., Cann, R. L., Carr, S.M., George, M., Gyllensten, U. B., Helm-Bychowski, K. M., Higuchi, R. G., Palumbi, S. R. and Prager, E. M. (1985). Mitochondrial DNA and two perspectives on evolutionary genetics. *Biological Journal of the Linnean Society*. 26: 375-400

Zouros, E., Freeman, K. R., Ball, A. O. and Pogson, G. H. (1992). Direct evidence for extensive paternal mitochondrial DNA inheritance in the marine mussel Mytilus. *Nature* (London) 359(6394)