Developing and assessing techniques for enhancing tropical Australian prawn fisheries and the feasibility of enhancing the brown tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf

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1998/222	**Developing and assessing techniques for enhancing tropical Australian prawn fisheries and the feasibility of enhancing the brown tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf**

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OBJECTIVES:

1. Develop a bioeconomic model to assess the costs, benefits and risk of enhancing the stock of brown tiger prawns (*P. esculentus*) in Exmouth Gulf
2. Collate and critically review the information relevant to the enhancement of prawn fisheries for the Exmouth Gulf prawn fishery, and related prawn fisheries and aquaculture
3. Assess the risks associated with prawn stock enhancement in Exmouth Gulf
4. Consider protocols for stock enhancement

NON TECHNICAL SUMMARY:

The prawn trawl fishery in Exmouth Gulf, Western Australia, is well managed and harvests a mixture of penaeid prawns. Catches of the high value, brown tiger prawn *Penaeus esculentus* have comprised about 36% of the annual catch in the 1990s. However, annual catches of tiger prawns are now about half the level they were in the 1970s and fluctuate markedly, from about 200 to 680 t. These changes in catch create uncertainty in the supply of prawns for export markets and force fishing and processing operators to have excess capacity to deal with good years. Managers, fishing industry and researchers are considering the option of enhancing the natural recruitment of brown tiger prawns by releasing juveniles in wild nursery areas to reduce natural fluctuations and increase the average annual catch.

This collaborative project (CSIRO, Fisheries WA, MG Kailis Group of Companies) assessed the feasibility of stock enhancement of tiger prawns in Exmouth Gulf by:

- developing a bioeconomic model
- examining the risks of changes in the genetic composition and introducing disease to the wild population of tiger prawns, and
- identifying further work that would be needed before stock enhancement should proceed.

This is the first stage in several stages that would lead to stock enhancement of tiger prawns in Exmouth Gulf. The project was initiated through a workshop of all project participants in Perth in July 1998.

Bioeconomic model

A bioeconomic model was developed in EXCEL to make it accessible to managers and industry. This model contains independent modules (linked worksheets) for the hatchery, production, nursery and fishery. The results from the model suggest that a release of 7 million juvenile prawns (1g) would increase catches of brown tiger prawns by about 100 t and that the median marginal revenue for this level of enhancement would be $1.2M (range = $0.8M to

$1.7M). The marginal revenue was affected mainly by variation in prawn prices and secondarily by the densities used to grow juvenile prawns. The variation in prawn prices should be considered a risk in any future enhancement project. The uncertainty about the best densities for producing juvenile prawns and the production environment (i.e. ponds or raceways) is an important area for future research and development. A further source of uncertainty in the model is the survival rates of prawns and how they vary at different stages of the enhancement (e.g. survival during transport and release, whether survival is density-dependent in the nursery).

The median difference between production costs and the median marginal revenue was about $540, 000. This can not be interpreted as strict profit because the model did not include all capital costs and because it used some assumptions that are not be realistic (e.g. 100% survival of juveniles during harvest and release). Sensitivity analysis showed that provided the mortality associated with the harvest, transport and release of juvenile prawns is less than 30%, the enhancement has a greater than 90% chance of still being profitable. Although the model did not include the costs of monitoring, the current results indicate how much can be spent on capital and monitoring for enhancement to be profitable. The predictions of the current model therefore represent "best-case" scenarios for stock enhancement and would be refined, as new information becomes available. The model also provides a rigorous framework for evaluating the possible success of other enhancement projects. The model will be provided to people on request and receipt of a disk, and self-addressed envelope.

Nursery habitats

Participants at the stock enhancement workshop recognised that little was known about the nursery habitats of brown tiger prawns in Exmouth Gulf, the dynamics of juvenile prawns in the nurseries, and predation rates on them. This information is needed to develop the best release strategies to ensure the success of a stock enhancement.

Risks of affecting the gene pool and introducing disease through stock enhancement

The risks of affecting the genetic composition of the wild stocks from the stock enhancement of penaeid prawns were discussed by a panel of industry representatives, research scientists, research managers and policy managers at the FRDC sponsored workshop on "Genetics in the Aquaculture Industry" held in Perth in October 1998. In this case the risks were considered low and recommendations were made for minimising the genetic risks. These were:

- Determine the genetic structure of the wild population prior to stock-enhancement
- Use only broodstock from the target population selected for enhancement
- Randomly collect broodstock (to avoid family groups)
- Trace individual families through rearing using genetic markers
- Release the same number of individuals from each of the captive-bred families
- Monitor the effects of the release using molecular methods (e.g. microsatellite DNA markers)

The risks of introducing disease into the wild population were also considered at the stock enhancement workshop and in further discussions with Dr Brian Jones of Agriculture WA. The protocols for assessing diseases in prawns have been developed as a part of the Fisheries WA program on Disease and Hatchery testing and a component of the "Tropical Prawn Diseases" project (FRDC 98/212). Any juvenile prawns produced for stock enhancement would be tested for disease using these protocols.

Conclusions

The bioeconomic model has shown that the stock enhancement of tiger prawns in Exmouth Gulf can be profitable. However, further information is needed on the production of juvenile prawns and the survival of juveniles during the release (i.e. harvest, transport, release), to make better predictions about the likely success of an enhancement. The technology for the production, harvest, transport and release of juvenile prawns needs to be developed. Further information is also needed on the nursery habitats of the juvenile prawns to develop release strategies that give the maximum chance of a successful enhancement. These information needs are the basis for a three year FRDC project "Developing techniques for enhancing prawn fisheries, with a focus on brown tiger prawns (*Penaeus esculentus*) in Exmouth Gulf" (FRDC 1999/222), which is the second stage in the overall plan for the stock enhancement of tiger prawns in Exmouth Gulf. If the results of Stage 2 are favourable, it would be followed by trial stock enhancements (Stage 3, 1 to 2 million juveniles) and a commercial scale enhancement (Stage 4, 7 to 10 million juveniles) that would attempt to increase the commercial catch by at least 100 t.

KEYWORDS: **stock enhancement, reseeding, bioeconomic model, disease risks, genetic risks, release strategies, seagrass.**

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Background

Enhancing fish stocks has the potential to be a useful management tool to increase fishery yields, rebuild over-exploited stocks and dampen fluctuations in catch due to variable recruitment. High fluctuations in catches of commercial species can lead to problems in processing operations and supplying fish to clients. A continuous supply of product allows the market share to be maintained and maximises the efficiency and profitability of the processing operation.

The enhancement of fish stocks also has the potential to provide more information about the biology of the species and the dynamics of the fishery, which can be used to assist managers in developing better harvest strategies. However, for stock enhancement or reseeding to be successful, the husbandry, biology and ecology of the target animal must be thoroughly understood, in particular:

1. the methods for producing, transporting and releasing large numbers of juveniles
2. the environmental requirements of the animals and the carrying capacity of areas where animals are to be released
3. the factors that affect the survival of the released animals (including predation), and
4. the methods of monitoring and assessing the success of releases

In addition, both the potential benefits of stock enhancement, and any risks to the environment and/or the wild fishery must be assessed.

Overseas work on the enhancement/reseeding of prawn stocks has shown that it can be successful but that the success of the enhancement program differs greatly in different countries, and for different sizes and species of prawn (see Rothlisberg et al. 1999). This means that before undertaking any commercial scale enhancement of prawns in Australia, it is essential to carefully assess the costs and benefits of stock enhancement as a management tool for Australian fisheries.

Scientists at the CSIRO Cleveland Marine Laboratories have been interested in the enhancement of prawn stocks since the early 1990s, when a workshop on stock enhancement was held at the Cleveland laboratory. Since then, CSIRO visited China to discuss the Chinese program of prawn reseeding, and participated in workshops to assess the potential for enhancement of king prawns in Venus Bay (South Australia), and tiger prawns in Moreton Bay (Queensland). They have also worked extensively on the ecology of juvenile tiger prawns (e.g. Loneragan et al. 1996) and been invited to present ideas on prawn stock enhancement at the first international conference on stock enhancement (Rothlisberg et al. 1999).

During these studies a simple bioeconomic model was developed to evaluate the costs and benefits from enhancing prawn stocks. The results of the preliminary studies have shown that the feasibility and financial viability of enhancing prawn stocks in Australia depend on two key factors: the cost and availability of the prawns produced for the enhancement; and the prices paid for the prawns that are caught in the fishery (see also Rothlisberg et al. 1999). Since these studies, the cost of producing postlarvae and raising the prawns to a suitable release size, have decreased substantially. It should be noted that in the above preliminary studies, only the price paid for the prawns was considered as a benefit. The other potential benefits of stock enhancement, such as the more continuous supply of prawns, the increase in efficiency of factory operations and more reliable supply of prawns to buyers, were not incorporated in the simple bioeconomic model.

CSIRO has also developed a suite of potential biological tags for small prawns to assess the success of stock enhancement (FRDC 93/093). Methods of characterising nuclear and mitochondrial DNA have advanced to a stage where the genotype of released juvenile prawns can be matched to that of their parents with great precision. Thus, we have a robust way of validating the enhancement of prawn stocks.

To see if enhancing prawn stocks can work in Australia, we propose to test the feasibility of enhancing and dampening the variability of tiger prawn (*Penaeus esculentus*) stocks in Exmouth Gulf, WA. The long-term objectives of the project are to decrease the inter-annual variation in catches and increase the long-term average catch by 100 to 200 t (average annual catch of tiger prawns in Exmouth Gulf over the last five years = 377 t, Fisheries WA 1998). In addition, enhancing prawn populations with marked individuals will provide more precise information on survival rates, productivity parameters for the early life history stages (particularly juveniles and sub-adults) and migration pathways. Large juvenile and sub-adult prawns are difficult to sample as typically they are migrating from the nursery areas to the fishing grounds. This information can greatly increase the ability of managers to obtain the maximum benefit from wild prawn resources and allow better harvesting strategies to be developed.

Exmouth Gulf is an ideal location in which to assess the feasibility of enhancing tiger prawn stocks by releasing juvenile brown tiger prawns (*Penaeus esculentus*). The reasons for this include:

1. There is the capacity to develop suitable hatcheries and aquaculture ponds in Exmouth Gulf where juvenile prawns could be produced at a reasonable cost.
2. The study area is close to the facilities of the MG Kailis Group of Companies at Exmouth, which minimises operating costs while techniques are being developed.
3. Recent FRDC funded studies have demonstrated that the juvenile brown tiger prawns can be produced on a commercial basis (FRDC 96/302).
4. There has been extensive research on tiger prawns in Exmouth Gulf and a comprehensive database has been developed over the years.
5. Brown tiger prawns do not move as much as some other species of prawns e.g. grooved tiger prawns *Penaeus semisulcatus*.
6. The fishery for tiger prawns in Exmouth Gulf is a discrete fishery with a high rate of exploitation (it is regarded as fully exploited) and a very sophisticated system of monitoring catches. The probability of capturing released prawns in the fishery is high.
7. This fishery has been well managed and is not in decline.
8. The fishery shows high levels of variation between years, with annual catches ranging from 205 to 682 t since 1987 (Fisheries WA 1998). This increases the potential benefits of stock enhancement.
9. One license holder, MG Kailis, holds 15 of the 16 licenses in the fishery, and is one of the collaborators and contributors to the project.

The full project was initially considered in three stages:

1. a 12 month feasibility study (this project);
2. an experimental scale enhancement (1 to 2 million prawns); and
3. a large-scale enhancement (much larger releases of prawns of possibly of 10 to 20 million prawns).

During the feasibility study, an additional stage in the procedure was identified. This stage aims to obtain information on: the best methods of producing large numbers of 1 g juvenile tiger prawns, and harvesting, transporting and releasing them in the field; and identifying the best areas and strategies to release large numbers of juvenile prawns. This additional stage (now Stage 2) “Developing techniques for enhancing prawn fisheries, with a focus on brown tiger prawns (*Penaeus esculentus*) in Exmouth Gulf” has since been funded by FRDC (1999/222).

The initial 3 stages, as originally conceived, are briefly described below.

Stage 1 – Feasibility study. A one-year study to review the data on the ecology and fishery for brown tiger prawns in Exmouth Gulf, and to complete a cost-benefit analysis and risk assessment for reseeding tiger prawns in Exmouth Gulf. This study used a simple bioeconomic model developed for assessing costs and benefits of enhancing king prawns in Venus Bay (South Australia) and tiger prawns in Moreton Bay (southeast Queensland). The cost-benefit analysis will use a range of estimated costs for local aquaculture to produce postlarvae and juveniles for the enhancement, and estimates of survival and growth, either from ecological studies of *P. esculentus* populations of Exmouth Gulf, or from studies in the Gulf of Carpentaria and Queensland's east coast. There will be an independent review of progress at the end of this study.

Stage 2 (now Stage 3) – Experimental scale enhancement. If the cost-benefit analysis and independent review indicates that enhancing prawn stocks is a viable management strategy for Exmouth Gulf, an experimental release of 1 to 2 million juvenile prawns will be undertaken to establish production and release techniques, refine population models, measure the carrying capacity of the juvenile nursery environment (e.g. Loneragan et al. 1996), test validation methods and assess environmental risks. This would be the subject of a second FRDC proposal to commence in July 1999. The results of the experimental release will also be independently reviewed at the end of each year of the study.

Stage 3 (now Stage 4) – Large-scale enhancement. If the experimental releases are successful, trial commercial scale enhancements will be undertaken at the expense of the local prawn industry partner, over two years. These releases will attempt to enhance the fishery by 100 to 200 t in each year and decrease the inter-annual variation in catches in the fishery.

All stages of the project involve collaboration between CSIRO Division of Marine Research, the MG Kailis Group of Companies and the Fisheries Research Division, Fisheries WA. Collectively we have the skills to undertake a feasibility study into the viability of enhancing prawn stocks in an Australian context, particularly as it applies to the brown tiger prawn fishery in Exmouth Gulf. We also have the skills and infrastructure to undertake the subsequent stages of the project, if the feasibility study and independent review show that this would be worthwhile. The outcomes of both the feasibility study and any subsequent work, will have application to prawn fisheries around Australia. Key issues to be addressed in the feasibility study are:

- bioeconomic modelling;
- experimental design and assessment;
- genetic monitoring, tag development and recovery;
- production of postlarvae and juvenile prawns, harvest and transport;
- assessment of the risk of introducing disease; and
- development of release protocols.

Need

Prawn fisheries throughout Australia are intensively fished and some have shown signs of overfishing. In some cases, the current stocks of prawns are now lower than those that would produce maximum yields. Prawn stocks can vary greatly from year to year because of environmental fluctuations and this leads to highly variable catches. Fishery managers must therefore adopt conservative harvest strategies to prevent fishers reducing stocks to dangerous levels in years when recruitment is low. However, the harvesting and processing sector tend to be on average, over-capitalised, in order to cope with years of high recruitment. Enhancement of prawn stocks through releasing juvenile prawns has the potential to reduce fluctuations in stocks. It therefore provides a possible way of adjusting the catching and processing capacity to more stable levels of prawn stocks, which would reduce the need for over-capitalisation.

The enhancement of Australian penaeid prawn fisheries has the potential to be a useful management tool to increase fishery yields, rebuild over-exploited stocks, and reduce fluctuations in catch due to variable recruitment. It also has the ability to improve the management of fisheries by collecting more precise information about the biological characteristics of the stock (e.g. survival and growth, production in nursery grounds, migration pathways and factors affecting fluctuation in populations). For stock enhancement to be successful, the biology and ecology of the target animal must be thoroughly understood (including the production of the postlarvae/juveniles, environmental requirements, carrying capacity, and all factors that contribute to mortality), and methods must be available to monitor and assess the success of the releases. Much ecological information for stock enhancement is now available for many commercially important species of penaeid prawn in Australia, and novel approaches to tagging prawns (e.g. stable isotopes, rare alleles and reporter genes), release strategies, and assessment of carrying capacity are being developed.

Most of the preliminary assessments of the costs and benefits of prawn stock enhancement in Australia have not assessed a particular fishery or region in detail – they have to some extent developed generic models. For our knowledge on how to enhance prawn stocks in Australia to progress further, it is essential to develop, apply and refine bioeconomic models to a specific region and fishery. For the reasons outlined above (see Background), the Exmouth Gulf Prawn Fishery is an ideal location to focus on applying the concepts and the simple model that have been developed from different studies around Australia. The very focussed study outlined in this report will help to evaluate enhancement projects for other prawn fisheries around Australia.

The beneficiaries of stock enhancement would be expected to contribute to the costs of research and monitoring, and ultimately pay for the enhancement. Therefore, stock enhancement must be cost-effective and a cost-benefit analysis using a bioeconomic model, is an essential part of any enhancement project. Bioeconomic models need to be developed in the early stage of the feasibility study. If the outcomes are favourable for enhancing tiger prawns in Exmouth Gulf, it will be used to optimise the design and management of the trial enhancement program proposed for Stage 2 of the full project.

Objectives

The original objectives of the project were:

(1) Develop a bioeconomic model to assess the costs, benefits and risk of enhancing the stock of brown tiger prawns (*P. esculentus*) in Exmouth Gulf.
(2) Collate and critically review the information relevant to the enhancement of prawn fisheries for the Exmouth Gulf prawn fishery, and related prawn fisheries and aquaculture.
(3) Use this information to develop protocols for enhancing stocks of penaeid prawns, both as applied to tiger prawns in Exmouth Gulf, and in Australia in general. This should include:
    (a) the production of large numbers of undamaged, optimally sized (10 mm carapace length) juvenile prawns that have been screened for known pathogens;
    (b) ways of ascertaining the optimal scale of enhancement for a site/fishery (number of prawns, number of sites);
    (c) strategy(ies) of release (where, when and how to release the juveniles without increasing mortality);
    (d) consequences of enhancing stocks on other parts of the ecosystem (habitat, prey, predators); and
    (e) methods to ensure that the results of stock enhancement can be rigorously evaluated.

In developing the project, objective 3 was split into two objectives: one to assess the genetic and disease risks of stock enhancement; and the second to look at developing protocols for stock enhancement of tiger prawns. This change in the structure of the objectives, raises the importance of considering the risks of stock enhancement. The objectives of the project became:

(1) Develop a bioeconomic model to assess the costs, benefits and risk of enhancing the stock of brown tiger prawns (*P. esculentus*) in Exmouth Gulf
(2) Collate and critically review the information relevant to the enhancement of prawn fisheries for the Exmouth Gulf prawn fishery, and related prawn fisheries and aquaculture
(3) Assess the risks associated with prawn stock enhancement in Exmouth Gulf
(4) Consider protocols for the stock enhancement, including potential release sites and monitoring.

Methods

Work on both the bioeconomic modelling to assess the costs and benefits of enhancement, and the critical review of the information (ecological, fishery, aquaculture) on tiger prawns in Exmouth Gulf, was initiated through a 2 day workshop in Perth (July 16&17, 1998). All project participants took part in the workshop.

Bioeconomic model

Model description

The true measure of the success of any stock enhancement program is its ability to increase fishery revenue by more than the cost incurred in the production, release and monitoring of juveniles produced by aquaculture and released into the wild. The cost of evaluating success through a real experiment is high and bioeconomic analysis is often used for this evaluation and should be considered an essential part of any enhancement project (Blankenship and Leber 1995, Rothlisberg et al. 1999).

We have developed a bioeconomic model to evaluate the feasibility of stock enhancement programs. Project participants developed the basic structure of this model at the workshop in Perth in July 1998. The model has been developed in EXCEL to make its output and basic assumptions easily accessible to managers and industry. Comprehensive analyses, however, should only be run by people familiar with the structure and properties of the model. The model contains independent components for: the hatchery, juvenile production, nursery ground and fishery. There are also components for the transport of juveniles from the production to the nursery areas, and for monitoring released juveniles in the wild environment. The model can be used to run bioeconomic analyses to evaluate different experimental designs for stock enhancement or to monitor the economic success of the enhancement.

Most model parameters are subject to uncertainty and it is important to consider this in the evaluation of enhancement programs. Monte Carlo simulation can be used to evaluate the uncertainty associated with model predictions and thus give a more realistic prediction of the success of enhancement programs. Commercially available software, such as Crystal Ball, is ideal for these analyses and was used to carry out Monte Carlo simulations to examine the effects of uncertainty in the parameters.

Model components

The model is implemented in EXCEL and has weekly time steps. Prawn dynamics are simulated through a size (length and weight) structured model. The model has a series of system and operational components, each of which is implemented in a single EXCEL worksheet.

The system components describe the different combination of physical environments and life history stages. They are:

S1 – Hatchery
S2 – Juvenile production
S3 – Transport
S4 – Nursery ground
S5 – Fishery

The operating components represent the modules used to implement simulation experiments. They are:

O1 – Model parameters (e.g. survival and growth rates, prices)
O2 – Output indicators (e.g. catch in weight and value)
O3 – Uncertainty and sensitivity analysis
O4 – Monitoring (e.g. number of samples required to detect enhanced prawns in the catch)

This model was used to evaluate the enhancement of the prawn fishery in Exmouth Gulf in Western Australia. Two enhancement scenarios were evaluated: 1. An experimental enhancement; and 2. A trial commercial scale enhancement (for details see below). Briefly, the aim of the experimental enhancement was to determine the minimum number of juvenile prawns to be released that could be detected by sampling the commercial fishery. The scenario for the trial commercial scale enhancement attempted to evaluate how many prawns would have to be released to enhance the fishery by 100 t. The parameter values used in the second evaluation are given in Appendix 1, and each component of the model is described below. With minor modifications, we believe that this model could be applied to other organisms and other fisheries.

S1. Hatchery

This comprises the brood stock and the hatched larvae. A detailed prawn hatchery model, containing the costs for using either wild or domesticated brood stock, has been developed by Preston et al. (1999). Their model was used to estimate the cost of production (W) of each larva (termed zoea in Preston et al. 1999) so that the current hatchery component can be simplified to only contain the output of the hatchery (i.e. the numbers of larvae required and their total cost).

S2. Juvenile production

Includes from larvae (as defined by the stage produced in the hatchery) to the juvenile prawns that are released in the nursery. The released prawns can have any size from that of a larva to that of a recruit (i.e. those prawns entering the fishing ground). Survival and growth are size dependent. The growth and survival rates are greater than those in the natural nursery areas.

In this component, the starting point for the calculations is a certain level of production of juveniles N_0 of certain weight W_e and the initial number of larvae are calculated from this target. Therefore, the initial number of larvae and the start of the production period are both calculated as a function of the survival and growth parameters and the target production levels.

Abundance in week t N_t is modelled as,

$$N_{t-1} = N_t \, e^{M_t}$$

where M_t is the natural mortality that is calculated as:

$$M_t = f \, a \, e^{b \, L_t}$$

Where L_t is the carapace length at week t, a and b are parameters defining how mortality changes with size in the wild population and f denotes the proportional improvement in survival of prawns kept in culture.

Individual growth is modelled as an exponential function of parameter d,

$$W_{t-1} = W_t \, e^{d}$$

To accommodate for the change in growth rate that occurs during the transition from post-larvae to juveniles, a different value of d is used for the juveniles, i.e. when prawns reach size W_j. Calculations are stopped when W_{t-1} reaches the weight of the first larval stage W_0. This determines the week when prawns are seeded to the wild nursery. Individual weight W_t is calculated from the length weight relationship,

$$W_t = a \, L^{b}$$

Two production systems were considered; ponds and raceways. The number of raceways or ponds required y is a function of the area of each pond A (m^2), the maximim biomass density at which prawns can be held d ($kg\,m^{-2}$) and W_{max} the maximum biomass of prawns (kg) to be held,

$$y = \frac{W_{\max}}{d \, A}$$

The production costs considered were the capital costs R of building each raceway or pond, and the operating costs. No attempt was made to calculate the net present value of the total investment and therefore, the desired internal rates of return and depreciation rates, were not considered. Such calculations are, however, easily done within EXCEL.

Operating costs G_t comprised costs of prawn feed, salary and pumping,

$$G_t = y(a\, s + y\,) + B_t \, h + (B_t - B_{t-1}) g \, t$$

where σ is the weekly cost of pumping per m^2 of pond or raceway, η is the cost of pumping per kg of prawns, y is the salary costs of maintaining one pond or raceway, γ is the cost of feed per kg of prawns, and τ is the food conversion ratio (i.e. ratio of food:growth in biomass).

S3. Transport

Includes only the cost of transporting the juveniles to the release site, which is a function of number of trips required to transport the juveniles and the number of release sites to be used in each trip. The number of trips is determined by the size of the juveniles, their number, the volume of the tanker/vessel used for transport, and the desired ratio of juvenile biomass to water in the tanker. The number of sites per trip is a function of the biomass of juveniles that can be released at each site. A daily cost rate is used to include the cost of harvesting, transporting and releasing.

The numbers n carried per tanker/vessel were estimated as,

$$n = \frac{V}{W_t(1+q)}$$

where

V is the volume of the tanker/vessel,
Wt is the weight of each prawn at the time of transport and
q is the ratio of seawater/biomass desired during the transport.

The number of trips of the tanker/vessel are therefore N_t/n, where N_t is the number of juvenile prawns produced in the production and to be released in the nursery area.

The minimum number of sites r required to release prawns is a function of the biomass that can be released per site B_s,

$$r = \frac{N_t W_t}{B_s} + 1$$

and the number of days required to release all prawns D,

$$D = \frac{N_t / n}{T}$$

where T is the number of trips per day that can be made.

Transport costs are therefore the product of the number of days and the operating costs of each day T_c

S4. Nursery ground

There are two sub-components, one corresponding to the wild stock and one to the enhanced stock. They have the same structure and only differ in the timing and the numbers of prawns entering the nursery.

The enhanced stock sub-component includes juvenile prawns from the time they are released to the time they recruit to the fishery. The size of released prawns can range from the size of a larva, to that of a recruit. Survival can be made dependent on the total abundance of prawns (wild and enhanced) in the nursery, however, this option has not yet been activated because of the difficulty of finding parameter values. The timing and number of prawns settling in the nursery can be varied.

The wild stock sub-component includes prawns from larvae to recruits to the fishery. Survival and growth are size dependent. Growth also varies seasonally. Survival can be made dependent on the total abundance of prawns (wild and enhanced) in the nursery. The timing and number of larvae settling in the nursery can be varied.

The abundance of the enhanced stock N_t and wild stock N_t^* in week t are modelled as,

$$N_{t+1} = N_t \, e^{-M_t}$$

$$N^*_{t+1} = N^*_t \, e^{-M_t}$$

where M_t is the natural mortality that is calculated as:

$$M_t = l \left(N_t + N_t^*\right) + a \; e^{b L_t}$$

Where L_t is the carapace length at week t, a and b are parameters defining how mortality changes with size and l denotes the coefficient of density dependent mortality. Note how mortality is a function of the combined abundance of the wild and enhanced stocks. Note also that there is no mortality associated with the transport or release of prawns into the nursery and that the mortality for prawns of the same size does not differ between the enhanced and wild stock.

Growth in weight is modelled as an exponential function of parameter d, but modified by a seasonal factor K_t that is equal to 1 at the peak of the growing season, and is smaller than 1 elsewhere

$$W_{t+1} = W_t \left(1 + k_t \left(e^d - 1\right)\right)$$

The biomass of the enhanced B_t and wild stock B_t^* are therefore calculated as,

$$B^*_t = N^*_t W^*_t$$

$$B_t = N_t W_t$$

The average individual weight of enhanced juveniles W_t and wild juveniles W_t^* in the nursery area at any particular time t will not necessarily be the same. These weights depend on the week when the wild stock recruits to the nursery area, on the individual weight of enhanced juveniles released in such areas and on the week when these enhanced juveniles are released. Wild juveniles start life in the nursery area during week j_o at weight W_0, the same weight that larvae have when they start in the production. The number of wild larvae starting life in the nursery area N_0^* is a parameter of the model and is the main determining factor for the size of the wild recruitment to the fishery.

Migration out of the nursery occurs at a fixed size L_m. Individual weight of migrating prawns is calculated from substituting L_m in the length-weight relationship.

S5. Fishery

There are two sub-components, one corresponding to the wild stock, and one to the enhanced stock. The structure of these two sub-components is exactly the same – they have been split to follow changes in numbers of prawns from the wild and enhanced stocks separately. Each sub-component has separate male and female populations. It includes prawns from recruits to adults (up to one year old). Growth is size and sex dependent but independent of season. Natural mortality is size dependent. Fishing mortality is size dependent (because of net selectivity) and changes as a function of seasonal changes in fishing effort. Egg production is seasonal and also a function of female size.

The price of prawns is considered to be dependent on size, but independent of season. Only the variable costs of fishing effort have been incorporated in the model. The profit obtained from the harvest of wild stock is the difference between the revenue and the variable cost associated with the wild stock harvest. For the enhanced catch, the marginal revenue is calculated to reflect the fact that the cost of harvesting the "extra" (=enhanced) stock is lower than that of harvesting the wild stock i.e. the costs for the enhanced stock included the processing costs but not the costs of fishing. The profit from the enhanced stock is then the difference between the marginal revenue from the enhanced catch and the cost of the enhancement program.

Abundance of the enhanced stock N_t and wild stock N_t^* in week t for sex j are modelled as,

$$N_{j,t+1} = N_{j,t}\, e^{-M_{j,t} - F_{j,t}} \qquad\qquad N^*_{j,t+1} = N^*_{j,t}\, e^{-M_{j,t} - F_{j,t}}$$

where F_t is the fishing mortality rate in week t, calculated as,

$$F_{j,t} = q\, f_t\, S_{j,t}$$

where q is the catchability coefficient, f_t is the weekly fishing effort and $S_{j,t}$ is the selectivity factor for prawns of sex j ($j=1$ for females and $j=2$ for males), and size L_t calculated as,

$$\begin{cases} L_{j,t} < L_0 \Lambda\ \Lambda\ \Lambda\ \Lambda\ \Lambda\ \Lambda\ \Lambda & 0 \\ L_0 < L_{j,t} < L_{100} \Lambda & \dfrac{L_{j,t-} L_0}{L_{100-} L_0} \\ L_{j,t} > L_{100} \Lambda\ \Lambda\ \Lambda\ \Lambda\ \Lambda\ \Lambda\ \Lambda & 1 \end{cases}$$

where L_o is the largest length where the probability of retention is zero and L_{100} is the smallest length where probability of retention is one.

Natural mortality is independent of abundance but calculated as a function of length,

$$M_{j,t} = a\, e^{b\, L_{j,t}}$$

where length is modelled with the Von Bertalanffy equation,

$$L_{j,t} = L_{\infty j}\left(1 - e^{-k_j}\right)$$

Note that, the natural and fishing mortality rates upon the enhanced and wild stocks in the fishery are assumed to be the same. Biomass is then calculated as the product of abundance and prawn weight,

$$B_{j,t} = N_{j,t} W_{j,t} \qquad B^*_{j,t} = N^*_{j,t} W^*_{j,t}$$

where weight is calculated from the weight-length relationship,

$$W_t = a\, L^b$$

Weekly prawn catch of the enhanced stock $C_{j,t}$ and wild stock $C^{*j}{}_{,t}$ in week t are estimated as:

$$C_{j,t} = \left(N_{j,t+1} - N_{j,t}\right)\frac{F_{j,t}}{F_{j,t} + M_{j,t}} \qquad C^*_{j,t} = \left(N^*_{j,t+1} - N^*_{j,t}\right)\frac{F_{j,t}}{F_{j,t} + M_{j,t}}$$

and the yield (catch in weight) is estimated as the product of the numbers caught and prawn weight,

$$Y_{j,t} = C_{j,t} W_{j,t} \qquad Y^*_{j,t} = C^*_{j,t} W^*_{j,t}$$

Egg production E_t is calculated as the product of the female abundance, the proportion of mature females n_t, and the number of eggs produced by each female c_t,

$$E_t = N_{1,t}\, n_t\, c_t$$

ν_t is a function of size and week and is calculated as,

$$\begin{cases} L_{1,t} < E_0 \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \ 0 \\ E_0 < L_{1,t} < E_{100} \Lambda \quad r_t \ \dfrac{L_{1,t-} E_0}{E_{100-} E_0} \\ L_{1,t} > E_{100} \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \Lambda \ r_t \end{cases}$$

where

E_o is the largest length where the probability of being mature is zero,
E_{100} is the smallest length where probability of being mature is one and
r_t is the proportion of mature females in week t.

The numbers of eggs produced by each female (fecundity) is also a function of size,

$$c_t = x + e L_{1,t}$$

We have assumed that the revenue derived from harvesting enhanced prawns is best calculated from estimates of the marginal revenue of catching enhanced prawns. This simplifies calculations and does not require estimates of the total cost of fishing. The value of the enhanced catch V_t is a function of the marginal revenue per kg for female and male prawns $w_{j,t}$ at week t and the weight of the catch,

$$V_t = Y_{1,t} w_{1,t} + Y_{2,t} w_{2,t}$$

where marginal revenue per kg $w_{j,t}$ is a function of the individual prawn weight and is defined by the price of commercial size categories $p_{j,t}$,

$$w_{j,t} = \frac{p_{j,t}}{p_{\max}} w_{\max}$$

and where p_{max} is the price per kg for the largest prawns and w_{max} is the marginal revenue per kg for the largest prawns.

O1. Model parameters

This component contains all the parameters for all the different components of the model. This facilitates analysis and enables uncertainty and sensitivity analyses to be completed. Parameter estimates from the Exmouth fishery were used when available. If these were not available, estimates from nearby Australian fisheries were used. Parameters for the hatchery and production of juvenile prawns are estimates from prawn aquaculture studies in Queensland. All parameter values used in the evaluation of the Exmouth fishery are given in Appendix 1.

Generally, estimates of parameter uncertainty were not available. We assume that some parameters are precisely estimated (e.g. length weight relationship, gear selectivity). We also assume that uncertainty in some parameters has little impact on the uncertainty of the predictions (e.g. salary costs of production, size at emigration from the nursery). For other parameters, we examined the minimum and maximum values of the parameter reported for other prawns (e.g. growth parameters) and/or the level of natural variability in the parameters (e.g. survival rates in the nursery, prawn prices). For all other parameters, we guessed the minimum and maximum likely values of the parameters. Three types of probability distributions were used, normal, uniform and triangular. Correlation was incorporated for those parameter pairs that were known to be highly correlated (e.g. growth parameters, prawn price and marginal revenue).

O2. Output indicators

This component contains all main indicators of performance that are calculated in a weekly and annual scale. The indicators considered were:

- Cost of juvenile production
- Juvenile biomass of enhanced and wild stocks in the nursery
- Biomass of enhanced and wild stocks in the fishery
- Catch in weight of enhanced and wild stocks in the fishery
- Egg production from enhanced and wild stocks in the fishery
- Revenue from wild stock, marginal revenue from enhanced stock and cost of fishing.

O3. Uncertainty and sensitivity analysis

A commercial add-on to EXCEL called Crystal Ball (Decisioneering 1998) was used to incorporate parameter uncertainty in the analysis. This add-on uses Monte Carlo simulation to estimate the uncertainty associated with the predictions of the model. It can also estimate the sensitivity of predictions to uncertainty in the parameters. We used Crystal Ball for estimating the uncertainty in the output indicators of the model.

The Optquest function within Crystal Ball was used for various parameter optimisation procedures such as:

- to refine parameter estimates so that predictions were consistent with observations from the wild fishery (e.g. to estimate the magnitude of natural recruitment)
- to estimate the production requirements for a particular enhancement objective (e.g. obtain 100 t of enhanced stock)
- to estimate the statistical precision of parameter estimates obtained during monitoring (e.g. precision of the estimate of the ratio enhanced/wild prawns in the catch).

O4. Monitoring

This component is used to estimate the sample requirements for monitoring adult prawns in the wild fishery. It estimates the minimum sample sizes required to achieve a minimum number of recaptures of enhanced prawns. The probability $p(n)$ of obtaining at least n enhanced prawns in a sample of m prawns randomly sampled from the commercial catch is,

$$p(n) = 1 - F(n)$$

where $F(n)$ is a binomial distribution function with parameters, m and q, the proportion of enhanced prawns found in the catch,

$$q = \frac{\sum_j \sum_t N_{j,t}}{\sum_j \sum_t N_{j,t} + \sum_j \sum_t N^*_{j,t}}$$

The only costs of monitoring considered are the cost of obtaining adult prawns at sea i for genetic analyses and the cost of genetic analysis for each prawn p. Total monitoring costs are therefore calculated as i plus the product of p and the minimum number of prawns required to be genetically screened g_s.

Simulation of enhancement scenarios
As stated above, the bioeconomic model was used to evaluate two enhancement scenarios:

1. Experimental enhancement
2. Trial commercial scale enhancement

Experimental enhancement

The objective of experimental enhancement is first to develop enhancement and monitoring techniques. The second objective is to improve parameter estimates for the bioeconomic model. Its success is measured by:

- The ability to detect whether enhancement and monitoring of the enhanced stock are technically feasible
- The ability to improve the analysis of the economic feasibility of stock enhancement

In the bioeconomic model, this scenario was defined by our ability to measure the contribution of the enhanced stock to the fishery catch. We defined a minimum acceptable precision for the estimated ratio of enhanced:wild prawns in the catch (that there is at least an 80% probability that the estimate is within ± 15% of the true ratio). We investigated the appropriate weight (0.5 g to 3.0 g) and the minimum number of enhanced prawns (0.5 to 3 million) to be released. Finding an ideal design is a complex decision involving minimising resources, maximising information gains, and ensuring appropriate statistical power. For simplicity, in our simulations we only considered the minimising average (100 runs) for production and monitoring costs, while maintaining a reasonable chance of estimating an accurate ratio of enhanced to wild stock in the fishery catch (80% probability that the ratio is within 30% of the true value). These evaluations were carried out for an "average" year scenario with a catch of 450 t and therefore simulations did not consider uncertainty in mortality.

Trial commercial scale enhancement

The objective of the trial commercial scale enhancement is to directly confirm the results of the economic feasibility of stock enhancement through a commercial scale trial. Its success would be assessed by the profit made after the enhancement trial has been completed.

In the bioeconomic model this scenario was defined by targeting an enhanced catch of 100t.

For this scenario we used 10,000 simulation trials with the full range of parameter uncertainty and obtained probabilistic predictions for the following indicators:

- Annual catch in the fishery from wild and enhanced stocks
- Cost of production and release of juvenile prawns grown in ponds and raceways
- Revenue from wild fishery catch
- Marginal revenue from enhanced fishery catch

We also estimated the sensitivity (percent of variance) of each prediction to all parameters that contained uncertainty during the simulation. Note that for parameters that are correlated, a prediction may appear to be sensitive to a parameter only through the correlation rather than through direct dependency.

Assumptions in the model

The bioeconomic model has many assumptions relating to the form or the relationships between state variables and the nature of the essential components of the model. The predictions obtained in our analysis therefore depend on a large number of these assumptions. Most of these assumptions are obvious and can be identified from the details of the model structure. Some of the most important assumptions are:

(1) There is no mortality associated with transfer of prawns for enhancement between transfer to production facilities, harvest, transport and their release. This is unlikely because some mortality is to be expected in the transfer of larvae from hatchery to production facilities, and from the production to the nursery area. Unfortunately, very little information has been found describing the importance of these sources of mortality.
(2) Prawn mortality is only density dependent within the nursery area. It has often been hypothesised that densities of prawns in offshore environments are so low (with the exception of some schooling species) that density-dependence is only likely to be a factor in the nursery area where densities of juveniles are higher than offshore. Although the bioeconomic model is structured to accommodate density-dependence, it has not been activated in our simulations.
(3) There is no density-dependence in growth or mortality during the juvenile production phase. Evidence from prawn aquaculture suggests that density-dependence can be important. However, the uncertainty in the feasible densities for production of juveniles (particularly in raceways) is so large that until it is reduced, it seems pointless to refine the model to take account of density-dependence during production.
(4) Enhanced prawns can be identified with 100% probability through genetic testing. The real probability of detection depends on a complex set of parameters including the amount of genetic variability in the wild stock, the number of microsatellites used for monitoring, and the number of individuals used as broodstock.

If one or more of the first three assumptions are not met, the catch from the enhanced stock would be smaller than predicted. If the last assumption is not met, the cost of monitoring will be greater than predicted.

Review of Information

Work on collating and reviewing the literature relevant to the enhancement of prawns, particularly tiger prawns in Exmouth Gulf, was presented at the Perth workshop. The review and collation of information continued and was used to assess the information needed before stock-enhancement should be attempted. The review of literature is presented in Appendix 2 and covers the topics of:

(1) Enhancement, reseeding for marine species, particularly penaeid prawns
(2) Exmouth Gulf – environment, habitat, development
(3) Prawn species – biology, aquaculture, fishery dynamics
(4) Release strategies

Assessment of risks to the gene pool and of introducing disease

The risks associated with stock enhancement of penaeid prawns were discussed by a panel of industry representatives, research scientists, research managers and policy managers at the FRDC sponsored workshop on "Genetics in the Aquaculture Industry" held in Perth in October 1998.

The scenario discussed at the workshop was broadly similar to that proposed for the stock enhancement of *Penaeus esculentus* in Exmouth Gulf. The critical factors discussed were:

- Will the released stocks have a major genetic impact on the natural population?
- What level of information is sufficient to enable an assessment to be made?
- What tools should be used to investigate genetic differences?
- Do genetic differences matter in the first place?

Development of protocols

Fisheries WA has been developing a protocol for scanning fish and crustaceans for disease as part of a Translocation and Hatchery Testing program (this encompasses FRDC project 98/212). The details of the recommended procedure are given in the Results and Discussion section of the report below.

Results/Discussion

Bioeconomic model

The optimum size of juvenile prawns at release time is a complex function of the cost of production and monitoring and the increased survival obtained by keeping juvenile prawns in the production facility.

Experimental enhancement

The results suggest that the cheapest alternative is to use 0.5 g prawns and release 2.5 million which would require sampling 1500 prawns from the fishery for genetic analysis. The second best result is to release 1 million 1.0 g prawns and sample 3000 prawns for genetic analysis.

Trial commercial scale enhancement

In the simulations, the wild catch ranged from 250 t to 1500 t and was pronouncedly skewed with a median of 570t (Figure 1). This matches the range of catches recorded for the Exmouth fishery.

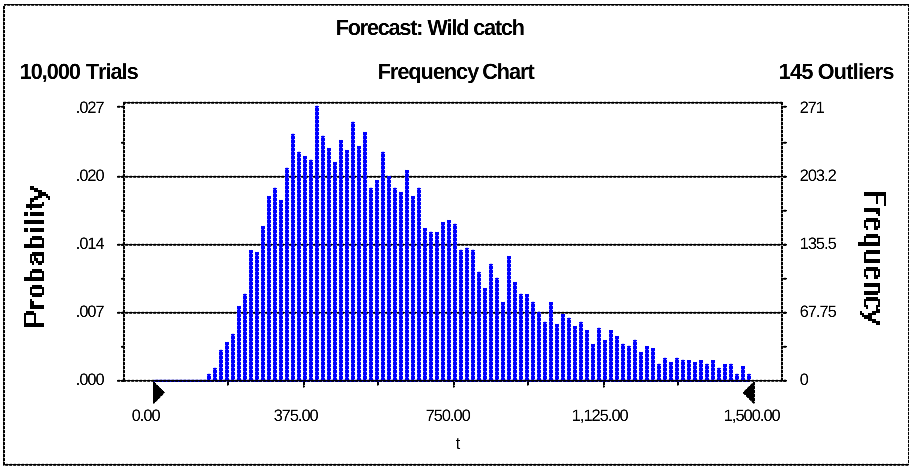

Figure 1. Catch predictions for wild stock during a trial commercial-scale (100 t) enhancement. In this Figure and Figures 2 to 8, the probability distributions were obtained by running 10,000 MonteCarlo simulations. In each simulation, parameter values were randomly varied according to the probability distribution of each parameter.

As expected, the enhanced catch varied considerably less, between 90 t and 105 t and was close to normally distributed (Figure 2).

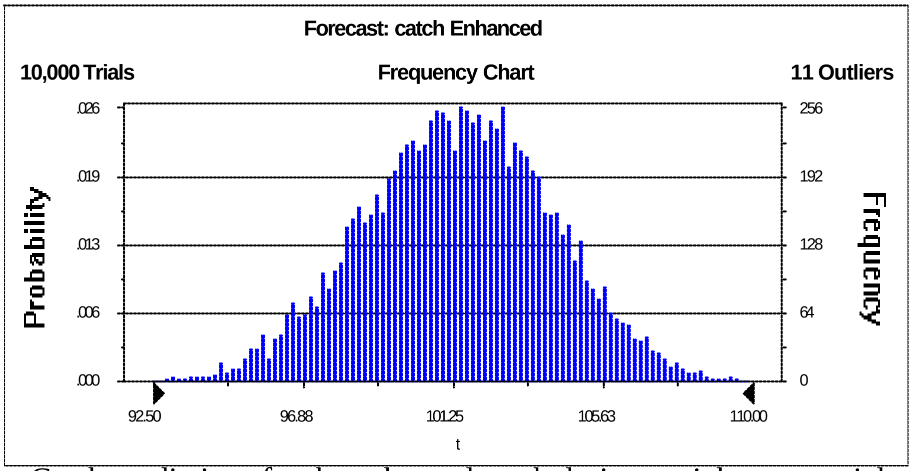

Figure 2. Catch predictions for the enhanced stock during a trial commercial-scale (100 t) enhancement. See caption to Figure 1 for more details on simulations.

The cost of production from raceways (Figure 3) was on average cheaper than that for ponds. Raceway costs ranged from $530,000 to $800,000 with a median of $630,000 (Figure 3). Pond costs ranged from $770,000 to $1.4M with a median of $970,000 (Figure 4).

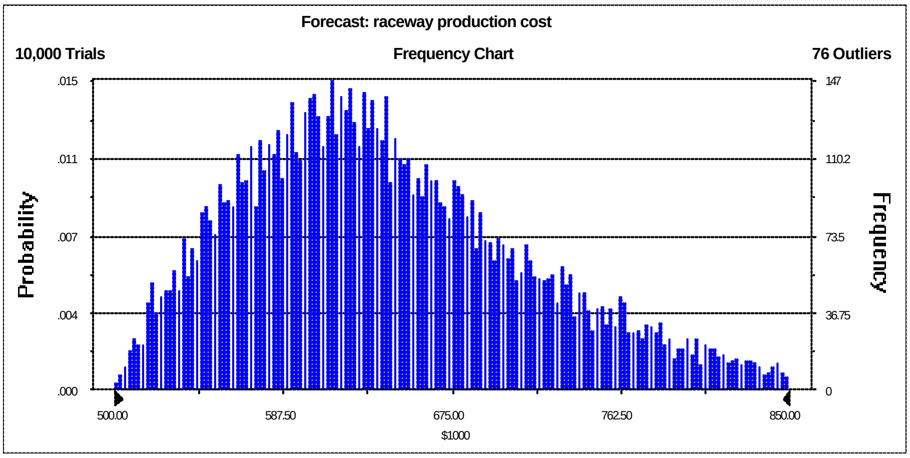

Figure 3. Raceway production costs during a trial commercial-scale (100 t) enhancement. See caption to Figure 1 for more details on simulations.

The revenue from the wild stock ranged by a factor of 10 between $3.1M and $31M because of the large range of wild catch (Figure 5). The median revenue of $10M for the wild stock is similar to the one reported for the Exmouth fishery.

The marginal revenue for the enhanced stock varied rather uniformly by a factor of 2 between $0.8M and $1.7M, again mainly due to the small range in enhanced catch (Figure 6). The median marginal revenue was $1.2M.

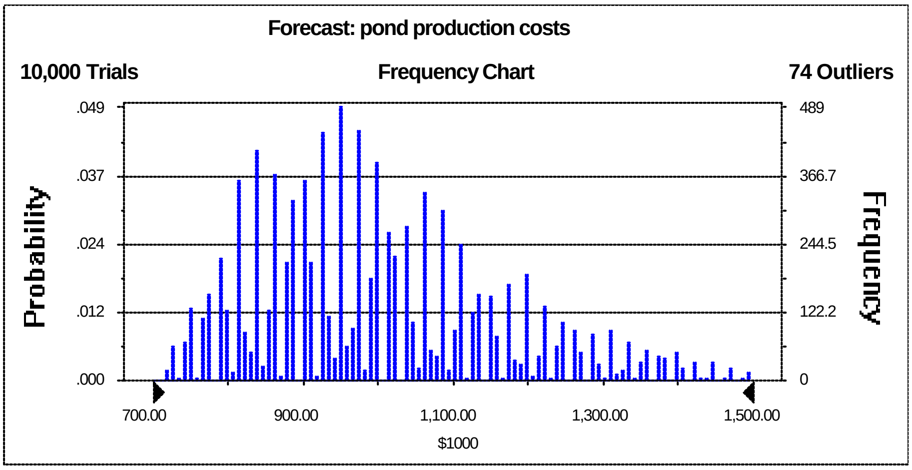

Figure 4. Pond production costs during a trial commercial-scale (100 t) enhancement. See caption to Figure 1 for more details on simulations.

Our results did consider part of the costs of monitoring, specifically the cost of monitoring the contribution of the enhanced stock to the total catch. These are not large, around $60,000 for the trial enhancement of 7 million juvenile prawns. This cost corresponds to the optimum monitoring level for an "average" fishing season. We defined optimum as the minimum number of samples required to obtain an estimate of the contribution of the enhanced stock to the total catch within 15% of its real value (with an 80% statistical power). In years of exceptionally high stock size (1200 t), the statistical power of our sampling would drop to around 70%. Other costs of monitoring related to for example, disease management have not been considered.

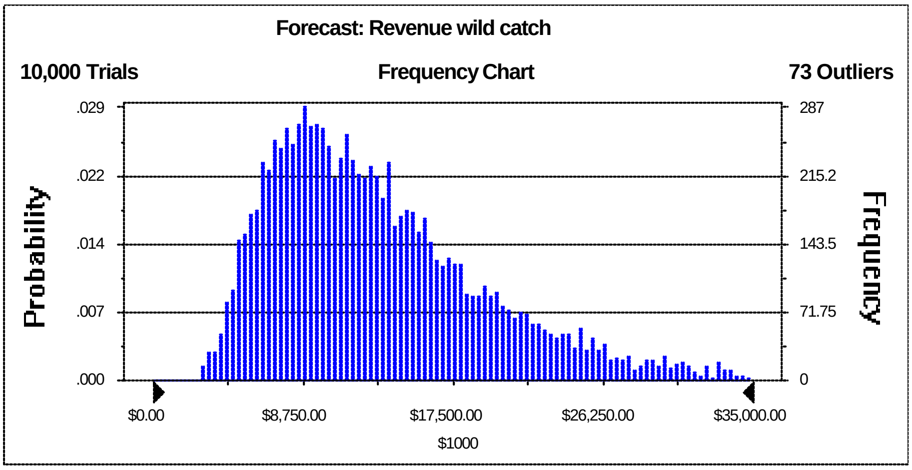

Figure 5. Revenue obtained from the catch of the wild stock during a trial commercial-scale (100 t) enhancement. See caption to Figure 1 for more details on simulations.

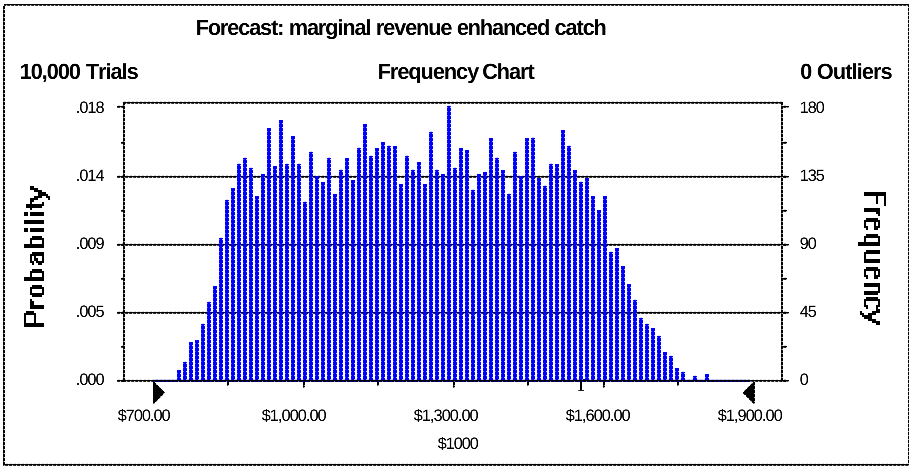

Figure 6. Marginal revenue obtained from the catch of the enhanced stock during a trial commercial-scale (100 t). See caption to Figure 1 for more details on simulations.

The difference between production costs and marginal revenue varied between $50,000 and $1M with a median of $540,000 (Figure 7). This can only be interpreted as an index of relative profits because it does not include capital costs and because it probably reflects somewhat unrealistic assumptions for some of the parameters in the model.

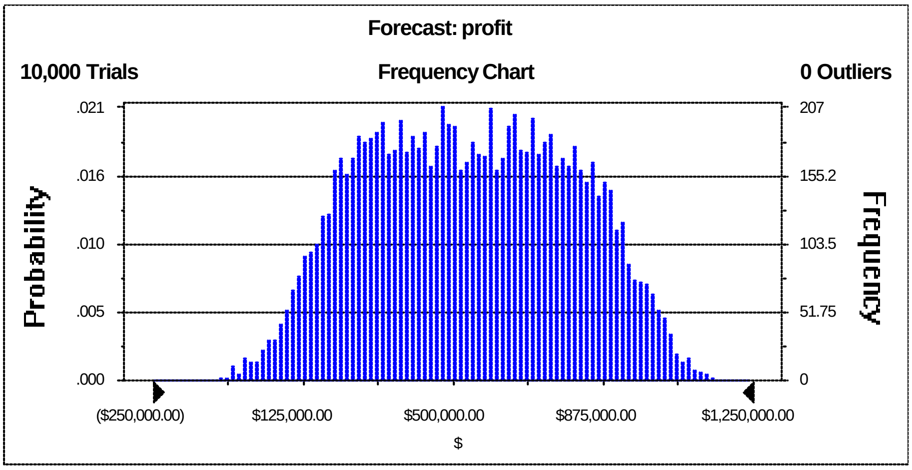

Figure 7. Profit obtained from the catch of the enhanced stock during a trial commercial-scale (100 t) enhancement. See caption to Figure 1 for more details on simulations.

To get an idea of the risk associated with the assumptions about extra sources of mortality we have estimated the percentage increases in "unaccounted mortality" (during harvest, transport and seeding) that would lead to a negative profit index. If the unaccounted mortality is lower than 30%, the probability of a negative profit index is less than 0.1 (Figure 8). If the unaccounted mortality is higher than 75%, the probability of a negative profit index increases to 0.5.

The capital costs associated with the production of 100 t of enhanced stock would be substantial. We have estimated that they may be in the order of $3M (value of land and facilities). Given a discount rate of 10%, an annual profit of $550,000 and a pond or raceway life of 10 years, the net present value of the production over the 10 years is $3.4M.

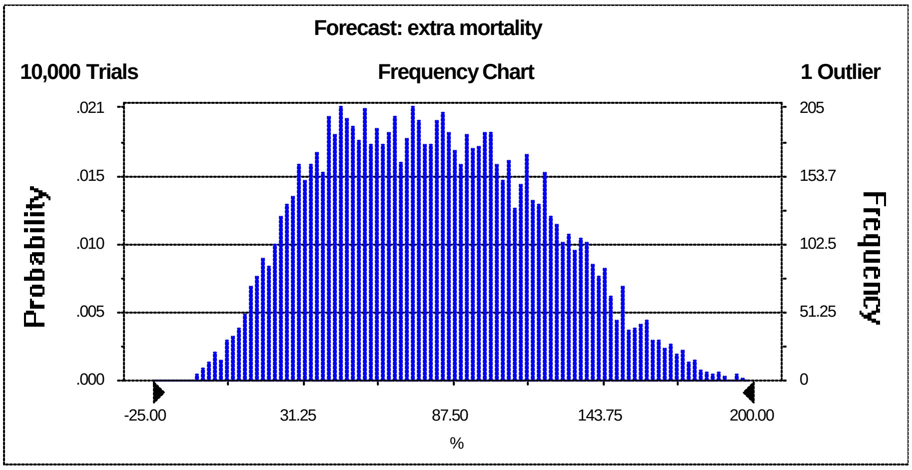

Figure 8. Extra mortality (not accounted for by the model) that would nullify profits from the catch of the enhanced stock during a trial commercial-scale (100 t) enhancement. See caption to Figure 1 for more details on simulations.

The uncertainty in the revenue of the enhanced catch is dominated by the sensitivity of these results to prawn prices. The uncertainty in production costs is dominated by the sensitivity to pond and raceway densities.

Discussion
Sensitivity analysis suggests that the greatest reduction in the uncertainty of the predictions will be achieved by reducing the uncertainty for the estimates of survival in the nursery area, prawn prices and feasible densities for producing juvenile prawns. It is well known that prawn prices and recruitment success (including survival in the nursery area) are very difficult to predict or control. Therefore, it would be best to focus future enhancement research on reducing the uncertainty in the feasible densities for producing juvenile prawns, and on minimising the extra mortality during the harvest, transport and release of juvenile prawns from the production site to the nursery area.

Some of the assumptions in the model mentioned will have a direct effect on these results. For instance, any mortality during the harvest, transport and release of juvenile prawns will proportionally reduce the revenue and catch (e.g. a 10% mortality will reduce marginal revenue by 10%) and increase the costs of monitoring. As we have shown, if these extra sources of mortality exceed 30%, the risks of the enhancement becoming uneconomic increases significantly. Future research needs to establish estimates for:

1. mortalities associated with transferring juvenile prawns from the hatchery to juvenile production site and from the production facility to nursery grounds
2. density-dependence in the production of juveniles.

Another approach to estimating the maximum carrying capacity for the nursery grounds is to assume that the largest catch ever observed in this fishery (1, 239 t in 1975) represents the carrying capacity for tiger prawns in Exmouth Gulf. The recruitment required to produce such a catch could be calculated and set to the maximum possibly. This can be achieved by increasing mortality during the nursery phase substantially, when recruitment is larger than this maximum.

To ensure that the trial enhancement is a success, it is probably better to choose a more conservative, albeit sub-optimal, enhancement design. We suggest that releasing one million 1 g juvenile prawns is the best strategy to adopt for the experimental enhancement. Although this strategy would be more expensive to monitor than releasing 2.5 million 0.5 g prawns, it should be less affected by unforeseen mortalities in the nursery, because prawns will be twice the size at the time of release.

A 10% reduction in annual profit would drop the Net Present Value of the trial enhancement to $3M and suggests that the ratio of capital costs to marginal revenue of juvenile prawn production should be reduced to make the investment more attractive. This could be achieved by attempting to produce two cohorts of juveniles for release each year. Given a production time of about 4 months to reach 1 g juveniles, this may still be possible in Exmouth Gulf and, in theory, would double the marginal revenue. Another possibility is to reduce the capital investment, an option considered seriously in Exmouth Gulf where raceways could serve a dual purpose: as hatcheries for oysters; and as a production environment to for juvenile prawns. These two options are not yet fully costed. For instance, we have not yet investigated the changes in revenue resulting from releasing juvenile prawns at sub-optimal times, which may be substantial.

Review of information
Twelve people participated in the workshop (Perth July 16, 17 1998): 5 from Fisheries WA, 5 from CSIRO Marine Research and 2 from the MG Kailis Group of Companies. The first day of the workshop focussed on some of the history of stock enhancement for prawns (including the history of development of this project), the biology and fishery for brown tiger prawns

(particularly in Exmouth Gulf), and the aquaculture of brown tiger prawns (including considerations for aquaculture of prawns in Exmouth Gulf). The general approach to the bioeconomic model that has been used to evaluate prawn stock enhancement in Australia was also discussed.

During the second day, we summarised the knowledge from day 1, highlighting areas that should be studied as part of a larger stock enhancement project in Exmouth Gulf. Most of the day focussed on developing the structure for the bioeconomic model, with some time spent on looking at issues for stock enhancement such as disease and genetics.

The group recognised that little was known about the nursery habitats of brown tiger prawns in Exmouth Gulf, or the dynamics of the juvenile prawns in this region. The importance of knowing the ecology of the juvenile stages has been highlighted in the literature review (Appendix 2), particularly in determining the size at release, the time of the release and the sites where the juvenile prawns should be released.

The main issues for the aquaculture of brown tiger prawns were in the production of juvenile prawns for enhancement – whether to use ponds or raceways to grow the prawns from postlarvae to juveniles of about 1 g (10 mm carapace length); how to harvest these juveniles; and how to transport them to the release sites. Research on the juvenile nursery habitats and the high density production of juvenile prawns were identified as part of the next stage in leading towards the stock enhancement of tiger prawns in Exmouth Gulf. They are important parts of the recently funded project "Developing techniques for enhancing prawn fisheries, with a focus on brown tiger prawns (*Penaeus esculentus*) in Exmouth Gulf" (FRDC 1999/222).

Assessment of risks to the gene pool and of introducing disease

Genetics

Initial discussions at the FRDC Genetics workshop centred on the need to:

- define "genetic impact"
- distinguish between a detectable change in the genetic structure of the target population (e.g. a change in allele frequency) *per se*, and
- whether the change had any quantifiable effects on the fitness of the population.

There was consensus that with the currently available sampling techniques and molecular DNA monitoring methods, changes in the genetic structure of the target population could be detected. However, opinions were divided on whether, or how, a detectable change in allele frequency constitutes a risk to the fitness of the natural population. In the absence of consensus on this point, the panel recommended that "precautionary principles" be adopted in any stock enhancement project to minimise any perceived or real genetic risks. This approach was further endorsed in the paper presented on "The genetic implications of translocations and stocking of fish and aquatic invertebrates" by Tom Cross (see workshop proceedings).

The panel recommended that genetic risks would be minimised by:

- Determining the genetic structure of the wild population prior to stock-enhancement
- Only using broodstock from the target population selected for enhancement
- Randomly collecting broodstock (to avoid family groups)
- Tracing individual families through rearing using genetic markers
- Releasing the same number of individuals from each of the captive-bred families

- Monitoring the effects of the release using molecular methods (e.g. microsatellite DNA markers)

As detailed in the proposal entitled "Developing techniques for enhancing prawn fisheries, with a focus on brown tiger prawns (*Penaeus esculentus*) in Exmouth Gulf" (FRDC 1999/222), the recommendations made by the panel have all been incorporated into the proposed research plan, including: determining the genetic structure of the population over two years using microsatellite markers; randomly selecting broodstock from the Exmouth Gulf population; and identifying released animals in the population using microsatellites.

Disease

Fisheries WA has been developing techniques for scanning fish and crustaceans for disease as part of a Translocation and Hatchery Testing program (this encompasses FRDC project 98/212). In this program, health profiles are completed on representative samples from individual batches produced in hatcheries or translocated into a fishery or aquaculture facility. From each batch of juveniles, 150 are selected at random, placed on slides, and their histo-pathology examined. Adopting this approach gives 95% confidence of detecting disease at a prevalence of 2% i.e. 2 diseased individuals in 100, or 20 in 1, 000. During the project, it is possible that Dr Peter Walker of the CRC for Aquaculture will have developed PCR primers for 3 prawn viruses. Dr Brian Jones of Agriculture W.A. is negotiating with the CRC for Aquaculture to use these primers to test for the presence of viruses in the batches of prawns. Batches of prawns would be tested for disease from the prototype raceways in Year 2 of Stage 2 of the Enhancement Project (FRDC 1999/222), even though we do not plan to release prawns during this year. If high mortalities were detected in a batch, further screening for disease would be carried out.

In Stage 3 of the Enhancement project (experimental release of 1 million juvenile tiger prawns), each batch of juveniles would have to meet the criteria developed by Fisheries WA before being released. Batches of prawns would not be released if the following were found during the screening of a batch:

1. a virus associated with a lesion
2. a protozoan associated with an inflammatory or degenerative lesion
3. a metazoan parasite associated with lesions that are known or suspected to be pathogenic to pearl oysters
4. a fungal infection which causes lesions
5. bacteria or rickettsiales associated with lesions or inflammation
6. unexplained lesions
7. inexplicable mortality in the batch which the certifying pathologist considers unacceptable.

Benefits

The beneficiaries of this work include the Exmouth Gulf Prawn Fishery, Australian Prawn Fisheries, and other Stock Enhancement projects in Australia. The Aquaculture Industry is likely to benefit from work proposed in Stage 2 of the Enhancement Project. The potential benefits to each of these groups are outlined below.

Exmouth Gulf Prawn Fishery. Stock enhancement would increase catches of tiger prawns, and reduce the year-to year variation in catches. This last benefit enables more efficient processing operations and increases the continuity of supply to buyers, which benefits industry. The precision of the information on the growth and survival of brown tiger prawns and the fishery in Exmouth Gulf would also be increased, which benefits the managers of this fishery.

Australian Prawn Fisheries (Northern Prawn Fishery, WA, SA, QLD). The more rigorous bioeconomic model developed for enhancing tiger prawns in Exmouth Gulf, will highlight the requirements needed to assess the costs, benefits and risks of enhancing prawn stocks. Estimates of survival for juvenile to adult prawns will also be of use for all other Australian prawn trawl fisheries, particularly those for tiger prawns.

Stock Enhancement Projects - The strategies being developed for enhancing the tiger prawn fishery of Exmouth Gulf, and assessing the success of the enhancement, would be applicable to stock enhancement programs for other prawn fisheries and other species e.g. black bream in the Swan River Estuary; scallops, flathead and whiting in Queensland. The model developed during this study provides a structure and framework for evaluating other enhancement proposals in different regions. The enhancement of prawn stocks in areas where prawn ponds are not currently found, (e.g. northern Australia, or Venus Bay, SA), would be much more feasible if the techniques for the intensive production of juvenile tiger prawns in raceways are successful (Stage 2 of the Enhancement Project, FRDC 1999/222).

Aquaculture Industry – The Australian prawn farming industry would benefit from the development of novel, high-density production techniques for juvenile prawns, particularly in arid environments (proposed in Stage 2). The industry will also benefit from the increased knowledge of the genetic diversity of *P. esculentus* in wild stocks. Ultimately, commercial prawn hatcheries could also benefit from additional markets for the postlarvae created by successful stock enhancement programs

Further Development

Sensitivity analysis suggests that the greatest reduction in the uncertainty of the predictions of the bioeconomic model will be achieved through a reduction in the uncertainty in the parameters of survival in the nursery area, prawn prices and in the feasible densities for producing juvenile prawns. It is well known that prawn prices and recruitment success (survival in the nursery area) are very difficult to predict or control. Therefore, it would be best to focus future enhancement research on investigating the feasible densities for producing juvenile prawns, and reducing the mortality in harvesting, transporting and releasing juvenile prawns.

Some of the assumptions of the model mentioned above will have a direct effect on these results. For instance, any mortality during the harvest, transport and release of juvenile prawns will proportionally reduce the revenue and catch (e.g. a 10% mortality will reduce marginal revenue by 10%). It will also reduce the ratio of enhanced to wild stock in the catch and therefore increase costs of monitoring. This suggest that it is imperative to test these hypotheses and establish estimates for:

1. mortalities associated with transferring juvenile prawns from hatchery to production system and production system to nursery
2. density-dependence in the production system.

In order to ensure that the trial experiment is a success it is probably better to choose a conservative approach. We suggest that releasing one million 1 g juvenile prawns is probably the best strategy to adopt for the experimental trial. Although this strategy would be more expensive to monitor than a release of 2.5 million 0.5 g juvenile prawns, it should be less affected by unforeseen mortalities in the nursery, because prawns will be twice the size at the time of release.

Conclusions

The bioeconomic model has shown that the stock enhancement of tiger prawns in Exmouth Gulf can be profitable. However, further information is needed on the production of juvenile prawns, and the survival of juveniles during their transfer from the production site to the nursery habitats in Exmouth Gulf (i.e. harvest, transport, release), to make better predictions about the likely success of an enhancement. The technology for the production, harvest, transport and release of juvenile prawns needs to be developed. Further information is also needed on the nursery habitats of the juvenile prawns to develop release strategies that give the maximum chance of a successful enhancement. These subjects form the basis of Stage 2 of the stock enhancement of tiger prawns in Exmouth Gulf: "Developing techniques for enhancing prawn fisheries, with a focus on brown tiger prawns (*Penaeus esculentus*) in Exmouth Gulf" (FRDC 1999/222), which is the second stage in the overall plan for the stock enhancement of tiger prawns in Exmouth Gulf. If successful this project would be followed by an experimental stock enhancement (Stage 3, 1 to 2 million juveniles) and a commercial scale enhancement (Stage 4, 7 to 10 million juveniles), which would attempt to increase the commercial catch by at least 100 t.

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Appendix 1: An example of the parameter values used in the application of the bioeconomic model to the Exmouth fishery in Western Australia.

Parameters where uncertainty is incorporated are in bold and are recognised for having a letter denoting the probability distribution used in the simulations and by having their corresponding parameters in parenthesis: Triangular T(Min, Mode, Max), Uniform U(Min, Max) and Normal N(Mean, Stdev)

Hatchery

cost per nauplius *W*	
$	**T(0.0003,0.0004,0.0005)**

Grow-out

		pond	raceway
	density (kg/m2)	**T(0.02,0.04,0.05)**	**T(0.5,0.75,1)**
	size (m2)	10000	50
pumping	per m2	0.1	0.25
costs	per kg	0.07	0.08
conversion	feed/bio	**T(1,1.25,1.5)**	**T(1.5,1.75,2)**
	feed cost	2	2
	Salary	500	84
	capital	50000	25000

Growth

Adults	L_{oo}	K	a	b
Females	**N(50,1)**	0.035	0.00000373	2.574
Males	**N(45,1)**	0.04	0.00000207	2.764

	Larvae
alpha	**T(2.7E-08,3.0E-08,3.3E-08)**
Delta	0.9 (wild) 0.82 (grow-out)

Mortality

Larvae-Juveniles		Subadults-adults
alpha	**T(0.943,1.11,1.22)**	**T(0.105,0.106,0.115)**
beta	-0.30828	-0.027
Culture	**T(0.06,0.07,0.08)**	

Recruitment

	Wild		enhanced
		weight	0.001
Number of Wild recruits	1.08E+10	Number of Enhanced recruits	13470000
week	41	week	2
length out of nursery (mm)		22	
weight out of nursery (kg)		0.011	

Appendix 1. Example of parameter values (cont.)

Fishing mortality

selectivity	
Length0	25
Length100	30
q	0.001

Reproduction

egg a	-5.36E+05
egg b	22573
Matur 0len	28
Matur 100len	36

Transport

seed biomass/site	20
tanker volume	1000
water volume/biomass	10
trips/day	5
cost per day	750

Seasonal patterns

month	week	fishing effort	relative growth	maturity	month	week	fishing effort	relative growth	maturity
1	1	0	1	0.7	7	27	105	0.6	0.05
1	2	0	1	0.6	7	28	105	0.6	0.1
1	3	0	1	0.5	7	29	105	0.6	0.1
1	4	0	1	0.5	7	30	105	0.6	0.1
2	5	0	1	0.5	8	31	105	0.6	0.2
2	6	0	1	0.5	8	32	105	0.6	0.2
2	7	0	1	0.4	8	33	75	0.6	0.2
2	8	0	1	0.4	8	34	50	0.6	0.3
2	9	0	0.9	0.4	8	35	25	0.6	0.3
3	10	0	0.9	0.3	9	36	0	0.7	0.3
3	11	0	0.9	0.3	9	37	0	0.7	0.4
3	12	0	0.9	0.3	9	38	0	0.7	0.4
3	13	0	0.9	0.3	9	39	0	0.7	0.5
4	14	105	0.8	0.3	10	40	0	0.8	0.6
4	15	105	0.8	0.2	10	41	0	0.8	0.7
4	16	105	0.8	0.2	10	42	0	0.8	0.8
4	17	105	0.8	0.2	10	43	0	0.8	0.9
5	18	105	0.7	0.2	11	44	0	0.9	0.9
5	19	105	0.7	0.2	11	45	0	0.9	0.9
5	20	105	0.7	0.1	11	46	0	0.9	0.9
5	21	105	0.7	0.1	11	47	0	0.9	0.9
5	22	105	0.7	0.1	11	48	0	0.9	0.9
6	23	105	0.6	0.1	12	49	0	1	0.9
6	24	105	0.6	0.1	12	50	0	1	0.9
6	25	105	0.6	0.05	12	51	0	1	0.9
6	26	105	0.6	0.05	12	52	0	1	0.8

Appendix 1. Example of parameter values (cont.)

Economics

Count/lb	wt(kg)	Price $	Marginal revenue $	Count/lb	wt(kg)	Price $	Marginal revenue $
60	0.00756	5	3.75	30	0.01512	7	5.25
59	0.007688	5	3.75	29	0.015641	10	7.5
58	0.007821	5	3.75	28	0.0162	10	7.5
57	0.007958	5	3.75	27	0.0168	10	7.5
56	0.0081	5	3.75	26	0.017446	10	7.5
55	0.008247	5	3.75	25	0.018144	15	11.25
54	0.0084	5	3.75	24	0.0189	15	11.25
53	0.008558	5	3.75	23	0.019722	15	11.25
52	0.008723	5	3.75	22	0.020618	15	11.25
51	0.008894	5	3.75	21	0.0216	15	11.25
50	0.009072	5	3.75	20	0.02268	17	12.75
49	0.009257	5	3.75	19	0.023874	17	12.75
48	0.00945	5	3.75	18	0.0252	17	12.75
47	0.009651	5	3.75	17	0.026682	17	12.75
46	0.009861	5	3.75	16	0.02835	17	12.75
45	0.01008	5	3.75	15	0.03024	17	12.75
44	0.010309	5	3.75	14	0.0324	17	12.75
43	0.010549	5	3.75	13	0.034892	19	14.25
42	0.0108	5	3.75	12	0.0378	19	14.25
41	0.011063	5	3.75	11	0.041236	19	14.25
40	0.01134	5	3.75	10	0.04536	19	14.25
39	0.011631	5	3.75	9	0.0504	20	15
38	0.011937	5	3.75	8	0.0567	20	15
37	0.012259	5	3.75	7	0.0648	20	15
36	0.0126	5	3.75	6	0.0756	20	15
35	0.01296	5	3.75	5	0.090719	20	15
34	0.013341	7	5.25	4	0.113399	20	15
33	0.013745	7	5.25	3	0.151199	20	15
32	0.014175	7	5.25	2	0.226799	20	15
31	0.014632	7	5.25	1	0.453597	20	15

Daily variable cost of trawling $ 1500

Appendix 2: Review of information on stock enhancement and Exmouth Gulf (Fiona Manson and Neil Loneragan)

1. Enhancement/reseeding for marine species, particularly prawns

Recently, research on the enhancement of marine fisheries resources has been reviewed by Munro and Bell (1997). They define stock enhancement as "a process whereby the abundance of free-living juveniles is supplemented by the release of juveniles reared in hatcheries or captured elsewhere (e.g., in offshore oceanic areas)". Enhancement of marine fish species began in the mid 19th century in response to declining wild fish stocks. However, these early attempts involved the release of unmarked, newly hatched fry, for which natural mortality rates were very high, and, in most cases, no evidence of increased yield was found. One exception to this was in the salmonid group, with fish being successfully reared and released into the wild (Munro and Bell 1997).

Recent progress in marine stock enhancement has come about with the development of modern tagging methods, and huge advances in the culture of marine species to the juvenile stage (Blankenship and Leber, 1995). These advances have lead to the culture and release of a number of fish and invertebrate species, with the aims of increasing species abundance, rebuilding over-exploited stocks, and reducing annual variability of catch. Stock enhancement is already carried out on an industrial scale in several countries: in Japan over 90 species are being restocked, involving 36 species of fish, 34 mollusc species, 19 crustacean species and 4 echinoderm species. In China prawns are released on an industrial scale, as are scallops in New Zealand, and red drum in the USA. Experimental trials are underway, with mixed success, for a large range of marine species including: striped mullet and Pacific threadfin in Hawaii, cod in Norway, white seabass in California, turbot in Spain, barramundi in Australia, lobster in the UK and Norway, geoduck clams in the USA, queen conch in the Caribbean, giant clams in the Philippines, abalone in New Zealand, Japan and California, trochus in Australia, Indonesia and Vanuatu, and sea cucumbers in the Solomon Islands (Munro and Bell 1997, Bannister and Howard 1991, Smedstad et al. 1994, Leber et al. 1995, 1996, Stoner 1994, Schiel 1993).

The earliest recorded enhancement of prawn stocks was in Japan (Seto Inland Sea), using postlarvae of the Japanese tiger prawn (*Penaeus japonicus*) and beginning in 1964. There was no reliable validation but a lot of support for the work. Much was learnt about the process of stock enhancement, and the cost benefit analysis was favourable (almost 2:1). This stock enhancement of prawn stocks was Government-funded, but in spite of its apparent success, was generally viewed as a public relations exercise. Enhancing prawns by farming them in an enclosed bay was also tried in Florida (using a number of species) from 1971 to 1974, but was closed down by 1978 because of limited success. Trial enhancements of prawn stocks were also carried out in Kuwait (1972-78), with funding from a Japanese aid program. However, the trial enhancements were not considered successful enough to continue the program, once the Japanese funding ceased.

China has been successfully releasing juvenile prawns on a large commercial scale into semi-enclosed bays, and monitoring the stocks and catches of prawns, since 1984. Because the natural populations of prawns are very low in some regions of China, the releases of prawns are reseeding the populations, rather than enhancing them. With reseeding, prawn catches increased by as much as 5-fold and interannual variation in stock size was reduced. Most of their reseeding is carried out in the north (Yellow Sea) with one species (*P. chinensis*, Chinese white prawn). About 2.5 billion juvenile prawns are released each year at a cost of $2.5 million (0.1 c each). At a recapture rate of about 10%, and at a size of recapture of 25 prawns per kg, this results in 10,000 t of prawns and a cost of production of only $0.25 per kg of prawns caught in the fishery! Reseeding works in China because its prawn aquaculture industry was producing about 200,000 tonnes (cf Australia's aquaculture production of 1,500 tonnes). Reseeding in China is very much a by-product of the aquaculture industry where excess postlarvae are produced and then raised to juvenile prawns at little cost. The Government pays the farmer for the juvenile prawns that are released, and the fishermen repay the Government to fish for them.

Enhancement of marine species can be a powerful management tool with the potential to increase fishery yields, rebuild over-exploited stocks and dampen fluctuations in catch due to variable recruitment. Blankenship and Leber (1995) have developed the "responsible approach concept" to optimise and control stock enhancement of marine species. The key components of the concept include the need to:

1. prioritize and select target species for enhancement;
2. develop a species management plan that identifies harvest opportunity, stock rebuilding goals, and genetic objectives;
3. define quantitative measures of success;
4. use genetic resource management to avoid deleterious genetic effects;
5. use disease and health management;
6. consider ecological, biological, and life-history patterns when forming enhancement objectives and tactics;
7. identify released hatchery fish and assess stocking effects;
8. use an empirical process for defining optimum release strategies;
9. identify economic and policy guidelines; and
10. use adaptive management.

Blankenship and Leber (1995) identify cases where each of these components has been successfully applied and they stress the importance of its implementation in present and future enhancement programs. The approach recommended above has been implemented in several recent enhancement programs. In a project on the enhancement of striped mullet (*Mugil cephalus*) in Hawaii, research on release strategies lead to an increase in survival rate of 400% for the enhanced fish in Kaneohe Bay, and released fish provided 20% of the recreational catch in Hilo Bay (Blankenship and Leber 1995).

Munro and Bell (1997) emphasise that stock enhancement is only feasible if the available habitat is not already fully colonised, and the trophic resources are not fully utilised by the wild stock and its competitors. Otherwise, any attempt at enhancement could lead to the displacement of wild stock by released, hatchery-reared stock. This situation arose in Norway where the experimental release of juvenile cod, *Gadus morhua* resulted in the displacement of wild cod (Smedstad 1994). It was concluded that food resources in the area were fully exploited by the wild fish, and therefore the addition of more juveniles did not lead to an overall increase in abundance of adults. However, in Hawaii, the release of hatchery-reared striped mullet *Mugil cephalus* did not appear to displace native fish, and the stock enhancement trials were successful in increasing abundance of this species.

2. Exmouth Gulf - environment, habitat, development

Exmouth Gulf (22°S, 114°E), on the northwest coast of Australia, is a large, shallow embayment extending for about 3,000 km^2. It is situated in a remote, dry tropical region, experiencing low annual rainfall and limited river runoff, with rare flooding events due to cyclonic activity. To the east of the Gulf are dry, extensive saline coastal flats, with a narrow strip of mangroves fringing the coast. This eastern side is largely inaccessible by road. On the western side of the Gulf is the Cape Range, where the towns of Exmouth and Learmonth and the Cape Range National Park are situated. Offshore to the west and north of the Cape Range is the Ningaloo Marine Park.

There have been several oil exploration projects carried out in the Gulf area, and there is a naval communications base (Harold E. Holt Naval Station) north of the town of Exmouth. Recreational fishing attracts tourists to Exmouth Gulf, while both the Gulf and the neighbouring Ningaloo Marine Park are visited by a large number of recreational divers.

A highly productive prawn trawl fishery has been operating in Exmouth Gulf since 1963 (Penn and Caputi 1986, Fisheries WA 1998). The main species taken in this fishery are *Penaeus esculentus* (36%), *P. latisulcatus* (43%), and *Metapenaeus endeavouri* (20%) and a few *Penaeus merguiensis*. The fishery is closely managed by WA Fisheries, and has an annual catch of about 1,000 tonnes (McCook 1995, Fisheries WA 1998). Catch and effort data for this fishery are well documented, and a stock recruitment relationship has been developed for tiger prawns. However, there is little information on the ecology of juvenile prawns and their nursery habitats in Exmouth Gulf.

Other than these prawn studies, there has been little scientific work carried out in Exmouth Gulf, and information regarding the environment, habitats and development in this region is scarce. However, there have been a small number of seagrass surveys carried out along the coast of Western Australia, including the Exmouth Gulf region (McCook et al. 1995, Walker and Prince 1987). The seagrass species found in Exmouth Gulf are all of tropical distribution, unlike Shark Bay to the south, which supports both tropical species at the southernmost limit of distribution and temperate species at their northern limit. A preliminary survey of seagrass undertaken by McCook et al. (1995) found very low abundances of seagrass species throughout Exmouth Gulf, with coverage rarely exceeding 5-10%. This scarcity of seagrass has been attributed to a lack of suitable substrate, with most of the sea bottom comprising hard substrate or highly mobile coarse sediments.

Despite the low seagrass abundance, Exmouth Gulf appears to be a highly productive ecosystem, with macroalgae, phytoplankton and salt-flat cyanobacteria the main primary producers (McCook et al, 1995). The region supports a productive prawn fishery, and is regarded as a major refuge for dugong and turtle. Estimates of dugong numbers range from 200 (Prince, 1986) to 1,000 individuals (McCook et al, 1995).

3. Prawn Species - biology, aquaculture, fishery dynamics

The brown tiger prawn, *Penaeus esculentus*, is a species endemic to northern Australia with a distribution from mid New South Wales, along the northern coast, to Shark Bay, WA. It is fished commercially as a component of the Queensland East Coast fishery, the Northern Prawn Fishery and WA fisheries. A considerable body of work has emerged detailing the species' biology and ecology, its life-history, nursery and adult habitats, reproductive patterns, and population dynamics. Brown tiger prawns have also recently been assessed as a potential aquaculture species in Australia.

Adult *P. esculentus* spawn in offshore waters, generally in late winter-spring, although the timing of spawning varies throughout the range of the species (Table 4). Within 2 to 3 weeks the larvae metamorphose to postlarvae and settle on seagrass beds in inshore or estuarine environments. The juvenile prawns settle in these habitats commonly between September and May, and remain there for about 4 to 11 weeks before emigrating offshore, where they recruit to the fishery (Haywood et al. 1995). In more temperate waters, such as those in Moreton Bay, the juveniles may remain in the seagrass beds for 10 to 16 weeks, and may overwinter for up to 34 weeks (O'Brien, 1994). *P. esculentus* in Exmouth Gulf conform to this typical life-history pattern, with juveniles settling in the hypersaline marine littoral zone along the eastern shore of the Gulf (Penn and Caputi 1986).

Other penaeid species show a similar life-history pattern, although the preferred juvenile habitat may vary between species (Table 1). For example, *P. semisulcatus* are found in algal beds as well as seagrass beds, and juvenile brown shrimp *P. aztecus* use saltmarshes as nursery areas (Loneragan et al. 1994).

When the juvenile *P. esculentus* reach a carapace length of approximately 10mm, they start to migrate offshore into deeper waters, passing through the sub-adult stage to become adults and recruit to the fishery. Most trawling for *P. esculentus* occurs at depths of about 10-20m, while *P. semisulcatus* are often found in deeper waters. A number of studies have been carried out to establish growth rates and mortality rates of both juvenile and adult tiger prawns (Tables 2 & 3).

4. Release Strategies

The success of any release program depends largely on the production of well adapted hatchery stocks which will survive in the field alongside wild stocks, and the development of appropriate release strategies (Stoner 1994, Munro and Bell 1997). There are a number of factors affecting the survival of juveniles which need to be considered when developing a release strategy: size at release, timing of release, release habitat, and stocking density or number released (Munro and Bell 1997). Several experimental releases have demonstrated the effects that changes in these release variables have on subsequent recapture rates.

Size at release

In most trial releases, size at release (SAR) is an important factor determining survival of juveniles, with a significant positive correlation between release size and survival. For the Chinese white shrimp, *Penaeus orientalis*, there was a threshold size of about 30mm total length, below which hatchery stock experienced high mortality in the wild (Liu, 1990). Mortality of softshell clam (*Mya arenaria*) juveniles were 3 times higher for small (mean 3.9mm shell length) and medium (mean11.2 mm SL) than for large (mean 17.8mm SL) clams (Beal and Kraus 1991). Several examples demonstrate the relationship between SAR and survival in juvenile fish e.g. found for striped mullet (Leber et al. 1995), cod (Smedstad 1994), and red drum (Willis et al. 1995). This size-dependent mortality is generally attributed to increased predation on smaller individuals; for example the high mortality on small clams is thought to be due to predation by crustaceans (Beal and Kraus 1991).

Time of release

The timing of a release can be a critical determinant of juvenile survival in the wild. The season for release is usually chosen to coincide with the natural juvenile stage of the species. For example, releases of *P. orientalis* in Jiaozhou Bay occurred in June to August, to correspond to the presence of juveniles from the natural spawning in May to June (Liu 1990). The value of this approach was demonstrated by Willis et al. (1995), when half of their 60,000 experimental juvenile red drum were released following the natural spawning season in spring, with the other half 6 months later. Of the latter group, there was only one fish recaptured, compared with 821 fish from the release following the spawning season group, suggesting that mortality of the out-of-season group was very high. Leber and Arce (1996) demonstrated that the release season can affect the survival of small striped mullet, with releases in summer resulting in zero recovery of fish less than 60mm, while some fish of this size group survived when released in spring. Similarly, survival of queen conch was better in spring releases compared to summer releases, due to an increase in predation during summer (Stoner 1994).

Release sites
To determine the most suitable site for a release, it is important to have a thorough understanding of the habitat and resources required by the species in both the juvenile and adult stages. Enhancement is most successful in habitats that are currently or historically significant as nursery grounds, and may fail on apparently similar sites where that species does not occur naturally (Stoner 1994). For example, the release of striped mullet onto an area which was not preferred nursery ground led to total mortality of the released juveniles, while releases onto 2 nearby sites known to be productive nursery habitat resulted in good survival (Leber and Arce 1996).

Density at release
Overstocking of juveniles in a habitat can have detrimental effects on their survival and growth, so it important to have some knowledge of the optimal stocking density for that species. This requires information on carrying capacity of the habitat, growth, mortality, and the trophic resources required by the species and its competitors. These factors can be highly variable, not only between species, but also for the same species at different sites and over time. Smedstad et al. (1994) concluded that the food resources in a Norwegian fjord were fully exploited by wild cod and its competitors, and therefore the addition of hatchery reared juvenile cod would lead to overstocking of this habitat. This may not be the case for juvenile tiger prawns where high biomass seagrass habitats appear able to support denser populations of juvenile prawns than are naturally found (Loneragan et al. 1996, 1998)

Munro and Bell (1997), and Leber et al. (1996) recommend carrying out pilot studies, with preliminary releases on a small to moderate scale, to determine the best release strategies before large-scale releases take place. A series of experiments is needed to find the optimum release size, season, stocking density and microhabitat. It is also important to understand the interactions of these factors with each other, as these can further influence success rates of releases.

A summary of release strategies for some commercial and experimental release programs can be found in Table 5.

Table 1. Summary of the nursery habitats of juvenile tiger and endeavour prawns from the literature.

Species	**Location**	**Habitat**	**Summary**	**Reference**
P. esculentus	Groote Eylandt	Seagrass	*Enhalus, Cymodocea/Syringodium, Halophila/Halodule*	Loneragan *et al.* 1994
	Groote Eylandt	Seagrass	Catches in $100gm^{-2}$ > catches in $100gm^{-2}$	Loneragan *et al.* 1998
	Embley River	Seagrass	*Enhalus, Halophila/Halodule*	Haywood *et al.* 1995
	Cairns Harbour	Seagrass	*Z.capricorni, Halodule pinifolia,*	Watson, Coles and Lee Long 1993
	Moreton Bay/ Toondah Harbour	Seagrass	*Zostera capricorni, Halophila*	O'Brien, 1994
	Moreton Bay	Seagrass	*Zostera capricorni, H.ovalis*	Young and Carpenter, 1978
	Torres Strait	Seagrass	*Thalassia hemprichii, E.acoroides, Cymodocea rotundata, H.ovalis, H.uninervis*	Turnbull and Mellors, 1990
	Cairns to Cape York	Seagrass	*Cymodocea serrulata, Syringodium isoetifolium, Halodule uninervis, Thalassia hemprichii, Halophila spinulosa, H.ovalis, Halophila decipiens, E.acoroides, Zostera capricorni*	Coles, Lee Long and Squire1985
	Groote Eylandt	Seagrass	Habitat Preferences - *Syringodium isoetifolium, Cymodocea serrulata, Halodule uninervis*	Kenyon *et al.* 1997
P.semisulcatus	Groote Eylandt	Seagrass	Habitat Preferences - *Syringodium isoetifolium, Cymodocea serrulata, Halodule uninervis*	Kenyon *et al.* 1997
	Cairns to Cape York	Seagrass	*Cymodocea serrulata, Syringodium isoetifolium, Halodule uninervis, Thalassia hemprichii, Halophila spinulosa, H.ovalis, Halophila decipiens, E.acoroides, Zostera capricorni*	Coles, Lee Long and Squire1985
	Laboratory	Seagrass	*Zostera capricorni*	Liu and Loneragan 1995
	Kuwait Bay	Algae	*Sargassum* sp	Jones and Al-Attar 1982
	Embley River	Seagrass	*Enhalus, Halophila/Halodule*	Haywood *et al.* 1995
	Embley River	Seagrass, Algae	*Enhalus acoroides, Halodule uninervis, Halophila ovalis, Caulerpa spp*	Vance *et al.* 1996

Table 1. Summary of the nursery habitats of juvenile prawns (continued)

Species	Location	Habitat	Summary	Reference
M.endeavouri	Cairns to Cape York	Seagrass	*Cymodocea serrulata, Syringodium isoetifolium, Halodule uninervis, Thalassia hemprichii, Halophila spinulosa, H.ovalis, Halophila decipiens, E.acoroides, Zostera capricorni*	Coles, Lee Long and Squire1987

Table 2. Summary of data on growth and mortality of juvenile tiger and endeavour prawns from a number of sources. F= females, M = males, C= combined males and females

Species	Location	Season	Growth (L ∞, K) F	M	C	Mortality	Estimate	Reference
P. esculentus	Cairns Harbour	All year	44, 0.18	35, 0.19		0.18-0.28	Von Bertalanffy growth model	Watson et al.1993
	Moreton Bay	All year			0.03-2.1 mm $CLwk^{-1}$	0.06-0.26 wk^{-1}		O'Brien 1994
	Groote Eylandt	Nov-Feb			0.9-1 mm $CLwk^{-1}$			Loneragan et al. 1994
P.semisulcatus	Cairns Harbour	All year	62, 0.10	38, 0.24			Von Bertalanffy growth model	Watson et al. 1993
M.endeavouri	Cairns Harbour	All year	43, 0.12	32, 0.23			Von Bertalanffy growth model	Watson et al. 1993

Table 3. Summary of data on growth and mortality of adult tiger and endeavour prawns from a number of sources.
[a] = Total length (otherwise L = carapace length), F = females, M = males.

Species	**Location**	**Season**	**Growth** (L∞, K) **F**	**M**	**Mortality**	**Estimate**	**Reference**
P. esculentus	Torres Strait	February	39.9, 3.9	34.1, 3.5		Von Bertalanffy growth model	Watson and Turnbull 1993
	East Torres Strait	Jan/Feb	43.6, 2.6	34.7, 2.9		Von Bertalanffy growth model	Watson and Turnbull 1993
	West Torres Strait	Jan/Feb	49.2, 1.4	34.7, 3.5		Von Bertalanffy growth model	Watson and Turnbull 1993
	Exmouth Gulf		40.9, 0.05	32.6, 0.05		Von Bertalanffy growth model	White 1975
	Groote Eylandt	February	44.8, 0.041	37.5, 0.034		Von Bertalanffy growth model	Kirkwood and Somers 1984
	East Torres Strait	Jan/Feb	42.4, 0.0091	37.2, 0.0057		Von Bertalanffy growth model	Derbyshire et al. 1990
	West Torres Strait	Jan/Feb	52.6, 0.0035	36.6, 0.0063		Von Bertalanffy growth model	Derbyshire et al. 1990
P.semisulcatus	Groote Eylandt	February	62.2, 0.061	38.1, 0.021		Von Bertalanffy growth model	Kirkwood and Somers 1984
	Inshore North-west GOC	All year	51.64, 0.043	37.5, 0.062		Von Bertalanffy growth model	Somers and Kirkwood 1991
	Offshore North-west GOC	All year	48.99, 0.038	39.37, 0.017		Von Bertalanffy growth model	Somers and Kirkwood 1991
	Combined North-west GOC	All year	47.42, 0.054	36.19, 0.073		Von Bertalanffy growth model	Somers and Kirkwood 1991
	Kuwait				F: 0.23 month^{-1} M: 0.44 month^{-1} C: 0.33 month^{-1}		Xucai et al. 1995
	Kuwait	Spring/ autumn	53, 1	52, 1.2	F: 1.7-1.75 M: 1.89	ELEFAN	Mathews et al. 1993

Table 3. Summary of data on growth and mortality of adult prawns (continued)

Species	Location	Season	Growth (L_∞, K) **F**	Mortality **M**	Estimate	Reference	
	India	All year	[a]261, 1.3	[a]210, 1.7	F: 1.3 M: 1.7	ELEFAN	Rao et al. 1993
	Kuwait	Jul-Oct	47.5, 0.04	42.5, 0.04		Von Bertalanffy growth model	Jones and van Zalinge 1981
M.endeavouri	Torres Strait	February	34.9, 4.9	34.9, 1.0		Von Bertalanffy growth model	Watson and Turnbull 1993

Table 4. Summary of data on the time of reproduction of tiger and endeavour prawns.

Species	Location	Peak Spawning	Range of Spawning	Reference
P esculentus	Groote Eylandt	Jun-Aug	All year	Crocos, 1987
	Low Islets, Qld	Mar-Apr	All year	O'Connor, 1979
	West Torres Strait	Oct-Nov	All year	Keating et al. 1990
	East Torres Strait	Jan-Mar	All year	Keating et al. 1990
	Torres Strait	March	All year	Somers et al. 1987
P.semisulcatus	Albatross Bay		Aug-Nov, Feb-Mar	Crocos and Van Der Velde 1995
	Groote Eylandt	Major - Aug-Sep Minor - Feb	Jun-Feb	Crocos, 1987
	Kuwait - from artisanal catches	Jan-Feb	Sep-Feb	Mohammed et al. 1981
	Kuwait - from industrial catches	Feb-Apr	Dec-May	Mohammed et al. 1981
M. endeavouri	Central Queensland		Oct-Jan	Courtney et al. 1989

Table 5. Summary of the release strategies used in stock enhancement programs for a number of marine species. SAR = size at release. *Comm* = commercial; *Expt* = experimental.

Species and Country	Reference	SAR	Season	Habitat	Density released	Number Released	Number of releases	Tagging Method
Penaeus orientalis Chinese Prawn China	Liu 1990	>30mm total length	June-Aug	Shallow waters		*Comm* *Expt* 1983 - 280,000 1984 - 2.5million 1985 35million 7million 1986 200million 47,000 1987 - 14,000	2 (pre-July, Jul-Aug)	Coloured polyethylene tags between 1st and 2nd somite
Penaeus japonicus Kuruma Prawn Japan	Kurata 1981	1-3 cm total length		Shallow inshore waters	100 m^{-2} max	150 million p.a.		none
Strombus gigas Queen Conch Bahamas	Stoner 1994	85-115mm shell length	April	Seagrass beds	1.2m^{-2}	2,552	1	Floy tags, cable ties
Homarus gammarus European Lobster England	Bannister and Howard 1991	11-15mm CL	Spring/ autumn	Boulder and cobble reefs		49,128	11 (2 per year)	Binary coded wire microtag inserted at base of 5th pereiopod
Mya arenaria Softshell Clam Maine,USA	Beal and Kraus 1991	8-10mm shell length	May	Intertidal	660 m^{-2} / 1320 m^{-2}	10 million p.a.		None (open field enclosures)
Gadus morhua Cod Norway	Smedstad et al. 1994			Near-shore shallow areas with macroalgae		1988 - 91,000 1989 - 72,000 1990 - 36,000		Floy tags, oxytetracycline, genetic tagging
Mugil cephalus Striped Mullet Hawaii	Leber et al. 1995, 1996	45-130 mm total length	August			29,354	1	Binary coded wire tags

Table 5. Summary of the release strategies (continued)

Species and Country	Reference	SAR	Season	Habitat	Density released	Number Released	Number of releases	Tagging Method
Sciaenops ocellatus Red Drum Florida	Willis et al. 1995	60-120 mm total length	Autumn/ spring	Habitat suitability index		60,000	2	Coded wire tags, internal anchor tags
Atratoscion nobilis White Seabass California	Drawbridge et al. 1995	31-317mm total length	All year			153,000	Monthly 1990-1993	Oxytetracycline, coded wire tags
Haliotis iris Abalone Chatham Island, New Zealand	Schiel, 1993	3-30 mm shell length	Jan-May	Small boulders on rocky reefs	50-70m^{-2}	80,000	8 sites 4 seeding times	Green bands on shell caused by changes in diet in hatchery

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Intellectual property

The model developed during this project is likely to be a valuable template for the evaluation of other stock enhancement projects. This model has been written in Microsoft Excel to provide maximum access for researchers, managers, industry and other interested parties. It will be distributed on request, to people with an interest in stock enhancement. However, the model will not be supported and no responsibility is accepted for how the model is used.

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