Variation in banana prawn catches at Weipa:

a comprehensive regional study

FRDC Project No. 2004/024

Final Report

June 2007

CSIRO Marine and Atmospheric Research

Cleveland Laboratories

Cleveland, Queensland 4163

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Variation in banana prawn catches at Weipa: A comprehensive regional study

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Edited by:
Peter C Rothlisberg and Thomas A Okey

June 2007

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We would like to dedicate this Final Report to Dr Burke Hill. Burke was an inspirational leader during CSIRO's earlier Albatross Bay study and also set a high standard of achievement for fisheries scientists in Australia. We hope this Report would have met with his approval.

1. NON-TECHNICAL SUMMARY

Outcomes Achieved To Date:

1.1 Introduction to the problem

Since about the year 2000 there have been very low catches in the Weipa Region of the Northern Prawn Fishery (NPF); these low catches were different to other areas of the NPF where they continued to fluctuate around long-term means and continued to fall within predicted levels. Industry and managers were concerned about these anomalous catch levels and debated whether or not the very low catches were a result of: overfishing; changes in the environment; changes in fishing practices; or the result of recent management changes. This project was meant to explore these possible hypotheses and advise management of a course of action.

1.2 Approach

The project was an 18 month desktop study which examined historical catch and environmental data by a variety of means. Three workshops were attended by experts from CSIRO, QDPI, universities, fishers and managers. Several approaches were simultaneously undertaken by four Working Groups. In addition there were also studies on: reproductive dynamics; fleet dynamics; trophodynamics; and fishing effort analysis. A Decision Support Framework was established for systematically examining the hypotheses, thresholds of accepting or rejecting them, and suggested management actions determined.

1.3 Outcomes of the Working Groups

Each of the Working Groups addressed the question of reduced catch in the Weipa Region in a different way.

A Qualitative Model was developed as both a Conceptual Framework for the project and a guide to interactions among the various impacts on the banana prawn population to providing general insights into the interactions and possible dynamics in the system. The full model incorporated the impacts of the fishery and the market, as well as effort trade-offs and effects of environmental and habitat factors on all prawn life history stages.

Key findings of the **Qualitative Modelling Working Group** include *inter alia*: 1. Instability in the system will arise when discarded bycatch support relatively high predation pressure; 2. CPUE was not a reliable indicator of stock abundance; 3. High early season rainfall should increase all life history stages and CPUE; 4. Late season rainfall should suppress all life history stages, but effect on CPUE is ambiguous; and 5. Reduced catch in Weipa reinforces a shift in effort away from Weipa.

The **Fishery Assessment Working Group** found there was insufficient power in the analyses to conclude that recruitment was not affected by a reduction in spawning biomass resulting from fishing, or the effect of environmental factors, or both. It was therefore suggested that management strategies should be put in place to allow recruitment in Weipa to recover to levels in the mid-1970s and mid-1990s. The Project's Decision Support Framework recommended a pre-season controlled-fishing experiment to test the recruitment collapse hypothesis prior to management actions.

The **Ecological Modelling Working Group** used both modelling and field sampling studies to examine trophodynamics linkages to explain the changes in banana prawn population size. The results indicate that changes in fishing effort within the range of changes observed over the last 20 years are capable of causing very large declines in banana prawn biomass through both direct and indirect effects. Simulations of changes in trawl fishing effort indicated that banana prawn populations are affected both directly through removals of biomass and indirectly through trophic cascades. Field studies using stable isotopes verified some of the simulated trophic linkages, while sampling of the predatory fishes on the juveniles nursery grounds showed no dramatic shifts between the 1980s and 2005.

The **Environmental Prediction Working Group** used a correlative statistical approach to look at linkages between catch and a small group of environmental variables (rainfall, evaporation, air temperature). The Working Group found no long-term change in timing of or downward trend in rainfall, and so changes in banana prawn catch cannot be explained by changes in rainfall. In terms of interannual variability, log(Catch) is only weakly predictable in both Weipa in Karumba based on rainfall data. With log(Effort) added as an explanatory variable, the catch is highly correlated with environmental variables in Weipa and reasonably correlated in the Mitchell region. In Karumba the environmental signal is the strongest – pre-season rainfall (or surrogates) is the dominant environmental predictor there. In Weipa however, environmental variables could not explain the observed multi-year trend in banana prawn catch probably because the prawn abundance estimates (catch and CPUE) are confounded by dramatic changes in effort since 2000.

1.4 Evaluation of hypotheses

Overall, nine hypotheses were considered during the project (Table 1-1). The three hypotheses that emerge as the most likely explanations for the observed catch declines in banana prawns are all fishing-related namely: recruitment overfishing (Hypothesis 1); a loss of searching power resulting from a reduction of effort in this region (H2); and indirect trophic effects of fishing (H8). All other hypotheses were deemed less plausible or discredited.

1.5 Decision Support Framework

A decision support framework was developed to provide empirical data that would further narrow down the alternative explanations for the recently observed declines in banana prawn catches; and to ensure the best management decisions in the context of the results of the present study. As part of the framework three surveys were proposed: (1) an “experimental fishing” survey – opening the fishery prior to the first season (in the Weipa area only); (2) a pre-season juvenile prawn survey in the nursery ground; and (3) a January recruitment survey. This framework and these surveys were designed to help resolve alternative hypotheses and allow management decisions for the Weipa banana prawn fishery (e.g. should the fishery be closed and for how long). A critical aspect of this framework is that the various alternative hypotheses can be re-tested or verified by subjecting the new information from these surveys to the statistical and dynamical analyses developed during the current project.

1.6 Future research

The different approaches taken by each of the Working Groups also pointed to new research areas to both fill voids in our understanding and add rigour to several of the analytical approaches. Two areas of future research stand out.

1. Common banana prawns (*Penaeus merguiensis*), if not unique, are unusual in their schooling behaviour. This schooling behaviour is developed after the juveniles leave the estuary and as recruits enter the fishery. The schooling behaviour requires a different style of fishing – aerial and echo sounding searching followed by short trawls. Therefore, fishing effort is split between searching and trawling. The schools of prawns are relatively hard to find in Weipa because they don't have a surface manifestation ("mud boil") and therefore aerial spotting is not used. Equally the probability of finding the schools is proportional the searching effort. The greater power provided by multiple boats searching simultaneously enhances the probability of encounter. Currently we can't quantify the relationship between searching and encounter. Equally if we don't know the required effort to find the prawns the use of catch or CPUE is a questionable (non-quantitative) measure of abundance. Currently, pre-season surveys, prior to the onset of schooling, are the most reliable estimate of stock abundance we have, but the history of these surveys is short and therefore has not been used in either stock assessment modelling or statistical assessments of environmental predictors. Surveys must continue and research is needed to: establish more reliable fishery logbook data that records effort; understand schooling behaviour of the prawns; and how catch or CPUE relates to stock size.

2. The project highlighted the relationship between the prawn and both its predators and prey. Fishing rates and management measures in gear type (TEDs and BRDs) could have both positive and negative impacts on prawn abundance through direct and indirect trophodynamic pathways. Equally, other legal or illegal fisheries (e.g. shark and sawfish) could also create trophic cascades that affect prawn abundance. Lastly, catchment developments that could affect the productivity of the estuarine and coastal nursery grounds could also affect habitat and food sources and therefore prawn recruitment dynamics. More work is needed on these trophic factors that affect prawn growth and survival.

Table 1-1 Ranking the likelihood of each explanation (hypothesis) for the observed decline in the Weipa Region's banana prawn catch, based on the analyses conducted during the project

Likelihood	Hypothesis
High	Recruitment overfishing (H1)
	The fleet has lost searching power (H2)
Medium	Indirect trophic effects of fishing (H8)
Low	Adult prawns are staying inshore (H4)
	Adult prawns are no longer schooling (H5)
	Direct effects of environmental change on banana prawns (H3)
	Indirect trophic effects of environmental change (H9)
Discredited	Pumping of groundwater has reduced run-off (H6)
	Recruitment has collapsed due to a pollutant (H7)

KEYWORDS: Banana prawn, *Penaeus merguiensis*, fishery, stock assessment, ecological modelling, qualitative modelling, environmental modelling, decision support framework

2. BACKGROUND

Until the late 1990s, the Weipa and Karumba regions were the most important areas for banana prawn fishing in the Northern Prawn Fishery, both having a similar long-term average annual catches of about 800 tonnes, with a value of over $12 million. However, since 1998, in each of 4 consecutive years, catches from Weipa have not exceeded 70 tonnes i.e. less than one tenth of the long-term annual average. This is despite good catches being taken from other regions of the Northern Prawn Fishery e.g. in 2001 and 2002, catches in the Karumba region were 2,230 and 1,837 tonnes respectively, substantially above the long-term average for the region.

The successive low catches in Weipa can be explained by several potentially interacting factors:

1. Prawn overfishing. A recently completed project showed that banana prawns do exhibit a stock-recruitment relationship (Vance et al., 2003)
2. Too little fishing time in a season to adequately search for prawns in an area where spotter planes can not be used,
3. Changes in the ecosystem such as the predator-prey balance, and/or
4. Environmental changes in the Weipa region e.g. the rainfall pattern or more specifically, the run-off to the estuary due to drought or changes in the catchment e.g. greater extraction of water from the water table.

Recent and current studies have investigated only a few of these aspects and concentrated on a limited number of factors affecting the prawns.

Extensive research has been carried out on the population dynamics, and aspects of the environment of banana and tiger prawns in the Weipa region (e.g. FIRTA 86/13, FRDC 89/13). This has resulted in the collection of comprehensive data sets for the biology of prawns and their fish predators. Although many individual components of these studies have been published in international journals and industry reports, the results from the different studies have not been synthesised across individual components. Furthermore, the data have not been analysed using some of the modelling techniques that have been developed since the completion of the six year Weipa study in 1992. These datasets, and those being collected from current FRDC and industry-funded projects (FRDC 2002/014 – Developing a new method of evaluating catch rates of spatially mobile and aggregating prawn resources; FRDC 2003/075 – Designing, implementing and assessing an integrated monitoring program for the NPF: developing an application to stock assessment) provide the basis of developing a broader understanding of variation in prawn catches in relation to fishing, biological and environmental factors.

The overall objectives of this proposal are to integrate data from a variety of sources and provide a framework for considering variation in the banana prawn fishery in relation to three broad categories of factors: fishing, biology and environment.

3. NEED

Research in the Northern Prawn Fishery has focussed on aspects of the fishery, biology and environment of the prawns and bycatch species. Recent studies have also started to look at the broader effects of fishing in the NPF. The NPF is moving to managing the fishery in an ecosystem context i.e. with a better understanding of the factors that affect prawn and non-target species populations, other than fishing. To achieve this goal, research, management and industry need to develop broader, and more integrated approaches to understanding different factors that are likely to affect the fishery. The development of these approaches parallel the NPF’s goal of moving to an Environmental Management System. The research in this proposal will build a framework for developing an understanding of variation in banana prawn stocks in the Weipa region, in an ecosystem context, and develop more integrated approaches for research and management strategy evaluation in the NPF. It will provide a prototype approach and models for potential application to the broader NPF and other prawn fisheries in northern Australia.

The Weipa region is a high priority area as catches have been only one tenth of the long-term average catch for 4 consecutive years, even though other regions have had extremely high catches during this time. These low catches in the Weipa region can not be explained by low rainfall alone. The decline in catch from Weipa has resulted in a decline in exported banana prawns in the region from a value of about $12 million a year less than $1.2 million each year.

The research in this proposal bridges two high priority research areas identified by NORMAC in its 2003 research priorities:

1. Assessment of the status of the fishery including management strategies for the fishery; and
2. Improved knowledge of environmental factors of importance to the fishery. It also addresses a priority research area identified by the NPFAG at its May 2003 meeting.

4. OBJECTIVES

The objectives of the project are to:

1. Examine the possible reasons (e.g. fishing, biological, environmental) for the currently low banana prawn catches in the Weipa region;
2. Integrate data and develop a framework and alternative models to test the various hypotheses that could explain low banana prawn catches;
3. Develop a decision support system to enhance management and operational decisions about prawn fishing; and
4. Assess of the relevance of the approach to other regions of the Northern Prawn Fishery and other prawn fisheries.

5. METHODS

The research in this project will develop conceptual, qualitative and other models to investigate alternative hypotheses (see below) for the decline in banana prawn stocks in the Weipa region. It will proceed in two main stages: a CSIRO-funded stage to collate and validate existing data sets in 2003/04; and work in this proposal that is planned to proceed through three focussed workshops and work by working groups between the workshops.

5.1 Hypotheses being investigated

1. Overfishing caused recruitment collapse;
2. Fleet can't find prawns because the reduced fleet has less searching power;
3. An environmental change has drastically reduced recruitment;
4. Fleet can't find prawns because the prawns are staying inshore;
5. Fleet can't find prawns because the prawns are no longer schooling;
6. Groundwater pumping has reduced runoff;
7. A pollutant has killed off the prawn stock;
8. Indirect trophic effect of fishing;
9. Indirect trophic effect of an environmental change.

5.2 Stages in the project

The project will proceed to collate, validate and synthesise a number of datasets for the region as input to the workshops, where models will be developed and refined. The main datasets and stages in the project are:

1. 1986-92 data - on prawn populations, predators, primary production.
2. Post 1992 data – collate data from more recent projects (see related projects below).
3. Synthesis of past data – CSIRO funded project for 2003/04.
4. Workshops (3) – in this proposal to develop conceptual framework, models and scope decision support systems.

5. Integration of results and evaluation of their application to other regions of the NPF and other species of prawns.

5.3 Research supported by CSIRO in 2003/04

Preliminary work funded by CSIRO in 2003/04 will collate and validate the extensive data collected on all life history stages of banana prawns, their fish predators and some aspects of the environment in the Weipa region between 1986 and 1992 (FIRTA 86/13 , FRDC 89/13). Current CSIRO funded work on the feeding ecology of pelagic fishes around Weipa may also provide additional data on prawn predation. These data, and those collected since this time will be used to provide the input to this proposal which will use recently developed modelling techniques that were not available when the original data were collected.

5.4 Integration with Other Projects

This project will incorporate the results of the new catch rates project (FRDC 2002/014), update and re-run the single species banana prawn model developed by Murdoch University (Dr Norm Hall) and CSIRO (ARF 98/716).

5.5 Workshops

The collation and synthesis work in 2003/04 will form the basis for a series of three workshops, with the participation of biologists, ecologists, fishery and ecosystem modellers. The purpose of the workshops will be to develop a framework for the approach and test hypotheses on the potential reasons for the declines in catches.

In addition to developing the framework for the approach, conceptual models (descriptive, qualitative and more formal) will be developed to help focus, integrate and identify gaps in the research and communicate the results of the research. These conceptual models will be revised as the project progresses.

The first workshop will focus on developing an integrated conceptual framework and models to test hypotheses (see below) about the reasons for the low catches at Weipa. The second workshop will continue the model development and include a component to develop different management scenarios and decision support tools. The third workshop will integrate the results from the previous workshops and use the decision support system to evaluate the predicted results of different management options. Both the second and third workshops will involve the participation of researchers, management and industry, possibly through the NPFAG.

5.6 Hypothesis testing

Testing the hypothesis that changes in fishing have resulted in low catches will involve the following activities:

(a) Further development of the recent banana prawn model to investigate stock and recruitment relationships at Weipa (Vance et al. 2003);
(b) Comparison of current log-book data on catch, effort and location of fishing with those from 1986-92;
(c) Comparison of recent industry, FRDC- and CSIRO-funded research to develop fishery independent measures of stock and recruitment from monitoring surveys with data from fishery independent surveys from 1986 until 1992 and since this time, including investigating schooling behaviour through analysis of these data sets (following Die and Ellis 1999).

Activities to investigate trophodynamic hypothesis:

(a) Developing preliminary ecosystem models (using a qualitative approach and the Ecopath/Sim/Space suite of software) based on the extensive data sets for prawns (e.g. Crocos and van der Velde 1995, Vance et al. 1998), their predators and the environment for Weipa. Previous work (FRDC 86/13, 89/13) showed that in the Embley estuary, Norman estuary and the inshore waters of Groote Eylandt, about 50 fish species are significant predators of prawns. In Albatross Bay alone, about 34 species of fish are significant predators of prawns. Those with the strongest impact on commercially important prawns are *Caranx bucculentus* and four species of elasmobranch. It was estimated that 2,950 t yr-1 of commercial penaeids was eaten by all fishes in Albatross Bay (Blaber et al. 1990, Salini et al., 1990, Brewer et al. 1991). Current work being undertaken by CSIRO on the feeding ecology of pelagic fish in Albatross Bay will also contribute data towards an ecosystem model. Dr Neil Gribble (Queensland Department of Primary Industry) has developed an Ecopath model of prawn fishing in the Great Barrier Reef and will be invited to participate in the first workshop.
(b) Modelling scenarios for changes in fishing effort (both the magnitude and pattern of fishing) on prawn and predator populations. Identify both observational and process data gaps for broader scale studies and develop a more whole of fishery approach that can then be extended and applied to ecosystem characterization studies.

Activities to examine interannual variation and trends of change in the environment:

(a) Investigate potential interannual variation rainfall and hydrology and their potential influence on larval dispersal to inshore nursery habitats.
(b) Collate and analyse data from other sources e.g. rainfall, river flow, level of water table and water consumption (COMALCO), dredging operations and dredge disposal, seagrass (Ports Corporation of Queensland).
(c) Collaborate with Queensland Government Departments to build databases on the river flows into the estuaries and coastal waters in the Weipa region (Natural Resources and Mines) and estuarine/coastal fisheries (e.g. mud-crabs, barramundi, Queensland Department of Primary Industry).
(d) Hold discussions with the Weipa communities and catchment organizations to document anecdotal changes in

5.7 References

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5.8 Research prioritisation

Given the timeline and budget of this project, it is clear that a full scale version of each model and the overall synthesis model would not feasible. However, this project will highlight the major factors affecting prawn catches in Weipa and prioritise future research.

6. RESULTS/DISCUSSIONS

6.1 Workshop procedures

This project was a collaborative desktop study that involved scientists from CSIRO (CMAR and CMIS), QDPI, Murdoch University, Griffith University, University of Queensland, AFMA and members of the northern prawn fishing industry (see Appendix II for full list of participants). Much of the work was conducted during three project workshops by four Working Groups. The workshops were facilitated by Jeremy Prince (Biospherics Pty/Ltd) and held at the CSIRO Cleveland Laboratories during November 2004, May 2005 and October 2005.

The first Workshop provided background presentations about the banana prawn fishery and past biological research. Three Working Groups were formed at this workshop:

1. **Qualitative modelling** (Jeff Dambacher, Leader) Qualitative ecosystem models were based on assigning simple qualitative relationships (+ or -) between various banana prawn life history stages, their predators and prey, environmental drivers and a bottom-trawl fishery. The models are intended to investigate the potential dynamics of the banana prawn ecosystem and fishery in terms of a wide array of potential factors that might have led to the observed decline in banana prawn catch. These analyses explore how the system might respond to changes in the environment or the fishery, and its potential for stability.
2. **Fisheries stock assessment** (Norm Hall, Leader) Estimates of daily catch per unit of effort (CPUE) for the banana prawn stock at Weipa were calculated using logbook data. The daily catch data for each year were subjected to virtual population analysis (VPA), and a tuned VPA, with both catchability and terminal biomass being estimated as parameters of the model. The resulting estimates of recruitment and spawning biomass were used, in combination with time series of rainfall, temperature and wind data, to explore whether recruitment was affected by spawning biomass and the effects of those environmental variables. In addition, a depletion analysis based on similar assumptions to the tuned VPA was fitted simultaneously to the daily CPUE data for all years.
3. **Ecosystem models** (Tom Okey, Leader) A preliminary mass-balance trophodynamic (computer) model was constructed by a broad collaboration of experts to represent the Albatross Bay marine ecosystem, Gulf of Carpentaria, Australia during the period 1986 to 1992. It was constructed using the freely available software Ecopath with Ecosim (www.Ecopath.org) for the purpose of exploring (and developing) hypotheses that would explain the recent declines in banana prawn (*Penaeus merguiensis*) catches in the Albatross Bay region. In general, these models are designed to characterize whole food

web trophic interactions and they can integrate non-trophic mediation effects and environmental forces.

At the end of the first workshop a fourth Working Group was formed:

4. **Environmental predictors** (Bill Venables, Leader) This Working Group considered the role of environmental drivers on the recruitment of the common banana prawn, *Penaeus merguiensis*. The analyses explored the relationships of environmental parameters associated with rainfall, temperature, evaporation and Southern Oscillation Index (SOI) with catch, or CPUE since fishery-independent indices of abundance were not available. These relationships were explored separately for the Weipa, Mitchell and Karumba regions and compared.

Workshop participants were split amongst the Working Groups for detailed analysis and discussion. Explicit cross fertilisation amongst the Working Groups was initiated at each workshop.

A considerable amount of analysis was conducted by Working Group members between the workshops, especially by their Leaders. Progress since the previous workshop was reported at the beginning of Workshops 2 and 3.

The list of hypotheses that might explain the decline of banana prawns in the Albatross Bay region was broadened from the initial three to seven during Workshop 2, and this was later broadened to nine. Detailed criteria and data needs for analysing these hypotheses were also established.

Industry participants and fishery managers were invited to attend Workshop 3 to contribute to the discussion of the project's findings and the development of a Decision Support Framework (DSF). The DSF is a scheme to classify, differentiate and test each of the hypotheses, and most of all to inform the implementation of pre-agreed decisions given available information and uncertainties. The last workshop also developed the basis for a proposal to AFMA for an Experimental Fishing Program to test one of the hypotheses in the Decision Support Framework.

Workshop Agendas are attached to show the style, depth and breadth of presentations, discussions and feedback. Detailed notes of Workshop presentations, questions and discussions have been provided in each of the project's Milestone Reports.

The body of this report contains the préces of the Working Groups Reports and some additional investigations. A large appendix (Appendix IV) includes the full reports (see footnote on title page of each précis for location of full report). Most of these appendix contributions are destined for publication in the internationally refereed literature. A detailed methods section for each of the studies is provided in these full reports.

Workshop 1 Agenda

Day 1, 9 November 2004

Morning (0900-1300)
Introduction to the workshop (Neil Loneragan, Jeremy Prince)

- Objectives
- Planned outputs
- Approach

Background on the biology

1. Introduction to banana prawn life history (Neil Loneragan, Peter Rothlisberg)
2. Adult distribution & reproductive dynamics, (Tonya Van der Velde, Peter Crocos)
3. Larval ecology & advection (Peter Rothlisberg, Scott Condie)
4. Postlarvae, juveniles & emigrants (Neil Loneragan)
5. Adult variation – schooling behaviour & rainfall models (Bill Venables)
6. Predation in the estuary and Albatross Bay (Steve Blaber, Shane Griffiths)

Afternoon (1400-1730)
Assessing the fisheries

1. Introduction – the fisher's perspective(Jeremy Prince)
2. Historical patterns of catch & effort from logbooks & VMS (Shijie Zhou, Wayne Rochester)
3. Fishery independent information from monitoring & new catch rate projects (Yimin Ye, Cathy Dichmont)
4. North Queensland net & pot fisheries (Neil Gribble)

Environment

1. Nutrients & primary production (Michele Burford, Peter Rothlisberg)
2. Oceanographic processes (e.g. ocean colour, currents and CARS) (Scott Condie, Ken Ridgeway)

Day 2, 10 November 2004

Morning (0830-1230)
Modelling examples

1. Current status of modeling approaches to banana prawn stocks in the NPF (Norm Hall)
2. Qualitative model (Jeff Dambacher)
3. Ecological models
4. Atlantis, In vitro (Beth Fulton)
5. Ecopath/Ecosim (Tom Okey, Neil Gribble)
6. Statistical Models (Bill Venables)

Afternoon (1330-1700)
Modelling approaches

1. Conceptual Framework (Jeremy Prince, Neil Loneragan, Tom Okey)
2. Discussion of approaches to model development (Jeremy Prince)

Summary of background data sources (Neil Loneragan, Steve Edgar, Chris Moeseneder)

1. input formats
2. access & distribution
3. use/IP issues

Day 3, 11 November 2004

Morning (0900-1300)
Modelling working groups:

1. Qualitative model (led by Jeff Dambacher)
2. Ecopath/Ecosim model (led by Tom Okey)
3. Fishery model (led by Norm Hall)

Feedback from Working Groups

1. Refinement of Conceptual Framework
2. Action items for next Workshop
3. Data requirements

Workshop 2 Agenda

Day 1, Tuesday, 3 May 2005

0900 - Introduction to the workshop (Peter Rothlisberg)

- Objectives
- Approach
- Planned outputs

Reports of working groups

0915 – Fisheries working group (Norm Hall)
0945 – Additional fisheries analysis (Jeremy Prince)
1015 – Environmental correlates (Bill Venables)

1045 – Morning Tea

1100 – Qualitative working group (Jeff Dambacher)
1130 – Ecosystem working group (Tom Okey)
1200 – Weipa predation sampling (Steve Blaber)

1230 – Lunch

1330 – Working group break-outs

1545 - Afternoon Tea

Working group reports

1615 – Fisheries
1630 – Ecosystem
1645 – Qualitative

Day 2, Wednesday, 4 May 2005

0900 – Working group breakout all morning

Working group reports

1115 – Fisheries group
1130 – Ecosystem group
1145 – Qualitative group

1200 – Lunch

1300 – Working group breakout

Working group reports

1615 – Fisheries
1630 – Ecosystem
1645 – Qualitative

1700 – Break

Day 3, Thursday, 5 May 2005

0900 – Working group final breakout

1030 – 1100 – Tea

Working group final report back

1100 – Fisheries
1130 – Ecosystem
1200 – Qualitative

1230 – 1330 – Lunch

1330 - 1530 – Milestone discussions (Neil Loneragan, Peter Rothlisberg)

- Develop models further
- Alternative management strategies / Decision support systems

Workshop 3 Agenda

Day 1, Tuesday, 11 October 2005

Working group reports and discussion

0900 - Introduction to the workshop (Peter Rothlisberg)

- Welcome
- Review project objectives
- Objectives of this workshop
  1. Approach
  2. Planned outputs

Reports of working groups (Jeremy Prince, Facilitator)

0930 – Qualitative working group (Jeff Dambacher)

1030 – Morning tea

1100 – Environmental correlates (Bill Venables/Elvira Poloczanska)
1200 – Ecosystem working group (Tom Okey),
Isotope Analyses (Michele Burford)

1300 – Lunch

Reports of working groups continued (Neil Loneragan, Chair)
1400 – Fisheries working group (Norm Hall)
1500 – Spatial contraction analysis (Jeremy Prince)

1600 – Afternoon tea

1630 – Day 1 discussion and synthesis: Re-examining the hypotheses and core uncertainties (Jeremy Prince, Facilitator)

1730 – Adjourn

Day 2, Wednesday, 12 October 2005

Evaluating the hypotheses and decision support systems

0900 – Review of the status of alternative hypotheses – Why did banana prawn catches decline? (Facilitator: Jeremy Prince)

- Results from analytical approaches
- Industry perspectives
- Remaining uncertainties

1030 – Morning tea

1100 – Management options and decision support systems (Facilitator: Jeff Dambacher)

- Structure
- Actions
- Data needs/outputs

- Thresholds/targets

1230 – Lunch

1300 – Breakout groups

1430 – Reports from breakout groups

1530 – Afternoon tea

1600 – Plenary summary of hypothesis evaluation, management options and decision support systems

1700 – Adjourn

Day 3, Thursday, 13 October 2005

Outlining management strategies and future research

0900 – What management actions and research projects could address remaining uncertainties? (Tom Okey, Facilitator)

- NORMAC Future Options Working Group Proposal
- Directed research (further analysis, modelling, field sampling)
- Other informative management actions

1030 – Morning tea

1100 – Working groups on future activity outlines

1230 – Lunch and adjourn meeting

1330 – Working groups (continue)

1430 – Working groups report back

1500 – Summary and wrap up (Neil Loneragan, Facilitator)

6.2 Working Group Abstracts and Abbreviated Reports

6.2.1 Reproductive dynamics of the banana prawn – Tonya Van der Velde *et al.*

Seasonal, spatial, and interannual variability in the reproductive dynamics of the banana prawn, *Penaeus merguiensis* de Man, in Albatross Bay, Gulf of Carpentaria, Australia[1]

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Abstract

The reproductive dynamics of *Penaeus merguiensis* de Man were investigated in the Albatross Bay region of the Gulf of Carpentaria, Australia from March 1986 to March 1992. Approximately 1,923 trawls were carried out over 66 monthly sampling surveys, with a total of 102,497 prawns caught of which 52,418 females were examined. An index of population egg production; calculated from female abundance (no. ha^{-1}), the proportion of females spawning (% ripe), and fecundity according to body size (mm CL); was used as an indicator of reproductive output. Egg production was seasonal with a spring spawning (Aug-Nov) and a late summer-autumn (Jan-Mar) spawning; giving rise to two clearly apparent cohorts, annually. Egg production was highest in autumn (6-month old spawners), due to the high abundance of new recruits, with another peak in spring (12-month old spawners) after the intense fishing period from April and May. Surprisingly, the relatively small number of eggs and larvae from these large 12-month old individuals are responsible for the single annual pulse of recruitment to the commercial fishery in summer and autumn 3 to 6 months later. The reason the large late summer/autumn spawning does not recruit inshore is because eggs and larvae are released too far offshore to be delivered to adjacent estuarine nursery grounds. The small numbers of larvae that do reach the nursery grounds during this period have poor survival because of less favorable nursery grounds conditions, mainly due to the low salinity and cooler water temperatures. However, during spring, the population of banana prawns (including the spawners) moves into very shallow waters, (8 to 15 m depth) close to nursery habitats. This spawning area within reach of the nursery habitat is defined as the “effective spawning envelope”.

Keywords: Penaeid shrimp, effective spawning, fecundity, egg production

[1] The full manuscript is in Appendix IV-1.

6.2.2 Qualitative Modelling – Jeff Dambacher

Qualitative Modelling of the Weipa Banana Prawn Ecosystem and Fishery2

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Introduction

This is a summary of a study that reports on qualitative analyses of banana prawns and their ecosystem to better understand why the level of banana prawn catch has recently declined in the Weipa region of Australia's northern prawn fishery. Qualitative ecosystem models are described and developed from first principles based on simple relationships between banana prawns, their food and predators, and a bottom-trawl fishery. The models are intended to investigate the potential dynamics of the banana prawn ecosystem and fishery in terms of a wide array of potential factors that might have led to the decline in catch. These analyses are developed along the lines of how an ecosystem might respond to changes in the environment or the fishery, and also it's potential for stability.

An array of possible explanations has been considered over the course of this study, and seven hypotheses remained as viable explanations for a decline in catch:

- Fishing has caused a collapse in banana prawn recruitment (to adult sizes)
    a. Recruitment overfishing (H1)
    b. Indirect trophic effects of fishing (H8)
- An environmental change has caused a collapse in banana prawn recruitment (to adult sizes)
    c. Direct effects of environmental change on banana prawns (H3)
    d. Indirect trophic effects of environmental change (H9)
- Adult prawns are still abundant, but fishers cannot find or catch them because
    e. The fleet has lost searching power (H2)
    f. Adult prawns are staying inshore (H4)
    g. Adult prawns are no longer schooling (H5)

The purpose of this work has been to draw together what is known about the banana prawn's biology, ecosystem, and fishery within a qualitative modelling framework that, in a rigorous manner, allows us to organize our thinking about how the system works. From this knowledge relatively simple models are developed that are used to explore the possible dynamics of the system, and from which we can hopefully increase our understanding, distinguish what is likely behaviour of the system from what is not, and to pose new and testable hypotheses for future management and research efforts.

Figure 6-1 is an example of how basic elements of the system can be portrayed qualitatively through sign directed graphs, or signed digraphs, where circles represent system variables, and links portray direct effects transmitted between variables. Positive effects, such as food for a predator, catch for a fishery, or recruitment for a juvenile life stage, end in an arrow, and negative effects, such as predation or harvest mortality, end in a filled circle. Each signed digraph represents the qualitative aspects of a system of differential equations, and analyses proceed by analysis of matrices via linear algebra (*i.e.* Dambacher *et al*. 2002, 2003a & b,

[2] The full manuscript is in Appendix IV-2.

2005), however, in this précis we have omitted all equations and matrices, providing instead a general summary of the main findings.

Banana prawn ecosystem

In developing qualitative models, we started with simple models for the prawn life cycle and then built in links to environmental influences, and subsystems involving food resources, predators, and fishery harvest. From the basic building blocks in Figure 6-1 a model of the whole system is constructed based on the four life stages of the banana prawns (Figure 6-2). This full model incorporates impacts from the fishery and effects of an array of environmental and habitat related factors that are thought to be important to the survival and reproduction of banana prawns in the Weipa region (Table 6-1). The full model is built around four prawn life-stages, conforming to what Dall *et al.* (1990) classify as a Type II life history — *i.e.* spawning takes place in marine waters and juvenile prawns live in estuarine waters. Banana prawn postlarvae settle in mangrove-lined estuaries, and juveniles are euryhaline and can tolerate low salinities (down to 5 ppt) in the upper reaches of rivers (Vance *et al.* 1990, 1998). Near the end of their juvenile stage, banana prawns migrate to inshore demersal habitats, and as adults live in deeper offshore areas. The migration of juveniles is influenced by prawn size, but can be triggered or accelerated by rainfall and associated effects on river flow and salinity (*i.e.* low salinities stimulate the migration of smaller prawns) (Staples and Vance 1986; Vance *et al.* 1998; Loneragan and Bunn, 1999). Spawning adults appear to move to shallow inshore areas near river mouths, but when early summer rains reduce inshore salinities, they move offshore to where they become available to the prawn fishery.

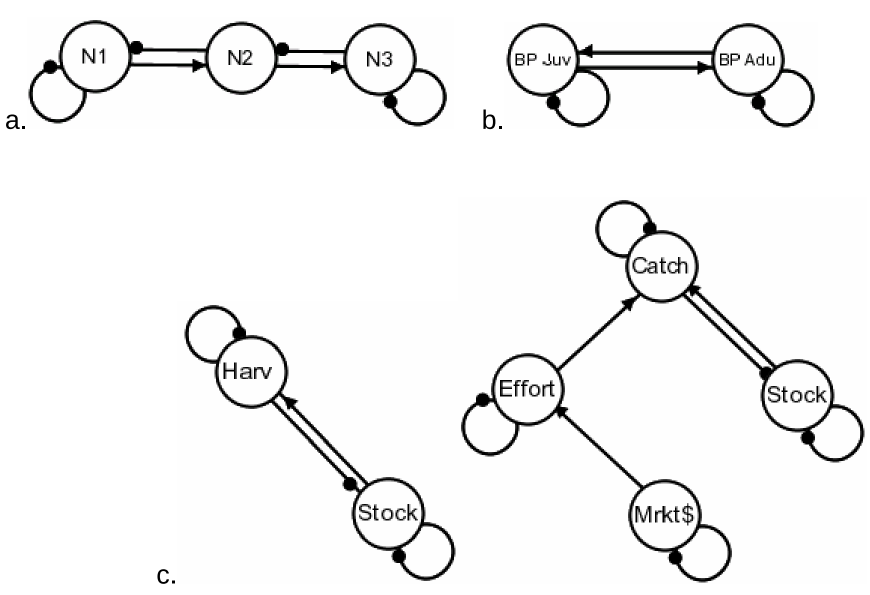

Figure 6-1:Signed digraph of: (a) minimum complexity model for Weipa banana prawn ecosystem, where banana prawns (N_2) are sustained by a food resource (N_1) and are consumed by a guild of generalist predators (N_3). Links between variables denote direct effects. Links ending in an arrow denote a positive effect, those ending in a filled circle denote a negative effect, and links connecting a variable to itself denote self-effects. In (b) the banana prawn (BP) variable has been split into a multiple life-stage model with juvenile (Juv) and adult (Adu). In (c) is a signed digraph model of a fishery harvest (Harv) variable and fish stock and an equivalent model where the harvest variable is split into a subsystem of catch, effort (boat days) and market price (Mrkt$), which is controlled by a global market.

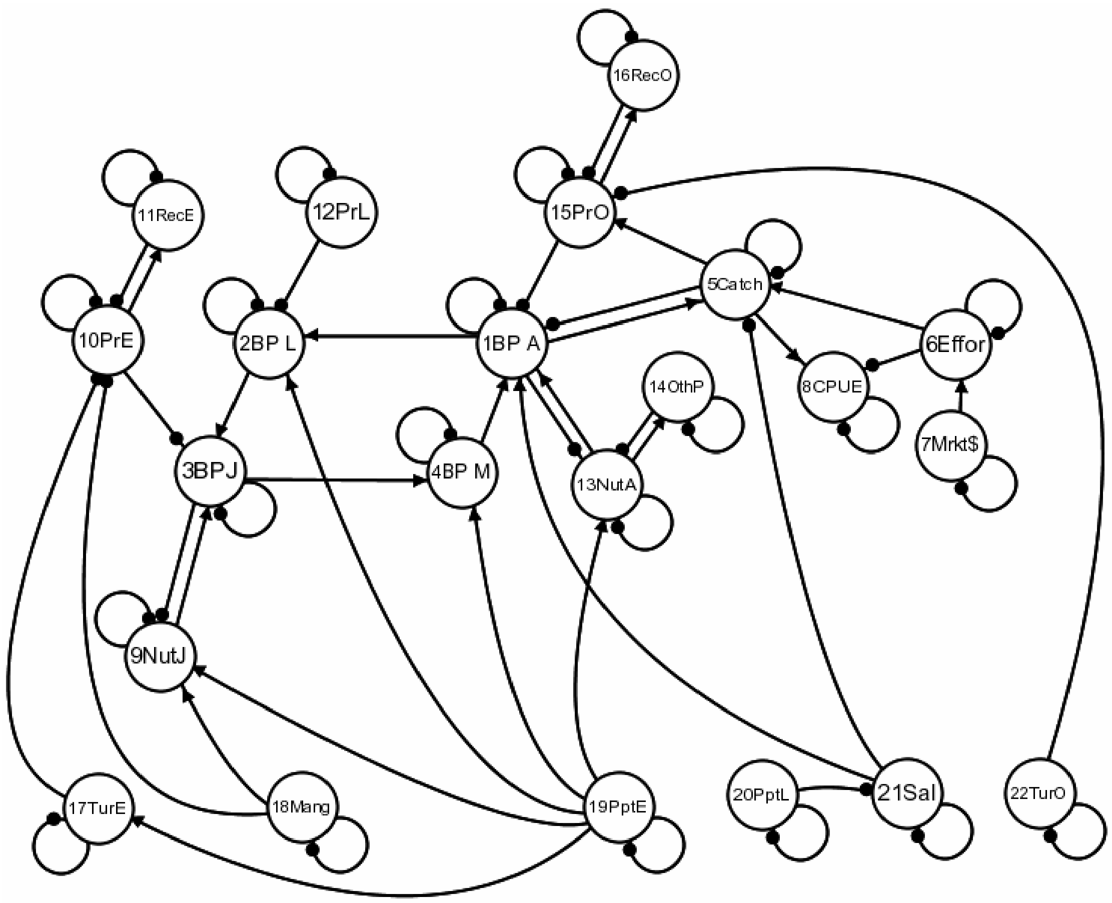

Figure 6-2: Signed digraph of Weipa banana prawn ecosystem, where numbers 1 to 16 represent biological and fishery harvest variables and numbers 17 to 22 are direct effects of physical and biological factors: 1. adult banana prawn, 2. juvenile banana prawn, 3. larval banana prawn, 4. migrant banana prawn, 5. catch of banana prawn, 6. fishery effort, 7. market price for banana prawn, 8. catch per unit effort, 9. juvenile banana prawn nutrition or food, 10. predation pressure in estuary, 11. recreational estuarine fishing, 12. predators of larval banana prawn, 13. adult banana prawn nutrition or food, 14. other prawn species, 15. predation pressure in ocean, 16. recreational ocean fishing, 17. estuarine turbidity, 18. mangrove habitat, 19. early or summer rainfall, 20. late or autumn rainfall, 21. near-shore salinity, 22. ocean turbidity.

The full model includes specific resources and predators for individual life stages, and recreational fisheries for top predators in both the estuary and ocean. Since banana prawns constitute a relative minor portion of the system's biomass and an equally minor portion of the total annual food resource of their predators (Salini *et al.* 1990), changes in their abundance are assumed to have a negligible effect on the biomass of their predators. Therefore the model omits a positive link between banana prawn life-stages and their predator variables. Other prawn species (*e.g.* tiger prawns) have been included as a potential competitor for food resources. The banana prawn fishery is shown with the added effect of discarded bycatch increasing local predation pressure on adult prawns, primarily through sharks (Hill and Wassenberg 1990, 1992, 2000). A response variable CPUE (no. 8) has been added to track changes in catch per unit effort. Variable no.'s 17 to 22 represent an array of environmental and biological effects that are known or suspected to influence the banana prawn ecosystem (Table 6-1).

Table 6-1: Links between environmental factors and biological variables in the Weipa banana prawn ecosystem model of Figure 6-2, where effects are listed as “from” and “to” the factor or variable

Factor or variable no.		
From	**To**	**Effect**
1	15	Adult prawns are a minor component of predator diet in marine waters, positive effect negligible.[†]
2	12	Postlarval prawns are a minor component of predator diet in the estuary, positive effect negligible.[†]
3	10	Juvenile prawns are a minor component of predator diet in the estuary, positive effect negligible.[†]
5	15	Shark consumption of discards increases local predation pressure.[‡]
17	10	Turbidity interferes with predator foraging in the estuary.[*, ††]
18	9	Mangroves trap and retain nutrients.[§]
18	10	Mangroves provide refuge from predators and cover in the estuary.[§]
19	2	Summer rainfall increases larval prawn food supply in marine waters.[*]
19	4	Summer rainfall increases prawn migration from estuary.[*, ††]
19	9	Summer rainfall increases juvenile prawn food supply.[*]
19	13	Summer rainfall increases adult prawn food supply.[*]
19	17	Summer rainfall increases turbidity.[*]
20	21	Autumn rainfall decreases near-shore salinity.[*]
21	5	Decreased near-shore salinity increases movement of prawns to fishing grounds, which influences prawn catchability.[*]
21	1	
22	15	Turbidity interferes with predator foraging in marine waters.[*, ††]

[†]: Salini *et al.* (1990).

[‡]: Hill and Wassenberg (1990, 1992, 2000).

[*]: Vance *et al.* (2003).

[§]: Manson *et al.* (2005).

[††]: Dall *et al.* (1990).

Given these general descriptions of relationships between system variables and environmental factors, it is possible to analyse the potential for stability in the system and to predict how the model system will response to either natural or human caused disturbances. These analyses can address how the system might behave due to changes in discard practices, fishing pressure, or drought cycles. Qualitative predictions of system stability and perturbation response are based on analysis of the feedback properties of the system, which depend entirely on how relationships portrayed in the signed digraphs.

The stability properties of the model in Figure 6-2 was shown to depend on a feedback cycle that included banana prawns, their fishery, and their ocean predators (*i.e*. BP A→ Catch→ PrO⊸ BP A). It is suggested that instability in this system can arise when discarded bycatch from the prawn fishery supports a relatively high level of predation pressure on banana prawns and when the statutory limitation of the fishery is weak. Other model configurations were analyzed that also depended on the prawn fishery exhibiting strong self-regulation for the whole system to be stable.

The response of the system to perturbation was investigated through various scenarios that involved environmental factors, such as level of rainfall, and the influence of the fishery. An important conclusion from these model results was that change in catch per unit effort (CPUE) will not necessarily function as a reliable indicator of a change in stock abundance. A high level of early season rainfall is predicted to increase the abundance of all life stages and also to increase CPUE in the fishery. Conversely, high levels of late season rainfall are predicted to suppress the abundance of all life stages of prawn, although the direction of change in CPUE is ambiguous. Thus the model predicts that the correlation between prawn abundance and CPUE will be positive when the perturbation is through increased early rainfall, but it can be either negative or positive for an increase in late season rainfall. A number of alternative models (not shown in this précis) were developed based on different assumptions about the trophic relationships in the system and the basic behavior of the fishery. Interestingly, all models generally gave consistent results and different only in the level of ambiguity for some response predictions. Two alternative models were constructed that explored overfishing and local concentration of fishing effort in the Weipa region (*i.e.* where effort follows local catch). Stability in both of these models depended on the fishery being sufficiently regulated, and both predict stock depletion for any input to the fishery variable.

Harvest subsystem

Lastly the allocation of fishery effort was investigated in a fishery harvest model that explicitly incorporated relative differences in benefit-cost ratios between different regions of the Gulf of Carpentaria. Allocation of fishing effort in the Northern Prawn Fishery has been described as possibly being a case where fishing effort follows change in local catch, but is also determined by relative differences in benefit-cost ratios between fishing in different regions of the Gulf of Carpentaria. We explored the dynamics between the prawn fishery in the Weipa region and other regions in the Gulf via an eleven variable model (Figure 6-3) that examines the effect of opportunity costs for fishing “here” versus “there” – *i.e.* with “here” being the Weipa region and “there” being elsewhere in the Gulf of Carpentaria. Since Weipa is the most northerly fishing region in the gulf, relocation to another region exacts a relatively long travel time and high fuel cost. In addition, turbidity in Weipa is usually too great to permit use of spotter planes to locate prawn aggregations, a technique commonly used to great advantage by the fishery in other regions. Hence, a boat operator deciding to remain in the Weipa region must weigh the benefit and cost of its catch in Weipa against opportunity costs for not fishing elsewhere. This model has a positive feedback cycle between catch and effort, but here via an intermediate variable (no. 9: B/CH) that allocates effort based on the benefit-cost ratio for the Weipa region.

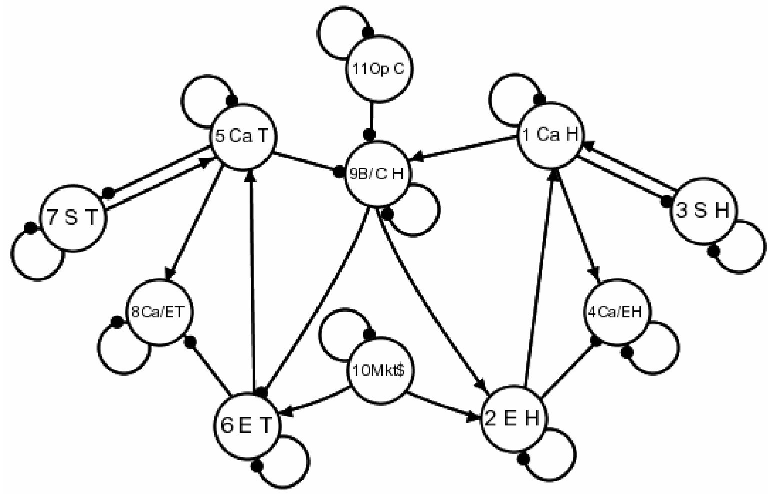

Figure 6-3: Qualitative model of effort allocation and opportunity cost for the Weipa region of Australia's Northern prawn fishery. Effort (E), in boat days, is allocated to the Weipa region, *i.e.* "here" (H) vs. other regions, *i.e.* "there" (T), in the Gulf of Carpentaria, depending on a benefit-to-cost ratio (B/C) for the Weipa region. This ratio is suppressed by an opportunity cost (Op C) for staying in Weipa region. Local prawn stocks (S) positively affect the level of catch (Ca) in each region, but catch in Weipa has a positive effect on the benefit/cost ratio, while catch from "there" suppresses this ratio. Effort in both regions is uniformly controlled by a global market price (Mkt$) for both domestic and wild caught prawns. Catch per unit effort (Ca/E) is included as a response variable for each region.

In general, any cause acting to reduce the catch of prawns in Weipa was reinforced by the positive feedback between effort and catch embedded in the harvest subsystem, thereby causing a shift in the location of fishing effort away from the Weipa region. Here again, a change in CPUE was not predicted to be necessarily correlated with a change in local stock size, as CPUE could either increase or decrease with a stock size depending on the strength of interactions in the system.

Summary

Predictions from the qualitative models developed in this study were generally consistent with the hypotheses considered as potential explanations of why the catch of banana prawns has declined in the Weipa region. The first hypothesis, that catches are low because of over harvesting banana prawns, was accounted for in alternative models that explored overfishing and local concentration of fishing effort. The second hypothesis, that an environmental effect was responsible for the low catches, can be considered through specific perturbations to the full model (Figure 6-2). The three hypotheses that catch has declined because the fishery can no longer find or catch prawns can be addressed in a number of ways. A decline in the searching power of the fleet is implied in Figure 6-3, which incorporate a positive feedback between effort and catch. This model accounts for this phenomenon as a trade-off in opportunity cost and catch levels in the Weipa region versus other regions in the Gulf. The hypothesis that adult prawns are staying inshore and are less available to the fishery can be accounted for in the full model in Figure 6-2 through a negative input to autumn rainfall, and in the five alternative models simply as a negative input to the harvest variable or subsystem. The hypothesis that banana prawn adults no longer aggregate is equivalent to the hypothesis that prawns are remaining inshore, as both deal with effects that reduce prawn catchability, thereby increasing prawn abundance and decreasing prawn catch.

A general conclusion from the analyses of all of the models is that system stability requires that the fisheries behave in a self-regulated manner, either through limitations in effort or catchability. Another important finding from this study is that a change in CPUE will not necessarily be correlated with a change in the size of the banana prawn stock. Thus, interpretations of long term changes in catch and effort data should consider whether there has been a change in prawn catchability, and whether effort has fallen in the Weipa fishery as a result of regional economic pressures. The models developed within this work can be viewed as a first attempt to provide a conceptual framework for understanding the dynamics of the Weipa banana prawn ecosystem and fishery. The simple models developed are not meant to be an endpoint, but rather a first means of comparison and a basis for future work.

Acknowledgements

This work is a product of many rewarding collaborations with workshop participants, for which the author is very grateful. Neil Loneragan provided useful suggestions and comments to a previous draft of this manuscript.

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6.2.3 Stock Assessment – Norm Hall *et al.*

The potential impacts of exploitation and environment on recruitment to the stock of banana prawns at Weipa[3]

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Abstract

Estimates of daily catch per unit of effort (CPUE) for the banana prawn stock at Weipa were calculated using logbook data for two core regions containing grid cells that had been consistently fished during the history of the fishery. The daily catch data for each year were subjected to virtual population analysis (VPA), under the assumption that no prawns survived at the end of each year and the correlations between the resulting population estimates and the daily CPUE data were calculated. Applying the Bonferroni correction, 15 of the resulting 34 correlation coefficients were found to be statistically significant, suggesting that the daily CPUEs could be employed as an index of abundance. However, very considerable variation in CPUE at any population size was evident in many of the results. It is likely that such variation is due to the aggregating behaviour of the banana prawns and the ability of fishers to detect and fish aggregations. Thus, although the CPUEs can be employed as a proxy for abundance, they are highly imprecise.

The daily catch and CPUE data were subjected to a tuned VPA, with both catchability and terminal biomass being estimated as parameters of the model. The resulting estimates of recruitment and spawning biomass were used, in combination with time series of rainfall, temperature and wind data, to explore whether recruitment was affected by spawning biomass and/or the effects of those environmental variables. The data provided strong support for the hypothesis of constant recruitment, considerably weaker support for the hypothesis that recruitment was affected by spawning biomass and essentially no support for hypotheses that recruitment was affected by the environmental variables either separately or in combination with spawning biomass. The analysis suggested that recruitment had declined since the early 1970s, remained highly variable but stable till 1997, before declining to low levels between 2000 and 2003 and possibly showing a slight recovery in 2004. No obvious trend was discernable in spawning biomass estimates. A depletion analysis, based on similar assumptions to the tuned VPA, was fitted simultaneously to the daily CPUE data for all years and produced results consistent with the finding of the tuned VPA that spawning biomass and the environmental variables appeared to contribute little towards improving the fit of the model to the data beyond that obtained by assuming constant recruitment.

The fact that there was insufficient information in the data to demonstrate a relationship between recruitment and spawning biomass and/or the environmental variables cannot be used as evidence that no such relationship exists. The imprecision of the CPUE data for banana prawns is likely to mask any signal of such a relationship in the data. Accordingly, in accordance with the precautionary principle, it would be prudent to manage the fishery under the assumption that such a relationship between spawning biomass and recruitment exists and

[3] The full manuscript is in Appendix IV-3

[4] Modelling of the fishery benefited greatly from the input and criticism of the Working Group, however the Group has not had the opportunity to critically review the final modelling results. Errors and inadequacies of this section remain the responsibility of the compiler, N. G. Hall.

may have produced the apparent decline in recruitment observed in the banana prawn stock at Weipa since 2000.

Introduction

Both exploitation and environmental variation have been proposed as being implicated in many of the collapses that have been recorded for fisheries around the world. The impacts to marine ecosystems of the exploitation of various target species are now also increasingly recognized as factors that may affect the sustainability of fish stocks. Little wonder then that, with the decline in catches from the Albatross Bay (Weipa) stock of prawns reported in 2000 to 2004 by vessels from the Northern Prawn Fishery, there was concern that, although the decline might reflect changes in fishing practices, either changes to the ecosystem or environmental factors or due to the impact of fishing on spawning biomass had led to reduced recruitment. In response to this concern, a study was initiated to explore whether information existed in the available data that might identify the factor or factors responsible for the decline and, thereby, to determine the implications for fisheries managers of the apparent reduction in recruitment.

Assessments of the stocks of banana prawns in the Gulf of Carpentaria have long been hampered by the lack of a reliable index of abundance of the stock and the fact that the recruitment to the exploited stock of the principle cohort occurs over a number of weeks and the fishing season is very short. Since the commencement of the fishery, fishers have taken advantage of the large aggregations ("boils") of prawns that individuals of this species form. Thus, the recorded catches exhibit considerable stochasticity due to the changing and aggregated nature of the spatial distributions of the prawns, coupled with the success of fishers in detecting and fishing aggregations. Although aerial spotting is used to locate the aggregations of banana prawns in the south-eastern Gulf of Carpentaria, searching for aggregations at Weipa is undertaken by the individual vessels as part of their fishing operations. The resulting catches per unit of effort (CPUE) calculated from the recorded catch for each day of fishing by the different vessels operating at Weipa range from very low to very high, *e.g.* a median minimum CPUE of 46 $kg.day^{-1}$ to a median maximum CPUE of 846 $kg.day^{-1}$, and maximum range of 5190 $kg.day^{-1}$, calculated over consecutive 5-day periods from 1970 to 2004 (for core region 1 and optimistic estimates of CPUE (see below)). When coupled with the fact that, particularly in recent years, there are often few vessels fishing, estimates of the area and fleet-wide CPUE for the Weipa fishery reveal considerable variability. Whether these estimates of CPUE provide reliable indices of abundance is thus a crucial question if the estimates are to be used as the basis for stock assessment.

The component of the overall study reported here is that dealing with the assessment undertaken to determine whether the decline of banana prawn catches at Weipa since 2000 is an artifact of the reduced area of coverage and intensity of searching and fishing by the fishing fleet in recent years or is likely to reflect a decline in recruitment resulting from a reduction in spawning stock caused by exploitation and/or the influence of environmental variables. Before attempting such assessment, however, the data were examined to determine whether values of CPUE calculated for the fishery could be used as proxies for the abundance of the prawns in the stock.

Methods

Processed daily logbook data for each vessel that fished in the NPF from 1970 to 2003 were obtained from Janet Bishop, CSIRO, and subsequently for 1970 to 2004 from Roy Deng, CSIRO. These latter data had been processed using the new effort split algorithm developed by Bill Venables, and were filtered to extract the logbook data for banana prawns for the Albatross Bay (*i.e.* Weipa) stock.

A preliminary exploration of alternative fishery models for the banana prawn fishery at Weipa was undertaken using age-structured and biomass dynamics models that employed annual catch and effort data, delay-difference and depletion models based on weekly catch and effort data, and a virtual population analysis (VPA) that was applied to both daily and weekly catch data and which assumed a terminal abundance of zero and constant size of prawns. Examination of the results derived from analysis of the newly-extracted banana prawn data revealed that the results from an earlier stock assessment of the banana prawn data (Vance *et al.* 2003, Chapter 7) had been influenced strongly by an adjustment for fishing power that had been made to the data used in that study. Thus, the stock-recruitment relationships reported previously were affected by those fishing power adjustments. While a detailed review of relative fishing powers was not undertaken in the current study, the effect of fishing power changes on the unadjusted CPUE data was taken into account by estimating the value of catchability separately for each year, except for 2000 to 2004 (see below).

Consideration of the data requirements for the new assessment indicated that an estimate of an abundance index derived from the annual catch and the annual nominal fishing effort would be unreliable due to the highly seasonal nature of relative prawn abundance and the changes in fishing pattern and spatial distribution of fishing since 1970. An abundance index calculated from daily or weekly catch and nominal fishing effort would overcome the first two of these problems, but calculation of such an index would still need to account for changes in the spatial distribution of fishing. Examination of the logbook data revealed that, while a core group of 6×6 n.mi grid cells had been consistently fished; many cells had been infrequently or never visited (see manuscript in Appendix IV-4 by Jeremy Prince). Thus, to ensure that calculated values of the average catch per unit of effort (CPUE) were not biased through the influence of the data from such infrequently-fished cells, estimates were derived using data for only those grid cells within two core regions of the Weipa fishery that had been the basis of most catches and the majority of fishing. Of the 140 grid cells in the Weipa region for which a non-zero average annual catch had been recorded, core region 1 comprised 26 grid cells in which the average annual catch had exceeded ~5,000 kg, and core region 2 was based on a smaller subset of 19 of these in which the average annual catch had exceeded ~7,000 kg (see Table 1 of detailed report in Appendix). The maximum average annual catch recorded for any grid cell in this region exceeded 66 t.

An estimate of the total banana prawn catch (kg) for the entire Weipa region was calculated using the data from all grid cells and the 1970-2004 data set (i.e. the data based on the revised effort-split algorithm). The total daily banana prawn catch (kg) and fishing effort (vessel-days) were also calculated for each grid cell, and used to derive an estimate of the daily catch per unit of effort (CPUE) for that cell. An average of these daily CPUEs was then calculated for each core region using: (a) only data for grid cells that had been fished, thereby producing an "optimistic" estimate of CPUE (*i.e.* assuming fishers detect and fish in the grid cells containing the greatest abundance of prawns); (b) all grid cells with the assumption that the CPUE in the non-fished cells was zero, thereby producing a "pessimistic" estimate of CPUE; and (c) all grid cells with the assumption that the CPUE in the non-fished cells was equal to the minimum of the CPUEs recorded in the fished cells, thus producing an estimate that is "intermediate" between the optimistic and conservative estimates.

Virtual Population Analysis

A virtual population analysis (VPA) was undertaken using the daily catch data recorded in the logbooks and the optimistic catch rates derived from core region 1. For this, it was assumed that the instantaneous coefficient of natural mortality M (day^{-1}) was constant,

$$B_{d-1,y} = B_{d,y} \exp[M] + C_{d-1,y} \exp[0.5M] \text{ (Pope 1972, 1984),}$$

body size of prawns remained constant throughout the year, and the biomass at the end of the year was zero. $C_{d\,y}$ is the mass of prawns caught on day *d* of year *y*. Following Lucas *et al.* (1979), the estimated value of M is set to 0.05 week^{-1}, *i.e.* M=0.05/7 day^{-1}. The resulting daily biomass estimates were compared with the observed CPUEs to assess whether it was appropriate to use CPUE as an index of abundance.

The VPA was repeated, but allowing for an unknown terminal biomass and tuning to match the available CPUE data. Thus, this terminal biomass was estimated, together with catchability, by minimizing (for the period from day 81 to 213 of each year) the sum of squared deviations between the natural logarithms ($\log_e(x+1)$) of the CPUEs ($I_{d,y}$) and the estimates of those CPUEs, where the latter were derived using the assumption of constant catchability within the specified period each year and the observation model relating the estimated daily CPUE ($\hat{I}_{d,y}$) to the corresponding biomass

$$\hat{I}_{d,y} = q_y B_{d,y} \,.$$

As limited data were available for more recent years, and precluded reliable estimation of parameters through fitting the model independently to the data for each year, the models for 2000 to 2004 were fitted simultaneously to estimate the terminal biomasses and an assumed common catchability for these years. In essence, this represents an attempt to share information on catchability available from the combined 2000 to 2004 data. It should be recognized that, when considering results for this period, this assumption introduces additional imprecision.

After subjectively filtering to eliminate parameter estimates resulting from several extremely poor fits of the model to the CPUE data, the resulting estimates of recruitment were regressed against the estimates of spawning biomass and environmental variables. The time series of environmental variables used were the rainfall recorded in each month from November to May, the average, minimum and maximum temperatures recorded from August to October and from November to February, and the average alongshore and onshore components of the wind strengths recorded from September to November and from January to April within each year (Vance *et al.* 2003, Chapter 7). Following Somers and Wang (1997), who calculated an index of spawning biomass as the average number of female prawns in the population between August 1 and October 31, a period that represented the peak of the Spring spawning, an index of total spawning biomass (*i.e.* both sexes) was calculated as average weight of prawns over days 213 to 304 of the year

$$S_y = \frac{1}{92} \sum_{d=213}^{304} B_{d,y} \,.$$

Recruitment was assumed to be related to spawning biomass through a model of the form described by Beverton and Holt (1957), modulated by the impact of the environmental variables J_{oy}, *i.e.*

$$R_y = \left\{ \frac{aS_{y-1}}{b + S_{y-1}} \right\} \exp\left[\sum_j c_j X_{j,y} \right],$$

where a, b and c_j are parameters that can be estimated by minimizing the sum of squared deviations between the values of recruitment and the estimates derived from the above equation.

Four models were fitted and compared: (1) constant recruitment, where b and c_j were set to zero in the above equation. Thus,

$$R_y = a\,;$$

(2) recruitment related to spawning biomass alone, where c_j was set to zero for each environmental variable j. Hence,

$$R_y = \left\{ \frac{aS_{y-1}}{b + S_{y-1}} \right\};$$

(3) recruitment related to environmental variables alone, where b was set to zero. Accordingly,

$$R_y = a \exp\left[\sum_j c_j X_{j,y} \right];$$

and (4) recruitment related to both spawning biomass and environmental variables, *i.e.* no constraints on b and c_j in the above equation. Models were compared by calculating and comparing the small sample version of Akaike's Information Criterion (Burnham and Anderson, 2002), AIC_c, where the conventional value of this Criterion is calculated as

$$AIC = n \log_e\left(\frac{SS}{n} \right) + 2p$$

and is then adjusted to produce the small sample version of the Criterion,

$$AIC_c = AIC + \frac{2p(p+1)}{n - p - 1}$$

and where SS is the sum of squares, n is the number of observations, and p is the number of parameters (including the estimate of the variance of the residuals). Use of the small sample version is preferred when $n/p <$ *ca* 40. The model which produces the smallest value of the AIC is considered to be the best of the alternative models. However, the data may also support, but not to the same extent, others among the set of alternative models. To explore the weight of evidence supporting each of the candidate models, AIC differences were calculated as

$$\Delta_j = AIC_{c_j} - AIC_{c_{\min}}$$

where the subscript j refers to model number j. Akaike weights were then calculated as

$$w_j = \frac{\exp(-0.5\Delta_j)}{\sum_k \exp(-0.5\Delta_k)}.$$

A depletion model with non-informative priors was also developed (see full report in Appendix IV-3). This model was based on very similar assumptions to those of the tuned VPA, but optimized a penalized log-likelihood function (*i.e.* a combined log-likelihood of the data given the parameters and of the parameters given prior probability distributions) rather than the sum of squared deviations of the logarithms of the CPUEs, when fitting the model to the data. The results were similar to those produced by the tuned VPA. Accordingly, the depletion model shall not be discussed in detail in this report.

Results

Prior to 1980, the number of days each year for which non-zero catches of banana prawns from Weipa were recorded in logbooks typically exceeded 50 (Figure 6-4). In the subsequent period, to 1997, the number on non-zero catch days had reduced to approximately 30 per year. However, the number of such days declined to approximately 11 between 1998 and 2000, before falling to 4 in 2001, 5 in 2002 and 1 in 2003, then recovering slightly to 10 in 2004. The duration of the period over which the majority of the annual catch of banana prawns at Weipa were caught, calculated as the number of days required to take an additional 90% of the annual catch following the capture of the first 5% of the annual catch, followed essentially the same trend as the number of non-zero catch days. It should be noted that both variables are constrained by the opening and closing dates imposed by fishery managers.

Virtual population analysis using assumption of zero terminal biomass

For earlier years until 1984, when the opening date of the banana season was changed to approximately 1 April, the estimates of abundance calculated using the VPA show a relatively slow decline at the start of each season before the prawns become vulnerable to the fishery (see full report in Appendix IV-3). Noting that it was assumed for the VPA that body size of prawns is constant; this decline reflects the impact of natural mortality. Subsequently, as the prawns become vulnerable to fishers, the abundance declines rapidly as a result of relatively heavy exploitation. The rate of decline decreases towards the end of the banana season, presumably as fishing effort is reduced. The decline that occurs when the prawns become vulnerable to the trawlers appears to have become more rapid in the 1980s and 1990s, as is reflected in the reduced number of days required to take the major portion of the catch (Figure 6-4).

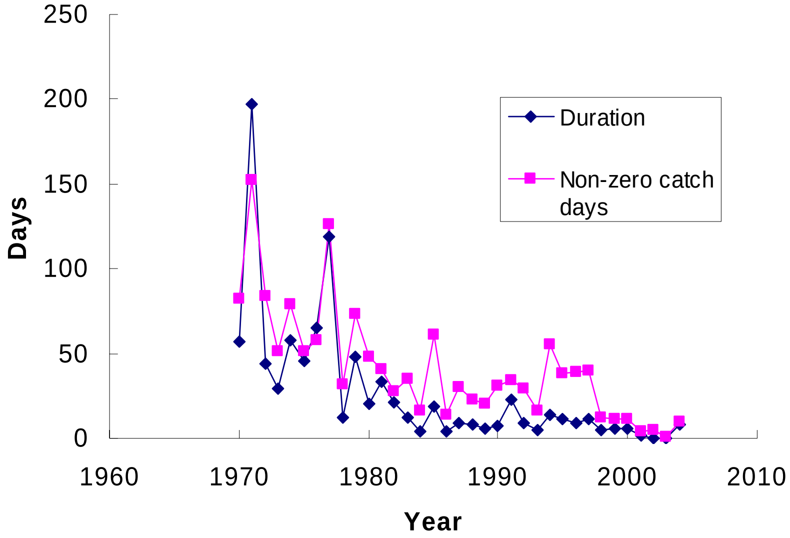

Figure 6-4: The period following the capture of the first 5% of the catch required to take the next 90%, and the number of non-zero catch days recorded in the logbook data.

The highly variable nature of the CPUE data for banana prawns is characteristic of the fishery at Weipa, reflecting searching for and capture of individuals of a species that are often highly aggregated. The population estimates obtained from the VPA were plotted against estimates of daily CPUE (Figure 6-5) to assess the adequacy of the assumption that CPUE could be used as an index of abundance, *i.e.* whether CPUE is linearly correlated with the intra-annual population estimates. Although there appeared to be a general tendency for CPUE to increase with population abundance, the data frequently exhibited considerable scatter. While for some years the correlation appeared relatively strong, for many, it was poor. In years in which recruitment to the fishery may have been delayed, a number of low values of CPUE were recorded for days in which a large population was estimated to be present. In others, high CPUEs were recorded later in the season when the predicted abundance was low, presumably resulting from the detection by fishers of an aggregation of banana prawns that was subsequently fished.

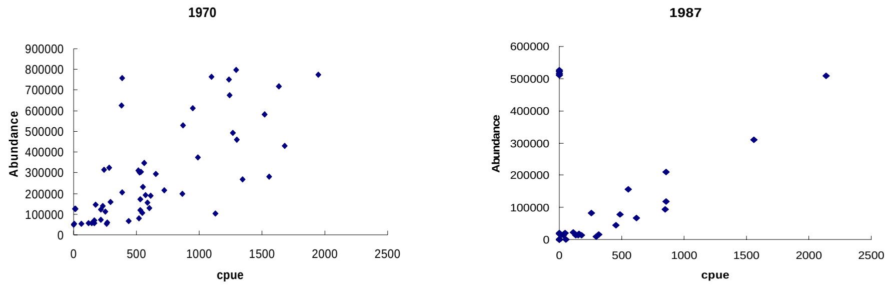

Figure 6-5: Relationship between the abundance of banana prawns at Weipa estimated using virtual population analysis of daily catch data and the recorded daily CPUEs for 1970 and 1987.

Twenty five of the 34 correlation coefficients for the years 1970 to 2002 and 2004 calculated using the predicted daily abundances and the recorded daily CPUEs were found to be statistically significant ($P < 0.05$), and 15 of these were less than $P = 0.05/34$, the critical level calculated using the Bonferroni correction for multiple comparisons. It should be noted, however, that the data for the two variables used when calculating the correlation coefficients are not independent.

Tuned virtual population analysis using estimate of terminal biomass

The results obtained from the tuned VPA that estimated the terminal biomass rather than assuming it to be zero were mixed, presumably reflecting the adequacy of the CPUEs as indices of abundance. While reasonable results were obtained for some years, those for other years illustrated the difficulty associated with fitting the model to CPUE data that contain a mixture of both low and high values over a relatively short period of days during which the abundances of prawns should have been approximately similar. For several years, the estimates of terminal biomass were so high and the catchability so low as to be infeasible. Such years were filtered from the estimates of recruitment and spawning biomass before attempting to fit the various stock-recruitment relationships.

The results obtained from the virtual population analysis indicated that recruitment had declined from the high values experienced in the early 1970s to become variable but relatively stable from 1973 to 1999 (Figure 6-6). Subsequently, it declined to very low values between 2000 and 2003, but appeared recover slightly in 2004. A considerable number of low values were apparent in the values of spawning biomass that were estimated by the model, but no obvious trend was detected (Figure 6-7). It should be noted, however, that these estimates are likely to be imprecise as they represent an extrapolation by the model to days 213 to 304 and thus lie outside the period used when fitting the model, *i.e.* days 81 to 213.

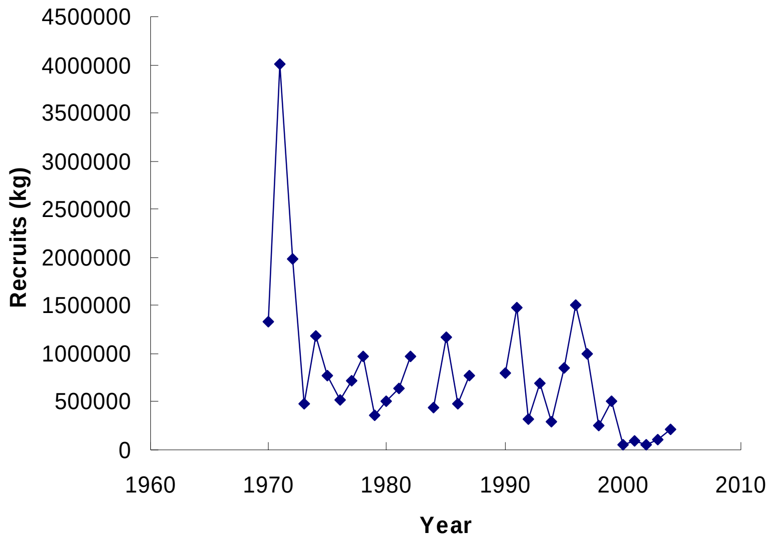

Figure 6-6: Estimates of recruitment of banana prawns at Weipa derived from the tuned VPA.

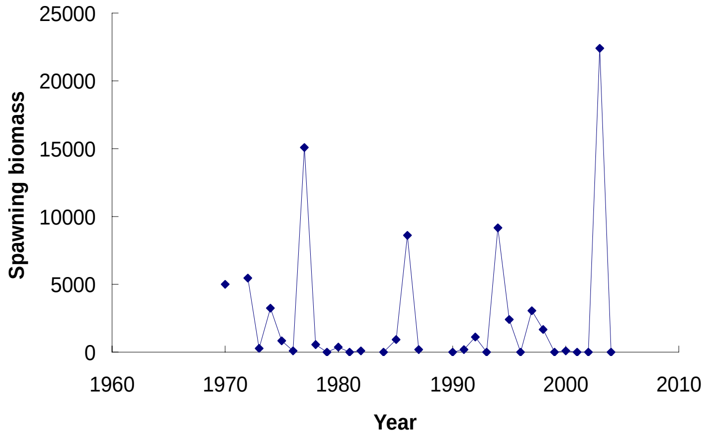

Figure 6-7: Estimates of spawning biomass of banana prawns at Weipa derived from the tuned VPA.

The model that produced the lowest value of AIC_c was the constant recruitment model. The data provided essentially no support for the models that incorporated the effects of the environmental variables, however there was some support for the model which assumed recruitment to be related to spawning biomass ($\Delta = 2.12$). The weight of evidence in favour of the constant recruitment model ($w = 0.74$) was, however, almost three times greater than that for the model that assumed a relationship with spawning biomass ($w = 0.26$).

Discussion and conclusions

Although there appears to be a relationship between the daily CPUEs recorded for banana prawns at Weipa and the underlying abundance of those prawns, there is considerable variation in the values of CPUE that might be observed for any given population size. The fact that the individuals of this species form large aggregations, and that fishers have the ability to locate and exploit these aggregations, explains much of this variability. While pooling of data over vessels, time and space would be typical methods of producing CPUE data with greater precision, the limited duration of the current fishing season at Weipa, coupled with the paucity of daily CPUE observations, allow the application of these approaches in only a very limited way. Although CPUEs have been calculated for two core regions in which fishing has historically occurred, the daily data for each region are often limited to a few vessels within a limited number of fishing grids. Thus, despite the attempt made to accommodate changes in the spatial distribution of the fishing fleet at Weipa, the resulting CPUEs remain imprecise, possibly explaining why the results of the depletion analysis were not markedly affected by the choice of core region employed when calculating CPUEs for the region.

Neither the tuned VPA nor the depletion model (see full report in Appendix IV-3) provided sufficient evidence to demonstrate a clear relationship between recruitment and the associated spawning biomass. Although the tuned VPA indicated some support by the data for such a relationship, the weight of evidence in favour of a constant recruitment model was approximately three times greater than that favouring a stock-recruitment relationship. While the results obtained from the tuned VPA indicated that recruitment between 2000 and 2003 was low, and that there had been a slight recovery in 2004, similar conclusions could not be drawn from the depletion analysis (see full report in Appendix IV-3). It should be noted that, in this study, the annual spawning biomass was calculated as the average biomass for days 213 to 304 for the entire Weipa region, not the biomass within the specific portion of this region that has been suggested as being likely to provide optimal conditions for effective spawning.

Results from the tuned VPA revealed essentially no support for the hypothesis that recruitment estimates had been affected by environmental variables. The depletion analysis suggested that, if any such impact was present, it would have resulted in higher recruitments in the early 1970s and in 1999 (see full report). There was no indication that environmental factors might have adversely affected the recruitment during the early 2000s.

Although the results from the tuned VPA provide no evidence of a strong relationship between recruitment and spawning biomass, the values of the AIC indicate some support for this hypothesis (*i.e.* $w = 0.26$). Recruitment to the banana prawn stock at Weipa appears highly variable and, although the recruitment for 2000 to 2004 appears markedly lower than earlier recruitment levels, there appears to be no indication of a declining trend in spawning biomass. Could the apparent decline in recent recruitment be attributed to an impact of fishing on spawning stock and, despite low levels of fishing effort, subsequent failure to recover due to low levels of recruitment? While it is feasible that a reduction of spawning biomass through fishing could have impacted the stock to produce the observed decline in recruitment, this could not be demonstrated with the data that are available for the banana prawn fishery at Weipa. It is also possible that environmental factors, acting either alone or in combination with the effect of fishing on spawning biomass, were implicated in the decline. Again, there is no evidence in the available data that this was the case. The highly variable and imprecise CPUEs provide insufficient information regarding the factors that affected recruitment to demonstrate that either spawning stock or environment affected recruitment. More importantly, however, there was insufficient power in the analysis to conclude, with confidence, that recruitment was not affected by a reduction in spawning biomass resulting from fishing and/or the effect of environmental factors. In the absence of such evidence, it remains appropriate to manage the fishery in accordance with the precautionary principle, *i.e.* under the assumption that recruitment is affected by a reduction in spawning biomass induced by fishing. Thus, appropriate strategies should be implemented such that, should the decline be due to the effects of fishing, recruitment of banana prawns to the Weipa region is allowed to recover to the levels experienced from the mid-1970s to the mid-1990s.

Models based on an improved depletion method have recently been developed at CSIRO and applied to data from several of the banana prawn fisheries of the Gulf of Carpentaria (Zhou *et. al*. 2007). These models, which incorporated stochastic fishing processes and allowed for overdispersion, provided a good fit to the data to which they were applied and offer a promising avenue for further studies.

Future research

There is little doubt that stock assessments for fisheries that exploit banana prawns are hampered by the lack of a long-time series of more accurate and precise indices of abundance. However, the survey data that have been collected over recent years are showing considerable promise and may provide such indices. The data available for other stocks in the Northern Prawn Fishery should be explored to determine whether they can offer information on the nature of the statistical distribution of the daily catches recorded by individual vessels and its relationship with the abundance of prawns within each stock. Such information would allow more appropriate use of the fishery data that are currently available. However, this distribution is certain to be affected by the nature of the searching process (aerial spotting or searching by vessel) and the impact of information “sharing” among fishers such that fishers converge to fish prawn aggregations that are detected. It is also likely to be affected by the abundance of prawns, the time within the year, the overall spatial distribution at that time and will presumably differ among stocks.

The typical types of logbook data, which are collected for most fisheries (*i.e.* catch, fishing effort, and location), are inadequate for a species that exhibits aggregations such as those evident for banana prawns in the Northern Prawn Fishery. There is a need to use the logbook data to consider the dynamics of the searching process and, for this, information on search time and fishing time need to be disentangled. We seek to determine information on the abundances of prawns both within and outside the aggregations, the abundance and characteristics of aggregations, and how catch statistics relate to the aggregated nature of the spatial distribution of prawns. A refined logbook accompanied by the collection of detailed GPS and data from the electronic equipment used by vessels when searching. An understanding of the overall distribution of aggregations for some stocks may be best obtained by analysis of the data collected when aerial spotters survey the stocks at locations such as Karumba, if access to such data can be negotiated. A detailed understanding of the changes in the overall spatial distribution of both prawns and fishers as the season progresses and as the banana prawns progress through their life cycle would also assist when attempting to interpret fishery statistics.

Acknowledgements

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6.2.4 Spatial Analysis – Jeremy Prince

Contraction of the banana prawn fishery of Albatross Bay in the Gulf of Carpentaria, Australia[5]

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Introduction

The catchability of a species (q - the proportion of a stock captured with each unit of effort) is very sensitive to the ability of fisheries to target aggregations as well as to factors that impact the ability of fishers to search for aggregations. The predictability of aggregation behaviour, particularly in the location of the aggregation in time and space, reduces the need to search, which increases catchability and thus the vulnerability of a stock to fishing as the stock size declines (Paloheimo and Dickie, 1964; Winters and Wheeler, 1985; Crecco & Overholtz, 1990; Hilborn and Walters, 1992; Prince, 1992).

Some species of prawns or shrimp, including the banana prawn (*Penaeus merguiensis*) form free-swimming aggregations although the reason for this behaviour is poorly understood (Munro, 1975; Somers, 1977; Dall *et al.*, 1990; Wassenberg & Hill, 1993). Fisheries for aggregating prawns are apparently prone to declines in catch (Kristjonsson, 1969; Marcelle, 1978; Van Zalinge, 1984; Penn, 1984; Mathews & Abdul-Ghaffar, 1986) and Penn (1984) argues that the targeting of aggregations is a factor making prawn fisheries prone to recruitment overfishing.

In this paper, we describe the contraction of the fishery at Weipa focusing on the relationship between catchability, stock area and stock size. The purpose of this analysis is to describe and highlight fishery dynamics we believe are suggestive of recruitment-overfishing.

Methods

Logbook data

We used processed daily logbook data for each vessel that fished in the NPF from 1970 to 2003, held by AFMA. The data have been analysed in a Microsoft Access database, and an ArcView Geographic Information System.

Time series trends

The average reported daily vessel catch rate (kg/day) from Weipa 1970 to 2003 was plotted against cumulative catch (kgs) for each year following the Leslie-Delury approach making it possible to estimate some index of catchability (the slope of the curve) and initial biomass available to the fishery from the intercept of the extrapolated line with abscise.

Normalized rank order curves

An alternative view of these spatial trends is derived through the use of ‘normalized rank order curves’ (e.g. Walters & Cahoon, 1985). The normalized rank order curves were also converted into a one dimensional ‘area index’ for each year, which is simply the total area under the normalized rank order curve of each year. The area index was calculated for each year in each stock region. The area index has also been plotted against total catch in each year for Weipa.

[5] The full manuscript with all figures is in Appendix IV-4.

Results

The estimated slope from the Lesley-Deluury analysis (Figure 6-8) increased gradually from between 0.0007 and 0.0041 during the first half of the 1970s to between 0.0060 and 0.0240 during the last half of the 1990s, suggesting that catchability may have increased by five to ten times. Plotting estimates of catchability against estimates of biomass suggests a negative relationship exists with catchability increasing as biomass declines (Figure 6-10).

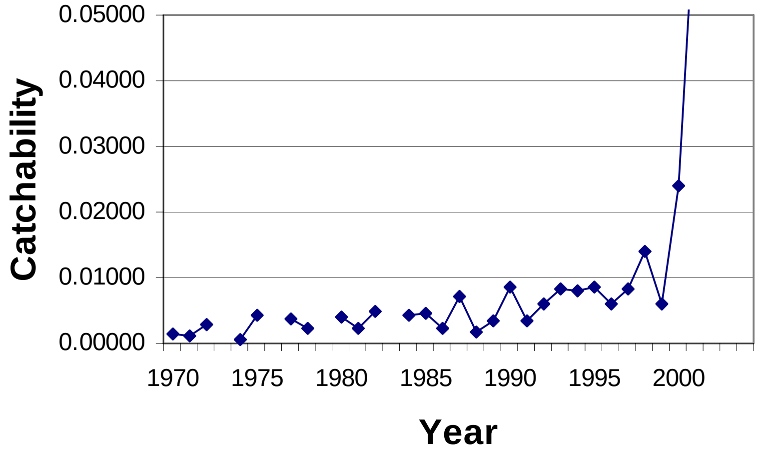

Figure 6-8: Estimated trend in catchability (q) in Albatross Bay 1970 to 2004; estimated from the slope of the seasonal trend in average daily catch rate versus cumulative catch through each season.

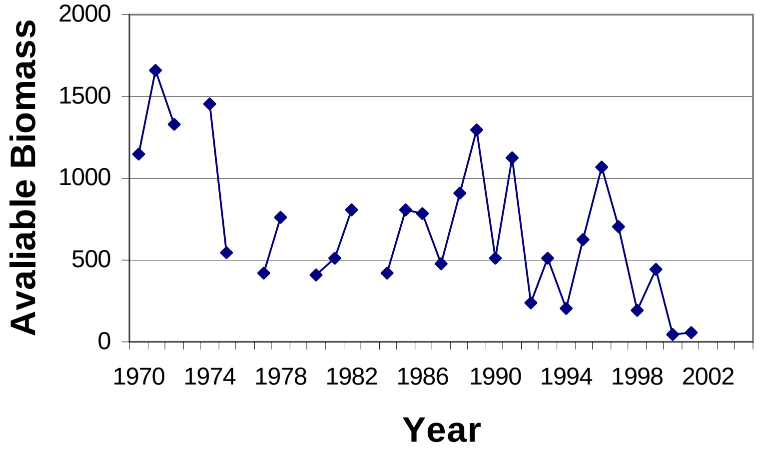

Figure 6-9: The estimated trend in available banana prawn biomass (t) in Albatross Bay 1970 to 2004.

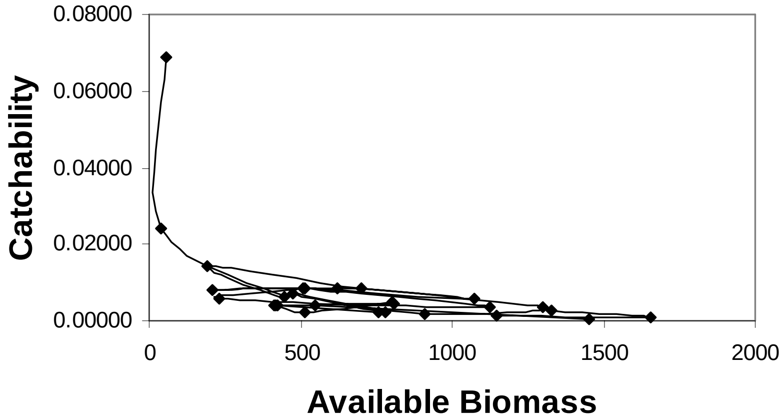

Figure 6-10: The plotted relationship between estimates of available banana prawn biomass (t) in Albatross Bay 1970 to 2004 plotted against estimates of catchability (q) in each year.

Figure 6-11 shows that catches have remained localized within the same area of Albatross Bay since 1970 and that catches have contracted towards the centre of that area. The normalized rank order curves presented in Figure 6-12 formalize the trend mapped in Figure 6-11 indicating greater dispersion of the catch in the earlier years of the fishery and an increasingly concentrated fishery in later years. Through the variability the progression over time is conspicuous. Years of widespread fishing became increasingly intermittent through the decades until recently when low catches are consistently taken from a very small area at the centre of the original fishing grounds. Our Rank Order Curve analysis of the other statistical zones of the banana prawn fishery suggest that similar, although less advanced, trends are also underway in other regions of the NPF (Figure 6-13).

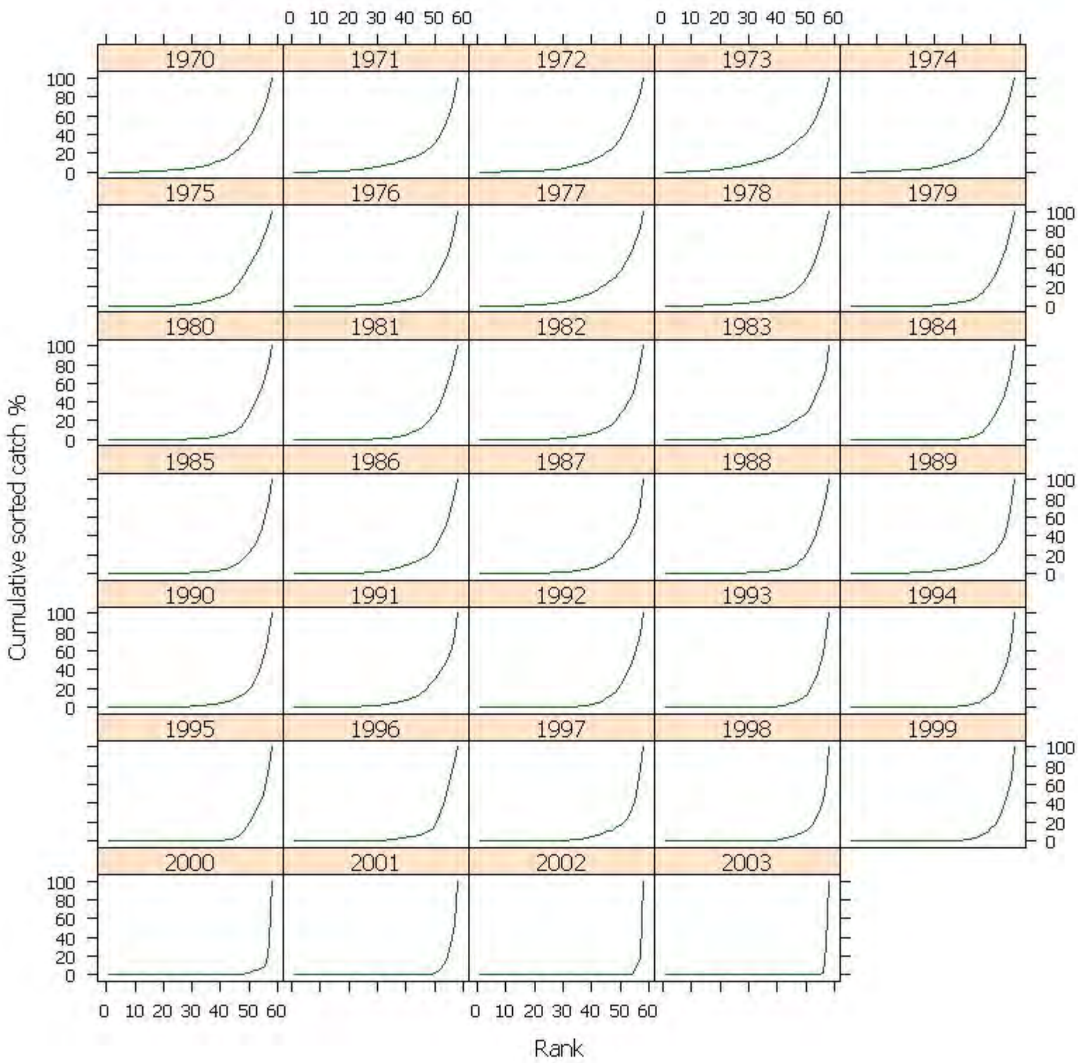

Figure 6-11: Normalized rank order curves for Weipa 1970 to 2003.

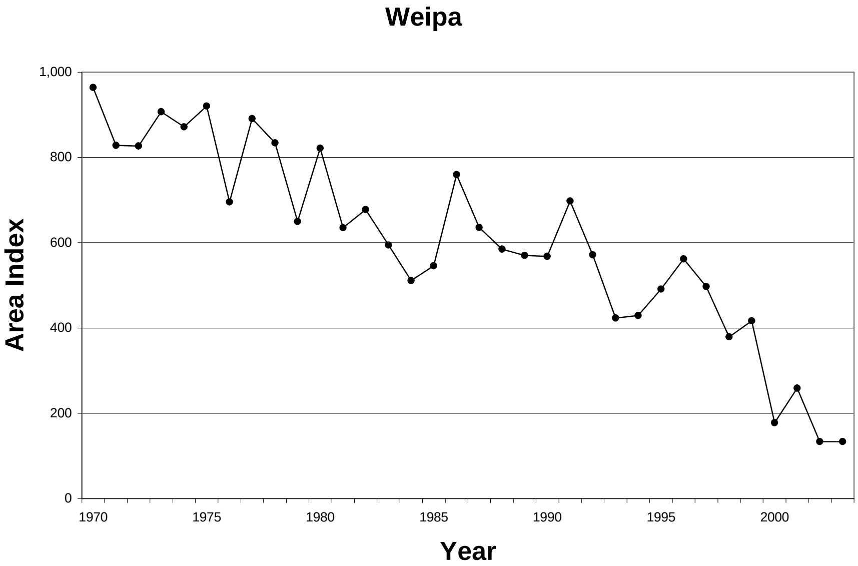

Figure 6-12: The trend in area index for Weipa 1970 to 2003. The area index has been calculated from the total area under the normalized rank order curve for each year.

Discussion

Stock assessments on NPF stocks (tiger and banana prawns) have tended to assume that catchability has been relatively constant and independent of stock size. Die and Ellis (1999) analysed within season trends in banana prawn catch rates during the 1977, 1991, and 1992 seasons with the aim of studying the relationship between catchability and stock size. They concluded that fisheries ability to target aggregations of banana prawns is likely to decline with smaller stock sizes, resulting in a linear relationship between stock size and catchability, rather than an inverse relationship. Their conclusion, however, was based largely on their assumption that “searching time is the main component of fishing effort,” and that the “area to be searched remains constant.” It is unclear whether they quantitatively or qualitatively tested this assumption. In parallel to the conclusions of Die and Ellis (1999) others have proposed that a loss of searching power following industry rationalization over the last decade has driven the recent banana prawn catch declines in the Weipa area.

The quality of the spatial data used here has considerably improved over time, some of the broader spread of catches in the earlier years may be attributable to errors in position fixing and data recording, however the long term decline in area index displayed in Figure 6-13 continues through each of these epochs suggesting that a real spatial contraction has occurred within Albatross Bay. These analysed trends are also consistent with the anecdotal accounts received from experienced fishers and which originally gave us cause to look at these data in this way.

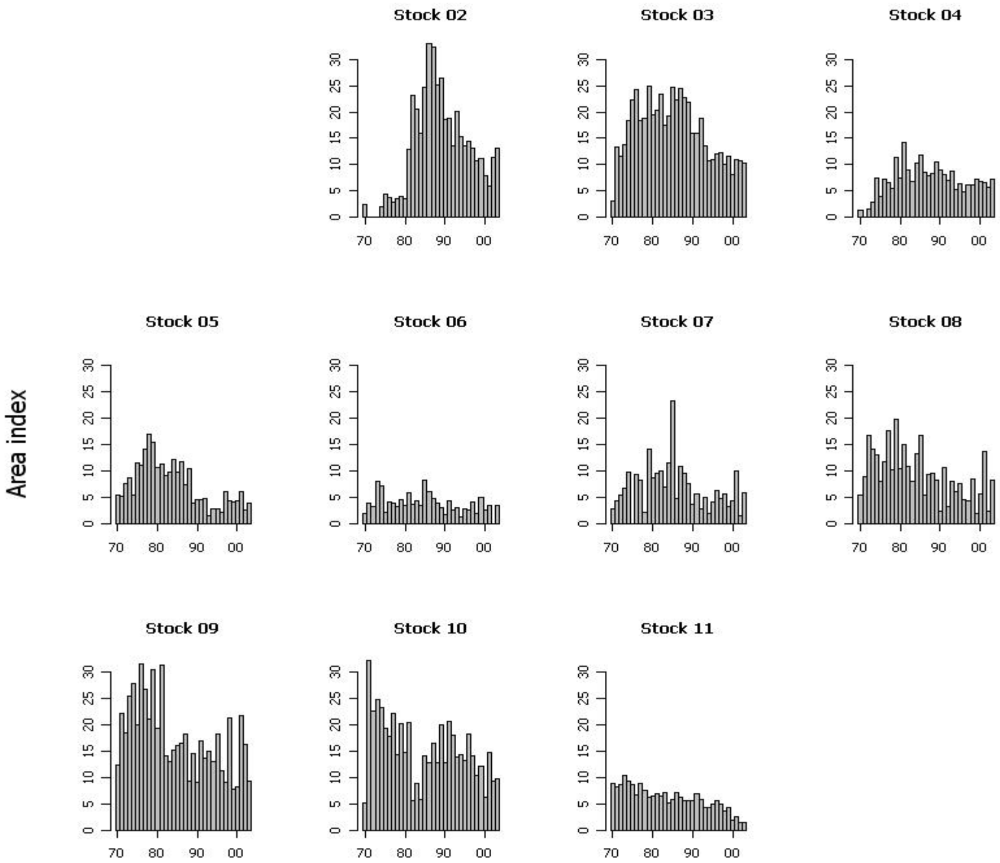

Figure 6-13: Trends in area index for statistical zones 1 to 11 of the Northern Prawn Fishery 1970 -2004. The area index has been calculated from the total area under the normalized rank order curve for each year.

In our opinion, three broad features of the data are apparent, through these analyses;

- The central area of catches, or hotspot, remains stationary and predictable through time.
- There is considerable inter-annual variability with years of fishing over a broader area being interspersed with years of fishing within a smaller area.
- The area of the Albatross Bay fishery has contracted towards the stable centre of the fishing area over the 1970 to 2004 time series.

In our view the contraction of fishing over time towards a stable and predictable hotspot will have enabled industry to progressively focus their searching power on the hotspot as it contracted. The catchability of banana prawns will thus have increased as stock size has declined, probably exponentially. While the results of our Lesley-Deluury analysis can be regarded as indicative only, the analysis presented in Figure 6-8, Figure 6-9, and Figure 6-10 are consistent with the notion of a steadily escalating catchability at low stock sizes, and despite declining nominal levels of effort and increasing rate of seasonal depletion.

The relatively steady contraction of the fishing grounds observed over several decades at Albatross Bay, and which is apparently also occurring more generally across the NPF, is consistent with a long term progressive impact like fishing rather than more recent attempts to rationalize the fishery. The banana prawns from the Weipa area meet all the criteria specified by Penn *et al.* (1989) for a penaeid stock that is likely to be vulnerable to recruitment-overfishing. While it cannot be proven by this analysis, the fishery dynamics described here are highly suggestive of recruitment overfishing driving a long term decline in catch and a contraction in the area of the fishery. Furthermore the possibility that this process is also at work in other regions of the fishery should also be considered.

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6.2.5 Effort analysis – Neil Loneragan

Effort analysis of the banana prawn fishery for the Weipa region

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Introduction

When commercial prawn fishing began in the Gulf of Carpentaria in the early 1960s, it initially targeted only the banana prawn (*Penaeus merguiensis*) - a species that formed dense aggregations that stir the sediment, making visible mud 'boils'. Catches of *P. merguiensis* peaked at more than 12,000 t in 1974 and have remained high, although they fluctuate from year to year (Dichmont *et al.* 2006). These large catches, together with open access to the fishery (which attracted large foreign vessels in the 1960s and 70s) and government boat-building subsidies, resulted in the fishing fleet growing to about 280 vessels in the early 1980s (Figure 6-14). Furthermore, because *P. merguiensis* is short-lived and aggregates, the fishery made substantial investments in processing and targeting equipment. The increased efficiencies led to the allowable number of fishing days being reduced from year-round in the 1960s, to a few months in the 1970s, and to just over a month in the 1990s and thereafter (Somers and Wang 1997).

Data from the logbooks were explored using simple linear regression analysis to detect whether there had been major changes in the relationship between catch and effort over three decades of the Weipa fishery and the available years of data since 1999. If the slope of the line has changed over time it suggests that fishing effectiveness (catchability) has changed, while a change in the intercept indicates that the available biomass has changed. Trends in the relationships were compared between Weipa (Stock area 11) and Karumba (Stock area 9) regions to see whether the relationship between catch and effort was consistent between these two regions.

Methods

Data on the total fishing effort for banana prawns and catch (log transformed) of banana prawns were examined in each of the decades from 1970 until 2000 and simple linear regressions were fitted to explain catch in terms of effort.

Results

The number of boats operating in the Northern Prawn Fishery has declined from 280 in the early 1980s to about 120 in the 1990s and then to 89 in 2005 due to the introduction of limited entry and various vessel buy back schemes (Figure 6-14a). The total number of days available for fishing each year was 237 in the early 1980s, with only an end of year closure to prevent growth overfishing. Following the introduction of the mid-season closure in 1987, the number of days available for fishing declined to 188 in 1987 (Figure 6-14b). The number of days available for fishing declined further in the 1990s following increases in the length of closed periods to rebuild the *Penaeus esculentus* stocks. Currently, about 150 days are available for fishing. The reductions in both the number of boats operating in the fishery and the number of days available for fishing each year has resulted in a nearly five fold decrease in the total number of boat days available for fishing from about 60,000 in 1984 to 13,350 in 2005 (Figure 6-14c).

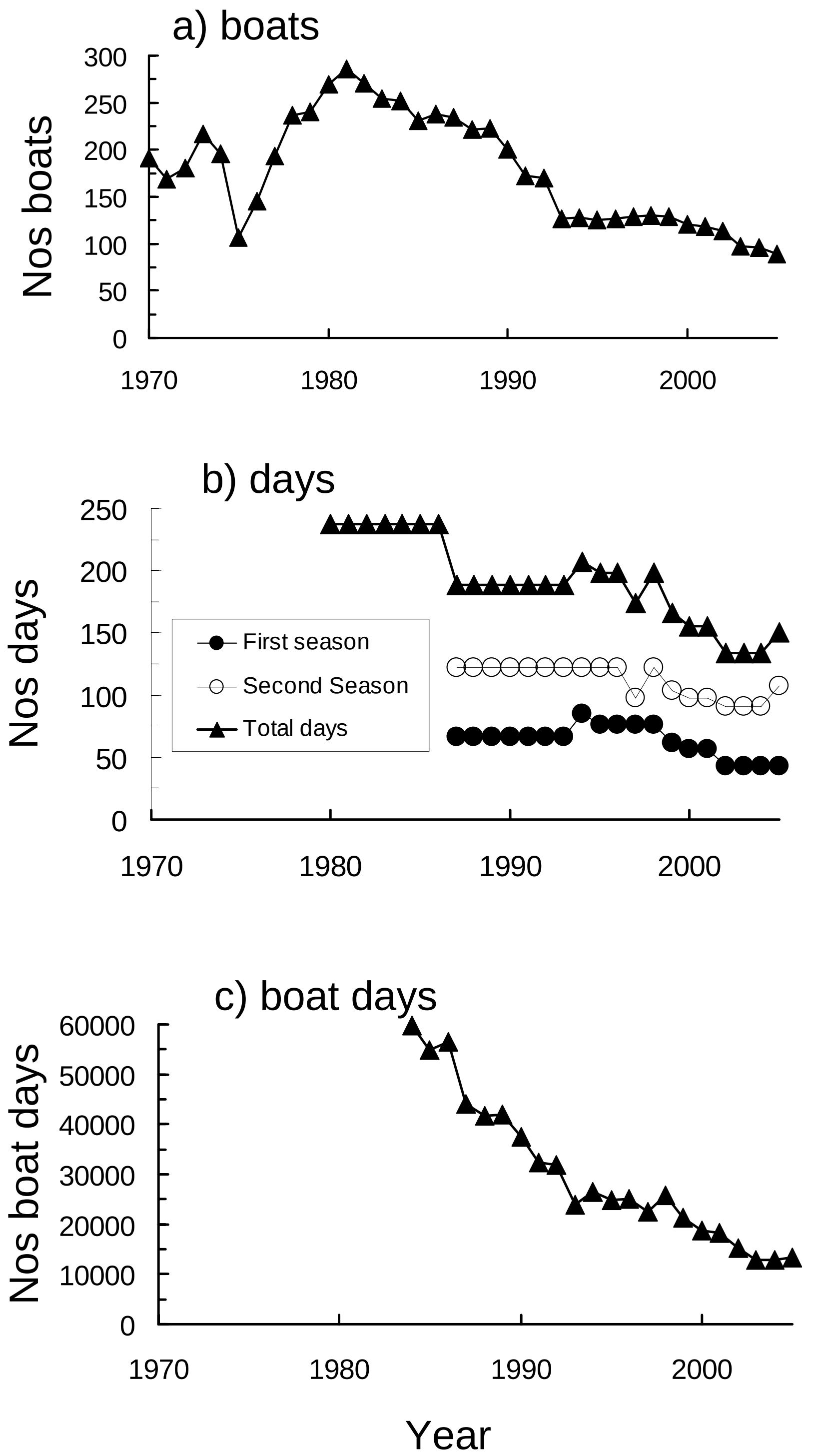

Figure 6-14. Number of boats fishing each year in the Northern Prawn Fishery from 1970 until 2004.

The notable drop in the number of vessels operating during the 1970s and the lack of boat day estimates prior to 1983 (Figure 6-14a, Figure 6-14c) reflects the considerable uncertainty about fleet size prior to the introduction of limited entry in 1980. Prior to 1980, different definitions of the eligible boats to be counted were used and this accounts for the large differences in numbers of vessels prior to 1980 compared to the "official" AFMA document. Many vessels from the east coast came into the Gulf of Carpentaria for limited times of a month or less, and this migration of boats into the Northern Prawn Fishery was variable from year to year, thus adding to uncertainty about which boats should be counted. The decision by fishers to participate in the NPF prior to 1980 depended on how participants regarded the relative probabilities of cyclones, bonanza catch post-cyclone, lack of infrastructure to cope with bonanza catches, and what other fishers were planning. All vessels fishing in the NPF were counted in the fleet audit, whereas the AFMA count may have had an eligibility criterion related to the number of months fishing in the NPF (Janet Bishop, CMAR, personal communication, 28 September 2006).

The total fishing effort in boat days per annum at Weipa (stock area 11) decreased steadily from the 1970s (600 to 1400 boat days per annum until the 1990s (400 to 800 boats days) but has shown a greater rate of decline since 1997 and not exceeded 100 boat days since 2000 (Figure 6-15). Fishing effort at Karumba (stock area 9) also declined between the 1970s (450 to 2546 boat days) and 1980s (75 to 557 boat days, except for 1981 with 2159 boat days) but did not continue to decline further and has always exceeded 345 boat days in each year since 1990 (Figure 6-15).

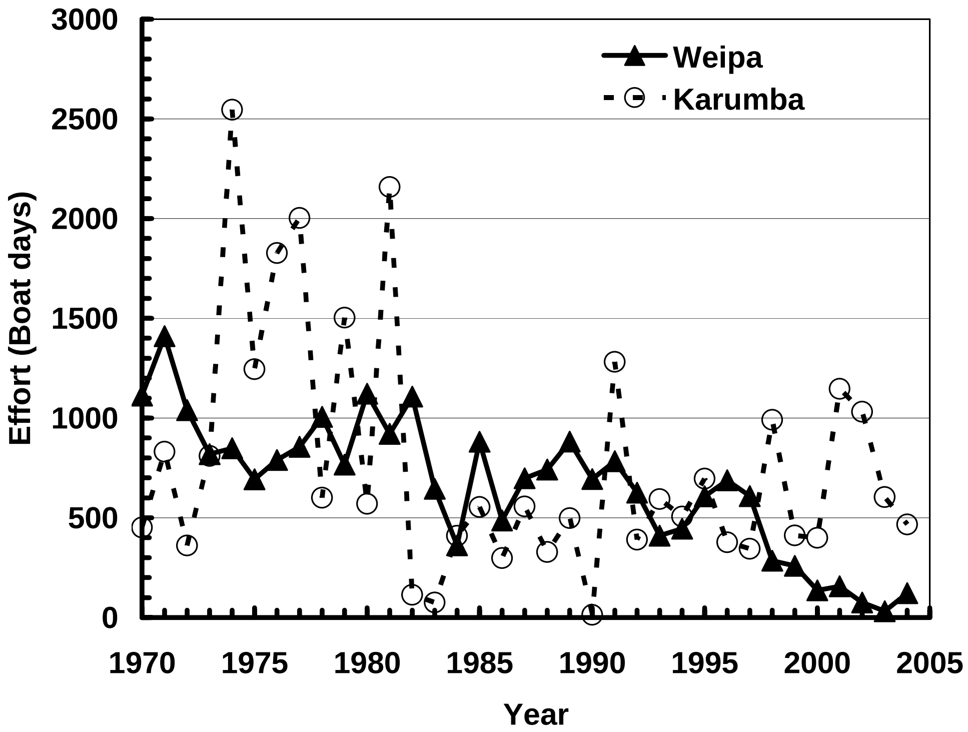

Figure 6-15. Fishing effort (boats days) on banana prawns in Weipa (stock area 11) and Karumba (stock area 9) from 1970 until 2004.

The decline in effort through the decades is explained by the decrease in the number of boats operating each year in the NPF and a reduction in the number of days available for fishing because of the introduction of seasonal closures (Figure 6-14).

At both Weipa and Karumba, the slope of the relationship between catch and effort in the 1970s and 1990s was about 2 to 3 times higher than that in the 1970s (Figure 6-16, Figure 6-17, Table 6-2), indicating a difference in the fisheries dynamics between these two decades However, in the 2000s, the slope of the Weipa relationship was low, while that for Karumba was the highest estimated.

The proportion of variation in total banana prawn catch explained by effort, varied greatly between decades at Weipa and ranged from 73% in the 1970s to only 23% in the 1980s (Figure 6-16, Table 6-2). In Karumba, the proportion of variation in catch explained by fishing effort

was more consistent and higher than at Weipa, ranging from 70% in the 1970s to 95% in the 1980s (Figure 6-17,
Figure 6-17Table 6-2).

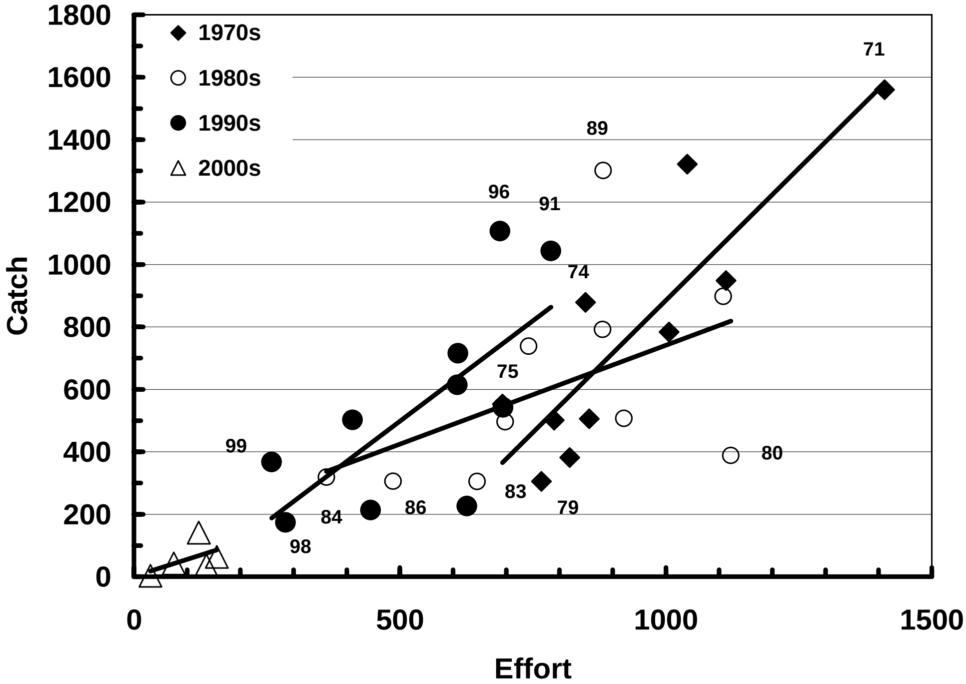

Figure 6-16. Relationship between total fishing effort (boat days) and total annual catch for Weipa (stock area 11). Lines show regression lines for each decade of data i.e. 1970s, 1980s, 1990s and 2000s. Equations and fit of the regressions are shown in Table 6-2.

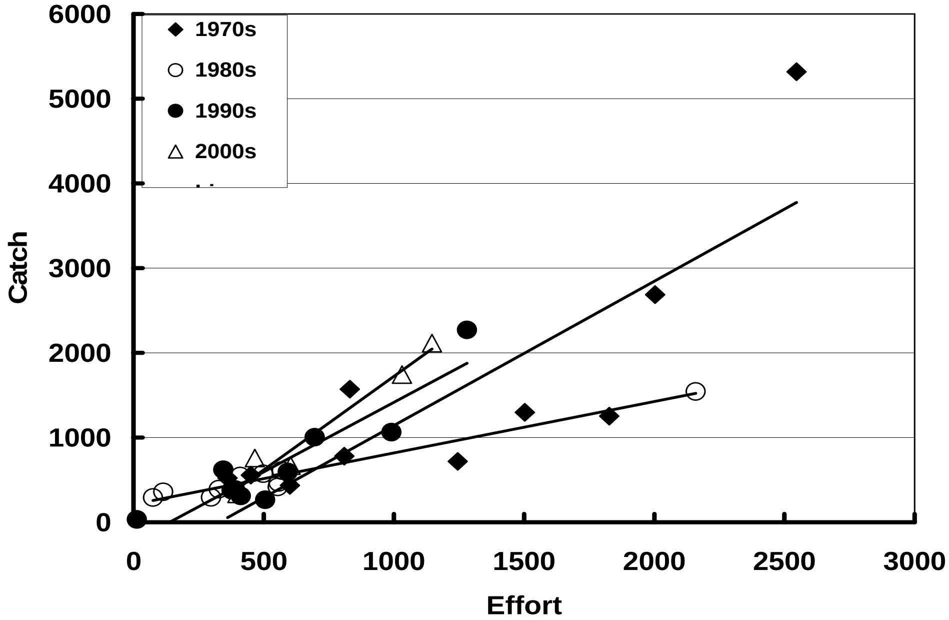

Figure 6-17. Relationship between total fishing effort (boat days) and total annual catch for Karumba (stock area 9). Lines show regression lines for each decade of data i.e. 1970s, 1980s, 1990s and 2000s. Equations and fit of the regressions are shown in Table 6-2.

Table 6-2. Summary of regressions equations for the relationship between annual catch (C) and effort (E) for banana prawns in each time period for (a) Weipa and (b) Karumba. N = 10 for each decade except the 2000s, where N = 5.

Region and decade	Equation	R^2
(a) Weipa		
1970s	C = 1.693E - 807.75	0.77
1980s	C = 0.634E + 107.53	0.23
1990s	C = 1.289E - 145.15	0.49
2000s	C = 0.543E + 0.744	0.28
(b) Karumba		
1970s	C = 1.702E - 558.91	0.70
1980s	C = 0.607E + 211.86	0.95
1990s	C = 1.643E - 228.63	0.85
2000s	C = 2.210E - 487.97	0.96

Discussion

These results, from simple descriptive analyses, highlight the different nature of the fishery at Weipa and Karumba and the change in relationship between catch and effort over the decades, particularly between the 1970s and 1980s at Weipa. They also highlight the difference in the relationship between Weipa and Karumba since 2000.

The results also suggest that the dynamics of the fishery are different in the two regions, particularly since the 1980s. Effort and catch show a strong, consistent relationship at Karumba but a weaker and less consistent relationship at Weipa. From discussions with fishers, Weipa is now fished by only a small proportion of the fleet and for short time intervals, while fishing effort has continued at Karumba where spotter planes are used to locate schools of banana prawns.

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6.2.6 Ecological Modelling – Tom Okey *et al.*

A trophodynamic (Ecopath) model of Albatross Bay: a fishing explanation for prawn catch declines[6]

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Summary

A preliminary mass-balance trophodynamic (computer) model was constructed by a broad collaboration of experts (Appendix IV-5) to represent the Albatross Bay marine ecosystem, Gulf of Carpentaria, Australia during the period 1986 to 1992-a time of relatively intense study in the region. It was constructed using the freely available software Ecopath with Ecosim (www.ecopath.org) for the purpose of exploring (and developing) hypotheses that would explain the recent worrisome declines in banana prawn (*Penaeus merguiensis*) catches in the Albatross Bay region. In general, these models are designed to characterize whole food web trophic interactions and they can integrate non-trophic mediation effects and environmental forces.

The primary usefulness of the model at this preliminary stage is as a transparent exhibit of the input parameters used, and as a framework for refining this information and planning data-gathering programs that will ultimately achieve an adequate level of predictive usefulness. The present Albatross Bay model should thus be viewed as a 'straw man' framework that can be refined with improved information, though the current version does provide provocative explanatory insights that might prove robust generally.

The Albatross Bay model is unique among Ecopath ecosystem models in that it explicitly integrates estuarine and marine 'sub-webs' in order to gain insights into the ecological (and fishery) importance of these connections and this interface. It was constructed this way because the life-cycle of prawns spans these sub-webs, and an understanding of their populations, communities, and dynamics cannot be achieved without considering these links. This ecosystem model also contains life-stage-based single species models imbedded in the overall food web to try to ensure that parameters representing prawn life stages are biologically consistent with each other.

The model is designed to focus on prawns within their broader ecosystem, but there is considerable uncertainty surrounding several aspects of the interaction of prawns and their greater ecosystem. Appendix IV-5details the derivation of the input parameters of the preliminary Albatross Bay model, while general methodology for this approach is described in this précis along with some preliminary analytical results.

This précis features: results of whole food web; trophodynamic simulations of the predicted effects of simplified, but reasonable, changes in prawn trawl catch rate ; and histories on banana prawn biomass in the Albatross Bay area. We constructed the present model to explore the overall responses to such fishing history changes (and potentially other types of changes). The goal here was to determine if such simulated changes would lead to predicted changes in banana prawn biomass that would be consistent with recent dramatic catch declines in the area. A

[6] The complete parameterisation and analysis of the Ecopath with Ecosim model of Albatross Bay are in Appendix IV-5.

secondary goal was to understand better the ways in which fishing effects might be manifested in banana prawn biomass.

Preliminary simulations using Ecosim's gaming interface and simple hypothetical fishing rate change scenarios (see Results and Discussion) indicated that banana prawn biomass would have declined considerably with either increases or large decreases in 1986 banana prawn trawling rates, and with increases in tiger prawn trawling rates. These effects are manifested in the model directly, but also indirectly through trophic cascades. The simulations also indicate that banana prawn biomass would have increased marginally with small decreases in 1986 banana prawn trawling and with a complete reduction of tiger prawn trawling. Combined increases or large decreases in the fishing rates of both prawn trawl fleets always caused predicted declines, again due to a combination of direct and indirect effects. A summary of these simplified scenarios is shown in Table 6-3.

Table 6-3. Predicted changes in banana prawn biomass in the Albatross Bay area between 1986 and 2006 based on simplified prawn trawling strategies.

Gear \ Strategy	Gradual doubling	Gradual removal of fishing	Stepped profile (doubling & decline)
Banana prawn trawling	90% decline (direct impacts; stock overfishing)	60% decline after a decade of 15% increase (direct impacts)	Signs of recovery after 85% decline
Tiger prawn trawling	70% decline (indirect impacts; ecosystem overfishing)	15% increase (indirect effects)	Signs of recovery after 70% decline
Banana & tiger trawling	98% decline (combined impacts)	65% decline after a decade of 15% increase (combined impacts)	No signs of recovery after complete decline

If these preliminary simulations are accurate qualitatively, one implication is that prawn trawl fisheries are "productive" because bottom trawling modifies the overall ecosystem to the benefit of prawns. This 'fishery facilitation of prawns' effect manifests in the present model through, for example, the reduction of the predators and competitors of prawns as the result of high levels of bycatch, or more specifically, a particular composition of bycatch. The humans in this system (i.e. the commercial prawn fishers) reduce their own competitors non-selectively through bycatch and this has generally tended to increase prawn biomass because prawn life habits and growth rates make them winners in the particular disturbance regime that trawling imposes on the whole community. In this sense, prawns are an indicator of disturbance or perturbation. The simulations also indicate that such a facilitative dynamic between fisheries and prawns would occur until the prawns are overfished directly or until this non-selective modification of the resident assemblage favours species that are effective predators of prawns, or until some combination of both effects overwhelmed the facilitative effect.

A related series of static analyses and simulations described in this précis indicates that some biotic groups in the Albatross Bay stand out as strong facilitators of banana prawns and that the reduction or removal of these biotic groups through prawn trawl bycatch causes cascading effects that decrease banana prawn biomasses by enabling the emergence (increase in biomass) of groups that prey on prawns. These emerging groups are referred to in this précis as "vampires from the basement." Some of these strong emergent dynamics are plausible explanations for recently observed declines in banana prawn catches in the Albatross Bay area, as these prawn facilitators are estimated to be adversely affected by prawn trawling and other fisheries. Strong facilitators of prawns include some shark groups, while vampires from the basement include stomatopods and octopus. This series of simulations provides further indications that prawn trawling is a plausible cause for the observed decline of banana prawn catches in the Albatross Bay (Weipa) area.

In addition to exploring these simplified scenarios of changes in fishing effort and catch rates, a more sophisticated type of simulation was attempted in which a number of historical time series of fisheries effort were derived, properly scaled, and imposed on the 1986 to 1992 modelled ecosystem to try to accurately reconstruct ecosystem changes to the present and to verify and tune the model structure and behaviour so that such simulations would have predictive accuracy. The question underlying this simulation was: 'Will the integration and precise expression of historical time series information from all of the system's fisheries (Commonwealth, State, and other) cause a projected decline in biomass of adult banana prawns (in the model) that might accurately match observed declines in catch?' And secondly, 'If fisheries information does not force declines in adult banana prawn biomass by itself during time periods of interest, can a combination of this fisheries information with observed changes in primary production force such declines, and thus improve explanations of recent observations of catch declines?'

This more sophisticated analysis was conducted, but the results are not considered reliable at the time of this writing because this complex ecosystem model is not yet considered to be robust because of the high level of temporal variability that these data impose on the biological functional groups, whereas the model is much more behaviorally robust to the simplified scenarios described above. Moreover, comparative time series of primary production for the Albatross Bay area (and extending for the past 20 years) are not available. The simplified scenarios discussed above are presently much more informative than those that attempt to reconstruct the complex dynamics of this tropical system at a fine inter-annual scale.

The preliminary nature of these simulations and the lack of dynamic verification of the results limit the inferences of this initial work beyond the emergent indication that prawn fisheries are a principal cause of the recent observed catch declines and that plausible mechanisms for these catch (and biomass) declines emerged in the model.

The preliminary Albatross Bay model points to key areas of research that might lead to breakthroughs in understanding the drivers and controllers of banana prawn population dynamics. More progress can be made on refining the stability, reliability, and predictability of the model if more time and effort can be devoted to this research, especially through collaborations among both domestic and international researchers. Collection of basic biological information in the following areas would improve the parameterisation of key components of the system: banana prawn biology, abundance, and trends; improved abundance estimates of the predators and prey of banana prawns (and of second and third order predators); focused studies on predators that might be key, but for which little information exists (e.g., stomatopods and octopods and other cephalopods); improved information about primary and secondary producers / production and detritus in the system; improved oceanographic and climatological trend information; and improved fisheries information.

Ecopath with Ecosim methods

Ecopath trophic models describe the state of energy flows in a food web. They are designed to include all biotic components of an ecosystem, and the most typical currency is biomass wet-weight (used here). Polovina (1984) developed *Ecopath* to study coral reefs at French Frigate Shoals. A variety of dynamic capabilities have since been added (e.g., Christensen and Pauly 1992, Walters *et al.* 1997, Walters et al. 1999, Christensen *et al.* 2000, Pauly *et al.* 2000). Scores of applications of *Ecopath with Ecosim* can be found at: http://www.Ecopath.org/, along with the freely distributed software and documentation. Although the formulations and basic concepts are accessible in these venues, the general approach is summarized Appendix IV-5.

Types of simulations that are possible

In addition to the main goal of constructing a preliminary Ecopath model for the Albatross Bay Ecosystem, the temporal dynamic simulation routines of Ecosim were the natural focus of this preliminary exploration. The main exploratory mode of Ecosim allows users to examine simulated multi-species (functional group) effects of user-specified simulated changes to fishing mortality (increases or decreases) either by a fleet or two or a particular functional group. This allows dynamic exploration of 'what if' questions and the trophically-dominant dynamics and relationships in the system, all through a user-friendly gaming interface. Other types of basic fisheries analyses (in a whole food-web context) include analyses of predicted community compositions at different levels of fishing. Both trophic and non-trophic interactions can be explored using these simulations, as can the interactions of biological and physical forces in shaping the environment. A time-series fitting routine within Ecosim is a more sophisticated type of analysis that is designed for reconstructions of ecosystem changes by specifying historical fisheries time series information. Here, time series representing the various explanations for catch declines are added to the model until the observed changes in the system are explained by the model, thus providing an overall (most likely) explanation of the relative roles of the various specified factors in causing the observed catch declines.

Albatross Bay model description

The spatial, temporal, and biological scope of the model was defined during project Workshop I, and this definition was refined thereafter. The scope of the Albatross Bay model is currently defined in five ways:

- Time: 1986 to 1992
- Vertical: 12º10'30"S to 13º 0'0"S latitudes
- Horizontal: Top of estuaries to 40 m isobath (two subsystems)
- Area: 5,788 km^2 area
- Biological functional groups (99 groups in 8 broad categories)
  - 2 marine mammal
  - 3 reptile
  - 4 bird
  - 33 fish
  - 9 prawn
  - 32 other invertebrate
  - 7 primary producer
  - 7 detritus

At Workshop II, experts helped refine the straw-man Albatross Bay model, and they helped to balance the model trophodynamically in order to prepare the model for simulations so that the project questions could be explored with the Ecopath/Ecosim approach. The Albatross Bay Ecopath model includes several design features for ensuring optimal usefulness:

- *Linked subsystems* – The estuary ecosystem and the offshore system that are linked to each other ecologically, especially with respect to organisms that move from one system to the other either ontogenetically or as adults;
- *Embedded stage-based models* – The model contains two stage-based sub-models describing the population dynamics of both banana prawn and tiger prawn categories, as partitioned into juvenile, sub-adult, and adult group, each with different diets, predators, habitats, and population characteristics;
- *Fisheries information* – Landings information by fleet and functional group are specified in the model, as is discard catch information and the fate of that discard. The model accounts for seven fleets that operate in the area:
  - Banana prawn trawl
  - Tiger prawn trawl

  - Line (Spanish mackerel)
  - Net (Mackerel / Shark)
  - Gillnet (Barramundi)
  - Pot (Mud Crab)
  - Recreational
- *Fish biomass and diet information* – The model contains rigorous diet and bycatch estimates for all the fish groups in the model. This is unusual for Ecopath models, and it is critical for addressing hypotheses related to the relative influence of fish predation mortality of prawns versus fisheries mortality of prawns.
- *Prawn diet information* – The model contains diet information for all the stages of the main prawn functional groups. These diets were collected from the literature as well as from the unpublished data of prawn experts at CSIRO Marine Research in Cleveland, Queensland.
- *Time series data* of catches, effort, CPUE, and indices of abundance – The Albatross Bay model uses available time series data sets so that simulations of change from the 1986 to 1992 period to the present can be driven by known changes in effort since that time and compared with observed changes in abundance and catch.

Results and discussion

The results of the trophodynamic modeling consist of both static and dynamic analyses. The static analyses are presented in the Results and Discussion and these include six static descriptions of the preliminary Albatross Bay model: (1) the basic parameters of the preliminary Albatross Bay model (Table 6-4); (2) a 'pedigree' assessment of the quality of the input data (Table 6-5); (3) a series of indices and flow estimates that summarize the characteristics of the modeled ecosystem (Table 6-6); (4) a brief description of the banana prawn sub-web (Figure 6-18); (5) a comparison of major sources of banana prawn mortality (Figure 6-19); and (6) an assessment of the relative impacts exerted on banana prawns by each of the functional groups in the model, as the model is currently specified (Figure 6-20). This latter analysis provides preliminary insights into the relative influence of particular functional groups on banana prawns.

Basic parameters

The basic parameters of the Albatross Bay food web (Table 6-4) provide a generalized description of the functional group components of the Albatross Bay model. Functional groups are listed in descending order of trophic level such that the apex predator groups are shown at the top and the primary producer and detritus groups are shown at the bottom. Parameters in bold have been estimated by the Ecopath routine, indicating gaps in independent empirical information about biomasses of various functional groups, for example. Biomass is expressed in wet weight, P/B and Q/B are the ratios of production and consumption to biomass, respectively, and ecotrophic efficiency (EE) is the proportion of production consumed within the system. Ecotrophic efficiency is often used as a 'balancing handle' during mass continuity balancing because an EE>1 is impossible and because particular functional groups have expected ranges of EE, given their natural histories, physiologies, and trophic roles. Diet compositions, fisheries information, and various other information that is also needed to characterise Ecopath models, are shown in Appendix IV-5. The technique to estimate the biomass of large/medium pelagic piscivores can be found in Appendix IV-6.

Table 6-4: Basic biological parameters used in the Albatross Bay model. Values in bold are calculated (outputs) by Ecopath.

Functional group name	*Trophic level*	*Biomass ($t \cdot km^{-2}$)*	*P/B (/year)*	*Q/B (/year)*	*EE*
Sea snakes	**4.97**	0.003	0.700	6.100	**0.811**
Lesser frigates	**4.82**	5.000E-05	0.080	36.700	**0.075**
Crested terns	**4.72**	3.400E-04	0.204	47.500	**0.000**
Sawfishes	**4.72**	0.040	0.123	2.575	**0.990**
Dolphins	**4.71**	0.003	0.100	41.070	**0.001**
Brown boobies	**4.71**	0.002	0.080	33.800	**0.000**
Large elasmo benthopelagic piscivores	**4.53**	0.060	0.500	7.856	**0.992**
Large benthopelagic invert feeders	**4.47**	0.002	0.547	7.792	**0.997**
Small benthic piscivores	**4.43**	**0.339**	1.042	5.168	0.950
Large teleost benthopelagic piscivores	**4.42**	0.523	0.451	3.421	**0.520**
Small pelagic piscivores	**4.30**	0.053	0.831	14.400	**0.837**
Large pelagic piscivores	**4.28**	5.650E-05	0.500	7.767	**0.014**
Common terns	**4.23**	3.600E-04	0.160	65.100	**0.000**
Large teleost benthic invert feeders	**4.21**	0.074	0.577	4.714	**0.977**
Medium pelagic piscivores	**4.19**	0.013	0.577	12.307	**0.930**
Small benthopelagic piscivores	**4.16**	**0.183**	0.868	8.172	0.950
Large elasmo benthic invert feeders	**4.13**	0.075	0.320	9.932	**0.530**
Large pelagic planktivores	**4.12**	**0.018**	2.188	16.150	0.960
Large teleost benthic piscivores	**4.11**	**0.089**	0.566	6.460	0.850
Crocodiles	**4.05**	**6.890E-05**	0.318	2.080	0.800
Small benthopelagic invert feeders	**3.91**	**1.687**	2.000	4.800	0.950
Estuary large elasmo benthopelagic pisc/prawn feeder	**3.89**	0.317	0.354	4.456	**0.149**
Octopus	**3.82**	**0.084**	2.370	7.900	0.900
Estuary large teleost benthopelagic pisc/prawn feeder	**3.80**	0.317	0.439	8.392	**0.998**
Scavengers	**3.73**	0.001	0.450	6.100	**0.994**
Estuary large benthic pisc/prawn feeders	**3.69**	0.496	0.370	4.067	**0.574**
Small benthic invert feeders	**3.67**	0.493	1.500	5.026	**0.982**
Estuary large benthopelagic invert feeders	**3.64**	0.074	0.506	5.375	**0.079**
Squid and cuttlefishes	**3.62**	**0.864**	2.370	7.900	0.950
Estuary small benthic invert feeders	**3.58**	**0.298**	1.280	11.100	0.980
Estuary large benthic invert feeders (Rays)	**3.50**	2.444	0.273	6.871	**0.000**
Polychaete feeders	**3.44**	**0.527**	1.450	7.554	0.950
Banana prawn subadults	**3.44**	0.020	3.120	27.181	**0.922**
Tiger prawn juvenile	**3.43**	0.012	3.400	45.234	**0.131**
Estuary planktivores	**3.42**	**0.315**	2.326	16.420	0.980
Estuary insectivores	**3.42**	**0.043**	0.690	9.500	0.980
Stomatopods	**3.41**	**0.345**	3.500	7.432	0.950
Banana prawn adults	**3.34**	0.079	3.200	19.200	**0.957**
Tiger prawn subadults	**3.32**	0.021	3.200	28.160	**0.937**
Tiger prawn adults	**3.32**	0.121	2.340	19.200	**0.663**
Estuary polychaete feeders	**3.30**	0.286	1.043	9.433	**0.325**
All other commercial prawns	**3.30**	**0.101**	3.000	25.000	0.900
Large gastropods	**3.28**	0.023	2.800	14.000	**0.389**
Turtles	**3.24**	0.035	0.192	3.500	**0.812**
Small pelagic planktivores	**3.20**	**2.770**	2.189	16.830	0.980
Thallasinid prawns (*Callianassa*)	**3.17**	**0.812**	3.000	25.000	0.950
All other non-commercial prawns	**3.17**	**8.830**	3.000	25.000	0.950
Sand crabs	**3.12**	**0.063**	2.800	8.500	0.900
Marine forams	**3.09**	**3.717**	12.500	25.000	0.950

Functional group name	*Trophic level*	*Biomass (t·km⁻²)*	*P/B (/year)*	*Q/B (/year)*	*EE*
Estuarine forams	**3.09**	**0.029**	12.500	25.000	0.950
Mud crabs *(Scylla serratta)*	**3.07**	**0.060**	2.800	8.500	0.900
Red mud crabs *(S. olivacea)*	**3.07**	**0.050**	2.800	8.500	0.900
Banana prawn juveniles	**3.03**	0.011	3.720	43.888	**0.123**
Other large crabs	**2.98**	**4.657**	2.800	8.500	0.900
Spatangoids	**2.93**	2.142	1.400	2.810	**0.142**
Crayfish	**2.87**	**0.011**	3.000	25.000	0.950
Asteriods	**2.77**	0.051	0.490	3.240	**0.132**
Large jellyfish	**2.73**	**0.015**	40.000	80.000	0.500
Marine ichthyoplankton	**2.62**	**0.002**	50.448	132.13	0.990
Marine small gastropods	**2.55**	**25.931**	2.500	14.000	0.980
Estuarine small gastropods	**2.55**	**0.209**	2.500	14.000	0.980
Small jellyfish	**2.44**	**0.027**	40.000	80.000	0.500
Estuarine ichthyoplankton	**2.41**	**5.700E-05**	50.448	132.13	0.990
Sessile epibenthos	**2.40**	4.985	0.800	9.000	**0.614**
Estuarine small crustaceans	**2.40**	**0.250**	7.010	27.140	0.980
Marine meiofauna	**2.36**	**8.342**	12.500	25.000	0.950
Estuarine meiofauna	**2.36**	**0.506**	12.500	25.000	0.950
Marine small crustaceans	**2.35**	**8.656**	7.010	27.140	0.980
Marine worms	**2.31**	**10.407**	6.850	27.400	0.980
Estuarine worms	**2.31**	**0.793**	4.600	15.900	0.980
Holothurians	**2.16**	0.065	0.610	3.360	**0.959**
Ophiuroids	**2.13**	**10.211**	1.400	2.810	0.950
Marine zooplankton	**2.12**	11.744	52.000	173.33	**0.201**
Estuarine zooplankton	**2.12**	0.757	104.00	347.67	**0.135**
Marine bivalves	**2.11**	**41.222**	1.209	23.000	0.900
Estuarine bivalves	**2.11**	**11.902**	1.209	23.000	0.900
Estuary pelagic herbivores	**2.10**	**0.261**	1.083	36.833	0.900
Echinoids	**2.01**	0.085	1.650	2.810	**0.691**
Dugongs	**2.00**	0.050	0.080	36.500	**0.747**
Benthic herbivores	**2.00**	0.024	1.510	35.167	**0.983**
Estuary detritivores	**2.00**	**1.991**	1.175	19.300	0.800
Estuary benthic herbivores	**2.00**	**0.006**	1.880	45.750	0.980
Insects	**2.00**	**0.015**	12.600	51.930	0.980
Marine microbial heterotrophs	**2.00**	**5.416**	100.00	215.00	0.950
Estuarine microbial heterotrophs	**2.00**	**0.494**	100.00	215.00	0.950
Marine phytoplankton	**1.00**	3.905	933.083	-	**0.345**
Estuarine phytoplankton	**1.00**	0.389	933.083	-	**0.318**
Microphytobenthos	**1.00**	**0.667**	706.496	-	0.950
Seagrass	**1.00**	**1.938**	2.145	-	0.600
Estuarine macroalgae	**1.00**	**0.852**	12.000	-	0.500
Marine macroalgae	**1.00**	**19.593**	12.000	-	0.500
Mangroves	**1.00**	**0.178**	3.300	-	0.400
Discards	**1.00**	0.700	-	-	**0.328**
Detached Marine macrophytes	**1.00**	5.000	-	-	**0.546**
Detached Estuarine macrophytes	**1.00**	5.000	-	-	**0.056**
Estuarine Water-column detritus	**1.00**	0.322	-	-	**0.214**
Estuarine Sediment detritus	**1.00**	250.000	-	-	**0.177**
Marine Water-column detritus	**1.00**	33.351	-	-	**0.306**
Marine Sediment detritus	**1.00**	250.000	-	-	**0.229**

Evaluation of the quality of input data

Ecopath's data pedigree routine enables qualitative evaluation of the quality of each input parameter, which is converted to quantitative estimates of data confidence in the form of pedigree indices that can then be used to calculate an overall model pedigree, which also takes into account the number of living biological groups. Data pedigree is data quality as judged by particular criteria that are standard in Ecopath models (shown in Appendix IV-5). These ratings are converted to confidence intervals estimates (+/- %) for use: in probability analyses that address uncertainty; to generally evaluate relative quality of the model; or to reveal and prioritize relative data gaps and needs for science research program planning. Overall pedigree values for models constructed with poorly collected data of low precision that are not locally-based are close to 0, while those constructed with high quality and locally collected data exhibit overall pedigree values closer to 1. The overall Ecopath data pedigree index of the present iteration of the Albatross Bay Ecopath model is 0.413 (with 92 living biological groups; the measure of fit (t* is 4.3). This ranking is better than many models, but it indicates that the Albatross Bay model could be refined further to increase its usefulness for management and policy applications.

Summarising the system

The Albatross Bay ecosystem can be summarized in a number of ways: comparison of this ecosystem with other ecosystems; comparisons of a past ecosystem with a present ecosystem; and assessments of system efficiency, structure and function, and mean trophic level of the catch (Table 6-6). For example, the mean trophic level of the catch is estimated to be 3.77. This is 0.43 trophic levels higher than the banana prawn trophic level (Table 6-4) because the bycatch that is captured along with the prawns in this system has a higher mean trophic level than prawns. The estimated trophic levels of prawn groups are higher than normally estimated for prawns because prawn diets are relatively well specified in the Albatross Bay model, and because prawns in this system are larger than in many other "shrimp" systems throughout the world.

The system is estimated to be net heterotrophic, as the sum of all production (and consumption) is greater than the calculated total net primary production (Table 6-6). It is also a high turnover system, as the total annual primary production / total biomass is 24. The total net primary production estimate of 4728 appears to be on the medium-low end of estimates of similar systems using modern models (e.g., Okey *et al.* 2004b).

Table 6-5 shows the estimated confidence intervals (+/- %) for each parameter estimate, based on qualitative ranking categories. Note that the confidence is reasonably high for many of the fish group estimates (confidence intervals are relatively low), whereas confidence is low for many other groups.

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Table 6-5. Estimated confidence intervals (+/- %) surrounding the Ecopath input parameter estimates, based on the qualitative ratings of data pedigree defined in Appendix IV-5.

Group	**B**	**P/B**	**Q/B**	**Diet**	**Catch**
Dolphins	80	20	20	80	50
Dugongs	80	40	40	60	50
Crocodiles	80	40	40	50	50
Turtles	80	40	40	80	50
Sea snakes	30	50	10	30	50
Lesser frigates	30	40	50	30	---
Brown boobies	30	40	50	30	---
Crested terns	30	20	50	30	---
Common terns	30	40	50	30	---
Large pelagic piscivores	50	50	50	30	50
Medium pelagic piscivores	50	50	50	30	50
Small pelagic piscivores	80	50	50	30	50
Sawfishes	30	50	50	30	50
Large teleost benthic piscivores	30	50	50	30	50
Small benthic piscivores	30	50	50	30	50
Large elasmo benthopelagic piscivores	30	50	50	30	50
Large teleost benthopelagic piscivores	30	50	50	30	50
Small benthopelagic piscivores	30	50	50	30	50
Large benthopelagic invert feeders	30	50	50	30	50
Small benthopelagic invert feeders	30	50	50	30	50
Large elasmo benthic invert feeders	30	50	50	30	50
Large teleost benthic invert feeders	30	50	50	30	50
Small benthic invert feeders	30	50	50	30	50
Polychaete feeders	30	50	50	30	50
Large pelagic planktivores	50	70	70	30	50
Small pelagic planktivores	50	70	70	30	50
Benthic herbivores	30	50	50	80	50
Scavengers	30	50	50	30	50
Estuary large elasmo benthopelagic pisc/prawn feeders	30	50	50	30	50
Estuary large teleost benthopelagic pisc/prawn feeder	30	50	50	30	50
Estuary large benthic pisc/prawn feeders	30	50	50	30	50
Estuary large benthopelagic invert feeders	30	50	50	30	50
Estuary large benthic invert feeders (Rays)	30	50	50	30	50
Estuary polychaete feeders	30	50	50	30	50
Estuary small benthic invert feeders	30	50	50	30	50
Estuary planktivores	30	50	50	30	50
Estuary detritivores	30	50	50	60	50
Estuary benthic herbivores	30	50	50	30	50
Estuary insectivores	30	50	50	30	50
Estuary pelagic herbivores	30	50	50	30	50
Octopus	80	20	20	30	50
Squid and cuttlefishes	80	20	20	30	50
Stomatopods	80	40	40	30	50
Banana prawn juvenile	80	20	80	30	50
Banana prawn subadults	80	70	80	50	50
Banana prawn adult	50	20	60	30	50
Tiger prawn juvenile	80	20	80	30	---
Tiger prawn subadults	80	70	80	50	---
Tiger prawn adult	50	20	60	30	50
All other commercial prawns	80	60	60	80	50

Group	**B**	**P/B**	**Q/B**	**Diet**	**Catch**
Thallasinid shrimp (*Callianassa*)	80	60	60	80	---
All other non-commercial prawns	80	60	60	80	50
Crayfish	80	70	70	80	50
Mud crabs *(Scylla serratta)*	80	60	60	80	50
Red mud crabs *(S. olivacea)*	80	60	60	80	---
Sand crab	80	60	60	30	50
Other large crabs	80	60	60	80	50
Large gastropods	30	60	60	80	---
Holothurians	30	50	60	80	50
Spatangoids	30	70	70	80	50
Echinoids	30	40	60	80	50
Ophiuroids	80	60	60	80	50
Asteroids	30	60	60	80	50
Sessile epibenthos	30	60	60	60	50
Marine bivalves	80	60	60	60	50
Estuarine bivalves	80	60	60	80	50
Marine small crustaceans	80	60	60	80	50
Estuarine small crustaceans	80	60	60	80	50
Marine worms	80	40	60	80	50
Estuarine worms	80	40	60	80	---
Marine small gastropods	80	60	60	80	50
Estuarine small gastropods	80	60	60	80	50
Marine meiofauna	80	60	60	80	---
Estuarine meiofauna	80	60	60	80	---
Marine forams	80	60	60	60	---
Estuarine forams	80	60	60	60	---
Large jellies	80	40	60	80	50
Small jellies	80	40	60	80	50
Marine zooplankton	30	10	40	50	---
Estuarine zooplankton	30	10	40	50	---
Marine ichthyoplankton	80	60	60	80	---
Estuarine ichthyoplankton	80	60	60	80	---
Insects	80	40	40	30	---
Marine microbial heterotrophs	80	40	40	60	---
Estuarine microbial heterotrophs	80	40	40	60	---
Marine phytoplankton	30	30	---	---	---
Estuarine phytoplankton	30	30	---	---	---
Microphytobenthos	80	40	---	---	---
Seagrass	10	10	---	---	---
Estuarine macroalgae	80	40	---	---	---
Marine macroalgae	80	40	---	---	---
Mangroves	80	70	---	---	---

Table 6-6. Summary of basic flows and indices in the Albatross Bay Ecopath model, wet weights.

Index	**Flows ($t \cdot km^{-2} \cdot year^{-1}$)**
Calculated total net primary production	4728
Ll Net system production	2613
Sum of all production	6126
Sum of all consumption	5764
Sum of all exports	4232
Sum of all respiratory flows	2116
Sum of all flows into detritus	10365
Total system throughput	22476
	Biomass ($t \cdot km^{-2}$)
Total living biomass	199
	Value (no units)
Total annual primary prod./total biomass	24
Total biomass/total annual throughput	0.01
Total primary production/total respiration	2.24
Mean trophic level of the catch	3.77
System omnivory index	0.24

The throughput of biomass from detritus is estimated to be twice that from primary production (Table 6-7), but the input parameters for most primary producer groups and all detritus groups in the model are highly uncertain and are considered placeholder values. This is a conspicuous limitation of the current model (and of the general knowledge about the ecosystem), as ‘bottom up’ hypotheses cannot be rigorously evaluated without improved knowledge in this area. The other major (general) limitation of the Albatross Bay model, in terms of understanding prawn dynamics, is the lack of rigorous information about higher trophic level organisms. This limits a full exploration of ‘top down’ control dynamics in the system.

Table 6-7. Flows ($t \cdot km^{-2} \cdot year^{-1}$) from primary production and detritus in the Albatross Bay model. Imports are not presented here.

Trophic level	From primary production					From detritus				
	Consumed	Export	To detritus	Respiration	Throughput	Consumed	Export	To detritus	Respiration	Throughput
VI	0.1	0	0.2	0.6	1.0	0.4	0.5	0.8	2.0	3.2
V	1.0	0.1	2.2	4.6	7.9	3.2	0.2	6.6	12.9	22.9
IV	7.9	0.3	16.3	24.7	49.1	22.8	0.4	46.1	63.3	132.6
III	49.1	0.3	84.0	90.8	224.2	132.3	0.4	300.0	287.7	720.4
II	223.6	0.1	901.6	820.4	1946.0	719.7	0	1128.4	808.2	2656.3
I	1945.5	0	2782.6	0	4728.1	2656.0	4230	0	0	11979.4
Sum	2227.3	0.7	3787.1	941.2	6956.4	3534.5	4231	1482.0	1174.3	15515.3

Many predators consume adult banana prawns, and adult banana prawns consume a variety of prey (Figure 6-18). Accurate specification of prawn sub-webs, i.e. the trophic relationships of prawns to their predators and prey, was emphasized (given priority) during the construction of the Albatross Bay model so that the prawn dynamics would be specified adequately.

Stomatopods can impose a very large proportion of the overall banana prawn mortality (Figure 6-18 and Figure 6-19) when even just 5% of the stomatopod diet is specified to be adult banana prawn. This 5% specified in the present model is based on the best available diet information from similar systems used during model construction. A preliminary sample of stomatopod gut contents was analyzed because these model results imply that predation of prawns by stomatopods (or other similar predators) might be key to understanding prawn dynamics in Albatross Bay, and because the notion of strong predation by stomatopods is consistent with fisherman observations and other anecdotal information. This special analysis indicated that stomatopods might consume prawns exclusively, at least during certain times of the year and from particular localities (Robinson 2006), implying that the specified 5% of the diet allocated to prawns is a considerable underestimate and that stomatopods would have a much bigger impact than that specified by the current version of the model.

Stomatopods impose this high mortality because the Ecopath algorithm calculated a very large stomatopod biomass in the Albatross Bay area based on the high demand for stomatopods in the fish diets specified in the model. Although it is quite possible that stomatopod biomass was somehow overestimated in the diets of fish predators, considerable downward adjustment would still impose a huge mortality on prawns with only a small stomatopod preference for prawns. We conducted some of the analyses presented in this report without specifying a prawn diet for stomatopods, as there were no available site-specific data about stomatopod diets (or abundance) from the Albatross Bay area or from anywhere in Northern Australia during the time of model construction. Other simulations with 5% of the stomatopod diet as prawn biomass, based on information from other regions indicated that stomatopods were key to the prawn dynamics, but other vampires from the basement emerged when we ‘underemphasized’ the role of stomatopods.

The issue of unknown or emerging predators is a critical one for Australia’s Northern Prawn Fishery, and this is but one example of important and fruitful avenues of research that are indicated by the current trophodynamic model. Improved information about predators such as stomatopods and octopods will be used to refine the model to improve its performance and usefulness in the coming years.

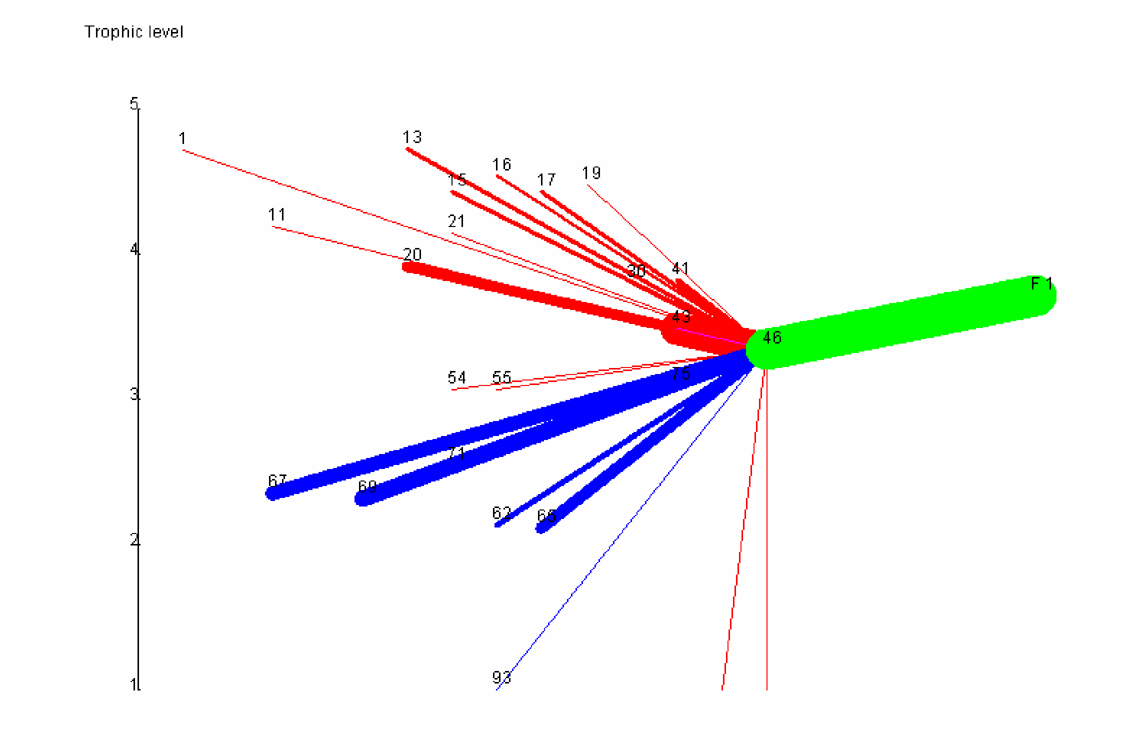

Figure 6-18: The adult banana prawn sub-web of the Albatross Bay area, Gulf of Carpentaria. Line thickness indicates relative magnitude of flows. Red lines are flows to predators (and detritus), blue lines are flows from prey, and the green line is the flow to the fishery. Numbers refer to the functional groups shown in Table 6-8. In this figure, vertical position indicates trophic level, but horizontal position is arbitrary, so the length of connector lines means nothing. F1 equals banana prawn fishery.

Table 6-8. Predators and prey of adult banana prawns in the Albatross Bay model. The numbers refer to the functional groups shown in Figure 6-18.

Predator	**Prey**	**Group name**
1		Dolphins
11		Medium pelagic piscivores
13		Sawfishes
15		Small benthic piscivores
16		Large elasmo benthopelagic piscivores
17		Large teleost benthopelagic piscivores
19		Large benthopelagic invert feeders
20		Small benthopelagic invert feeders
21		Large elasmo benthic invert feeders
30		Estuary large teleost benthopelagic pisc/prawn feeder
41		Octopus
54		Mud crabs *(Scylla serratta)*
55		Red mud crabs *(S. olivacea)*
43		Stomatopods
	62	Ophiuroids
	65	Marine bivalves
	67	Marine small crustaceans
	69	Marine worms
	71	Marine small gastropods
	75	Marine forams
	93	Discards

Note: Refer to Appendix IV-5 for the species compositions of fish groups.

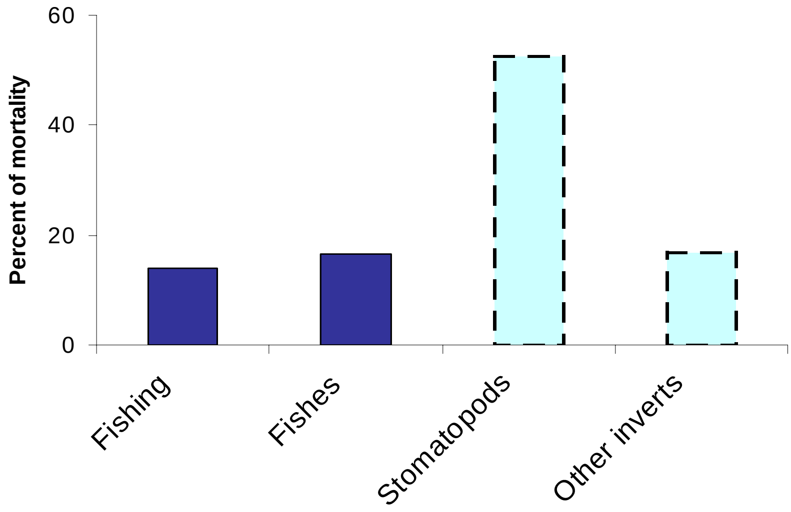

Figure 6-19: Relative mortality imposed on adult banana prawns in Albatross Bay by major consuming groups. Dashed (lighter) bars indicate high uncertainty in those functional groups. The stomatopod bar is the result of adult banana prawns making up only 5% of the overall stomatopod diet (see text).

An analysis indicating the possible relative magnitudes of direct and indirect trophic impacts of each functional group in the system on the three identified life stages of prawns (in a steady state context) Figure 6-20 indicates those species that might be strong facilitators of banana prawn biomass (the larger bars above zero) and those that might have strong negative effects on banana prawn biomass (larger bars below zero). The large positive bars towards the lower end of the figure (lower trophic levels) represent prawn food items, which obviously have a positive trophic effect on banana prawn life stages. Strongly positive bars towards the top of the figure (high trophic levels) generally represent predatory facilitators of banana prawns, whereas strongly negative bars at upper-mid trophic levels represent vampires from the basement-predators of banana prawns that later analyses indicate emerge significantly when key apex predator groups are removed. Competitive effects are indicated by both positive and negative bars at middle trophic levels. This static analysis of mixed trophic impacts is a useful screening tool for choosing profitable dynamic simulation strategies. It is based on the approach developed by Leontief (1951) and later applied to ecological systems by Hannon (1973), Hannon and Joiris (1989), and Ulanowicz and Puccia (1990). It also serves as a form of ordinary sensitivity test (Majkowski 1982).

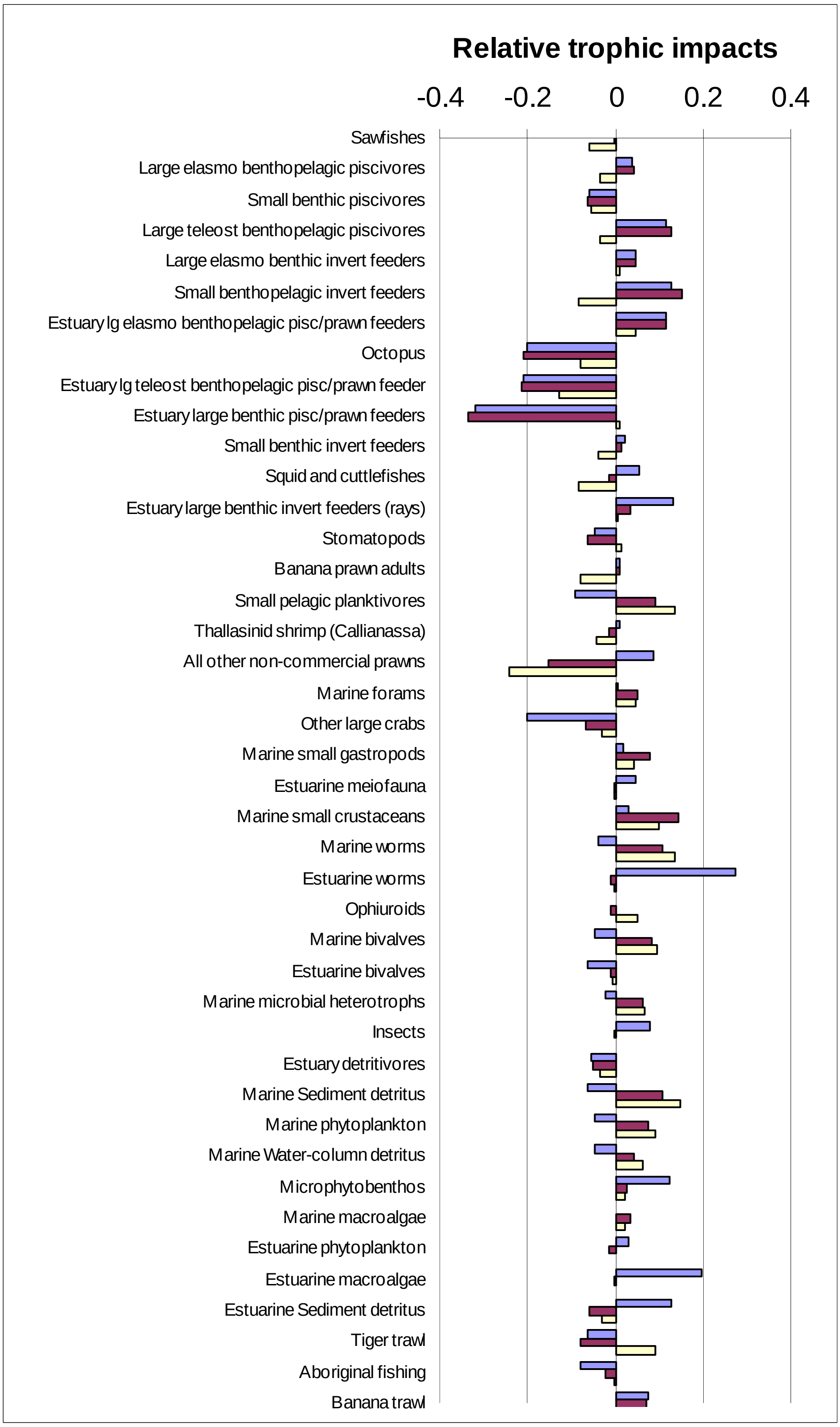

Figure 6-20. Estimated relative trophic impact of each functional group in the Albatross Bay model on banana prawn juveniles (blue), subadults (red), and adults (white). This static 'trophic impacts' analysis indicates that functional groups with values above zero provide beneficial trophic effects (i.e. facilitate prawn group biomasses), whereas groups with values below zero tend to reduce prawn group biomasses. The version of the model depicted here does not include stomatopods feeding on prawns, and so does not show the overwhelmingly large negative effect of stomatopods on banana prawns. Groups not indicated to cause ≥ 5% change were excluded from this figure.

Simplified trawl impact scenarios

Preliminary simulations using Ecosim's gaming interface and simple hypothetical trawling strategies indicted that banana prawn (*Penaeus merguiensis*) biomass in the Albatross Bay area would have declined considerably with either increases or large decreases in 1986 banana prawn trawling rates (directly through stock overfishing), and it would have declined considerably with increases in tiger prawn trawling rates (indirectly through 'ecosystem overfishing').

A simulated gradual linear doubling of banana prawn trawling from 1986 levels would have decreased banana prawn biomass by ~90% (Figure 6-21a). This prediction manifests (in the model) as direct impacts (i.e. stock overfishing). The simulations also show that a gradual doubling of tiger prawn trawling from 1986 levels would have decreased banana prawn biomass by ~70% (Figure 6-21b), but in this case the effect manifests indirectly through increased predation of banana prawns caused by a fishery-initiated shift in the Albatross Bay biotic assemblage (ecosystem overfishing). A gradual doubling of both banana and tiger prawn trawling fishing caused a ~98% decrease in banana prawn biomass through combined stock overfishing and ecosystem overfishing (Figure 6-21c).

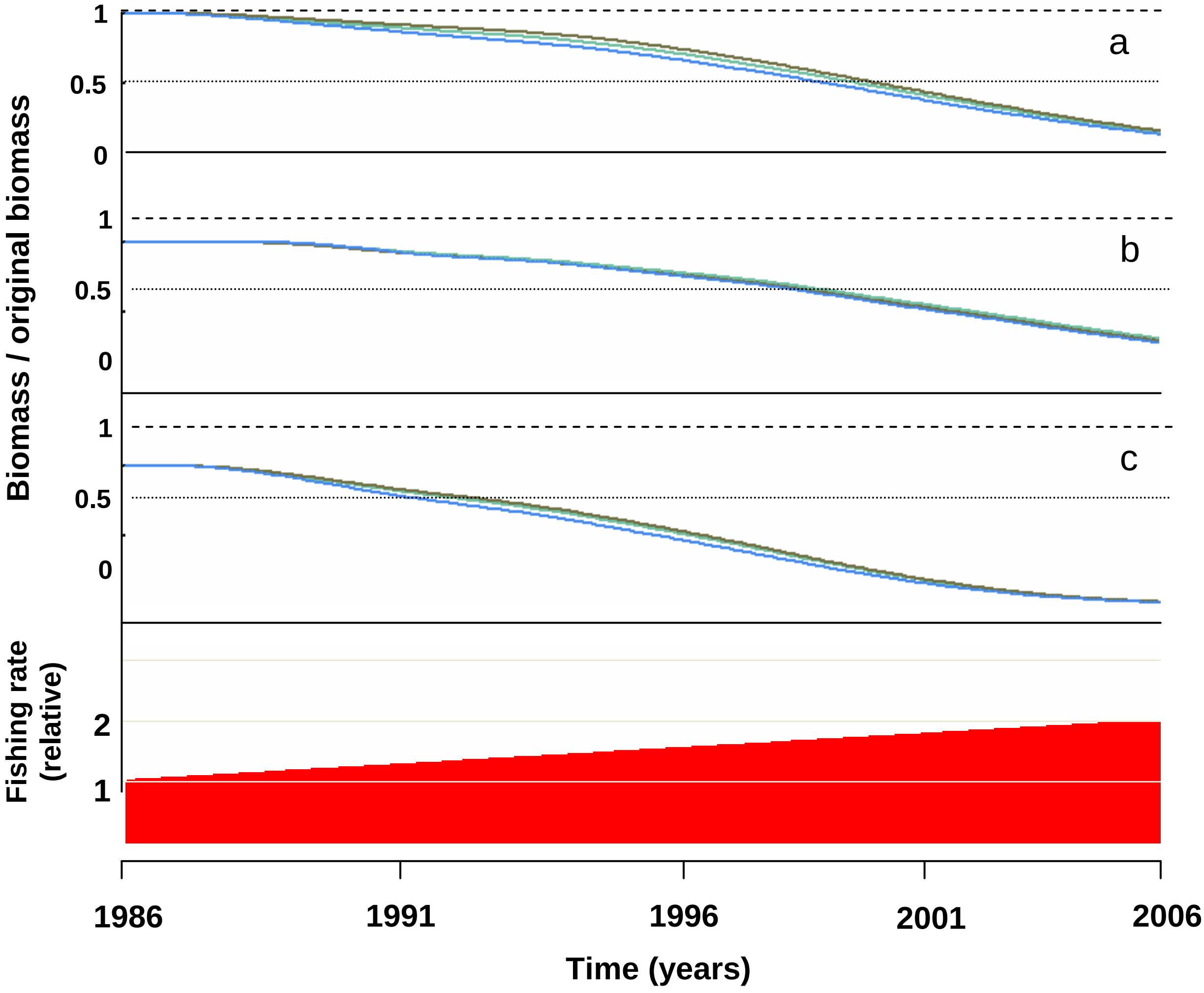

Figure 6-21: Predicted biomass trajectories of juvenile (green line), sub-adult (brown line), and adult banana prawns (Penaeus merguiensis) (blue line) in response to an hypothetical gradual doubling of (a) banana prawn trawling, (b) tiger prawn trawling, and (c) both from the 1986 level.

A simulated gradual linear decrease in prawn trawling in the Albatross Bay area from 1986 levels to zero by 2006 (whether banana prawn trawling, tiger prawn trawling, or both combined) lead to predicted increases in banana prawn biomass for about 12 years, followed by considerable declines in biomass (to ~40% of 1986 levels) in cases where banana prawn trawling was eliminated (Figure 6-22). Stated another way, the simulation indicates that anywhere between 50% and 75% of the 1986 fishing rate (by banana prawns or both fleets) would lead to noticeable increases in banana prawn biomasses. Fisheries economic analyses should therefore indicate that fleet efficiency and profitability would be considerably enhanced at these considerably lowered fishing rates.

Elimination of tiger prawn trawling lead to sustained moderate increases in banana prawn biomass (Figure 6-22b). Again banana prawn trawl impacts manifest mostly directly (i.e. stock overfishing), whereas tiger prawn trawl impacts manifest indirectly (i.e. ecosystem overfishing).

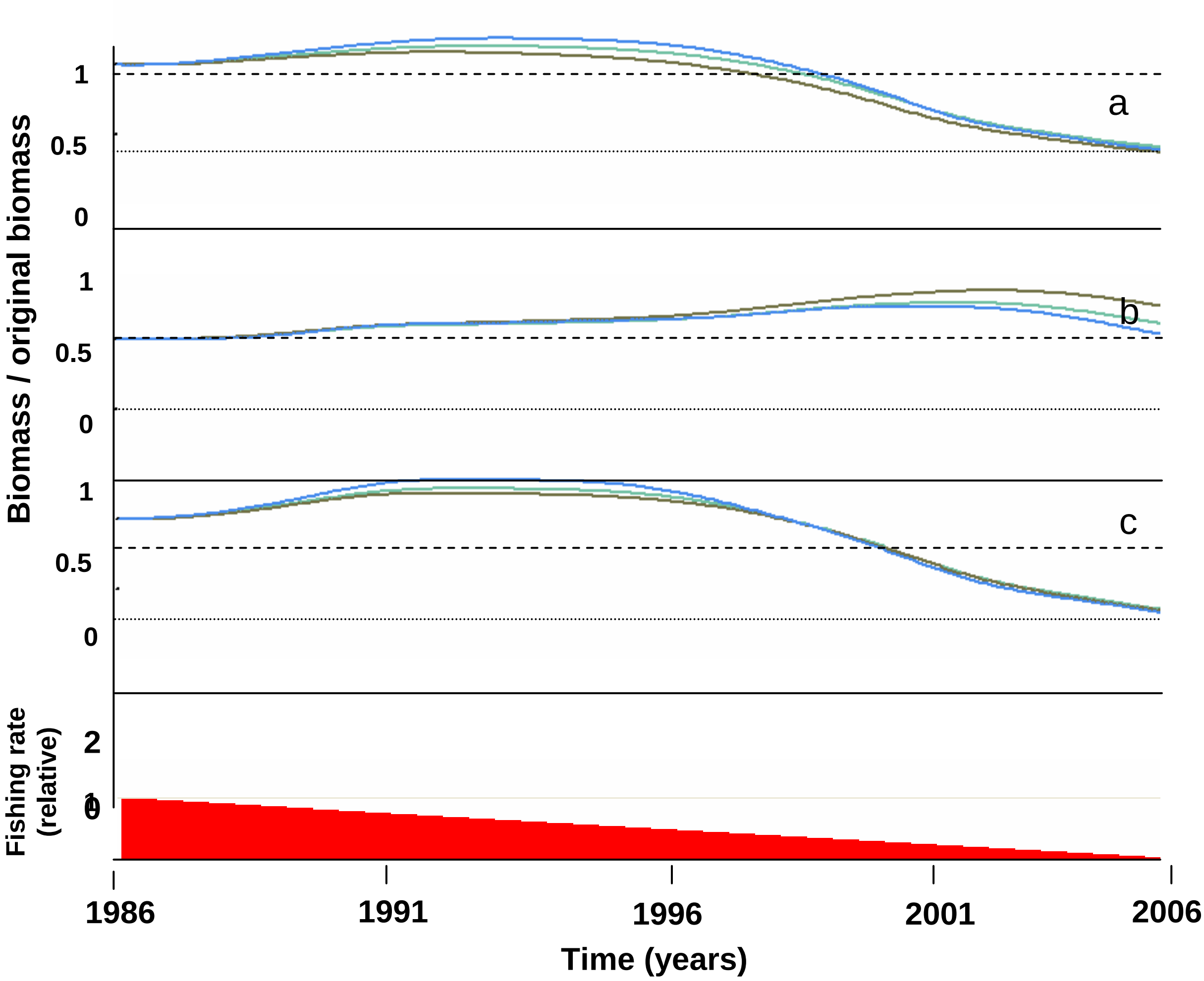

Figure 6-22. Predicted biomass trajectories of juvenile, sub-adult, and adult banana prawns (Penaeus merguiensis) in response to a gradual removal of: (a) banana prawn trawling; (b) tiger prawn trawling; and (c) both from the 1986 level.

A simulated trajectory of prawn trawling, i.e. a gradual doubling of fishing rate from 1986 to 1989 followed by a steady rate until 1996 and then a gradual decrease to zero in 2006, led to expected decreases during the early years of the simulations followed by signs of recovery after either banana or tiger prawn trawling rates decreased sufficiently in the most recent years of the simulation (a and b). Banana prawns failed to recover in the simulation of both prawn trawl fleets were exposed to the same scenario. This fishing strategy is a hypothetical caricature of the actual history of fishing rates in this system, which is considerably variable, but the results seem reasonable given this preliminary simplification, as they illustrate plausible outcomes of such a simplified “target-based” strategy.

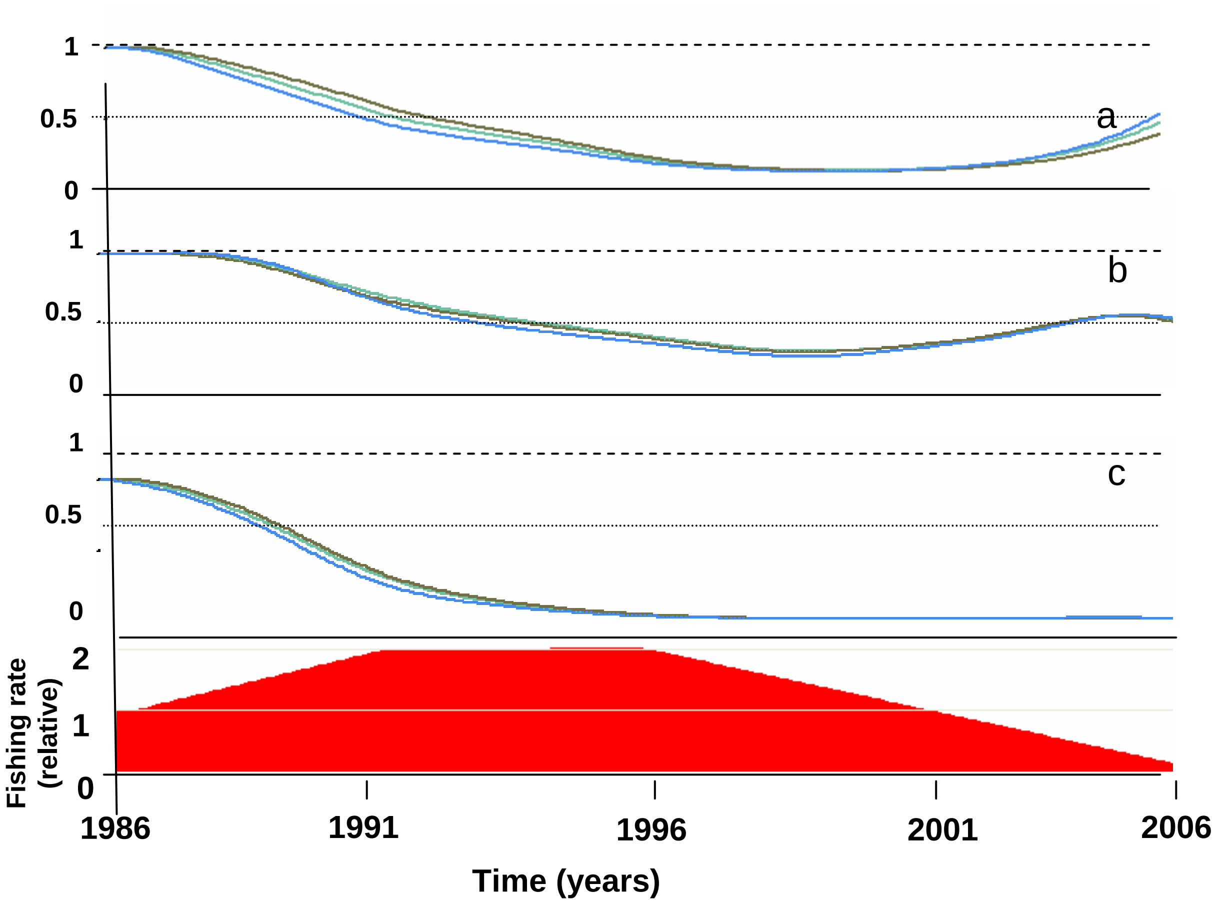

Figure 6-23. Predicted biomass trajectories of banana prawn (*Penaeus merguiensis*) juveniles (green line), sub-adults (brown line), and adults (blue line) in response to caricatured trawling rate history scenario shown in bottom panel: a gradual doubling from 1986 to 1989 then a gradual decrease from 1996 until the present of (a) banana prawn trawling; (b) tiger prawn trawling; and (c) both from the 1986 level.

Examination of the broader community effects of a gradual doubling of both banana prawn and tiger prawn trawling rates from 1986 levels (Figure 6-24) indicates that Albatross Bay area prawn trawl fisheries modify the structure of the biological community strongly-reducing the biomasses of a broad array of functional groups (mostly those at upper to mid trophic levels) while allowing another suite of functional groups to increase (mostly at mid to lower trophic levels).

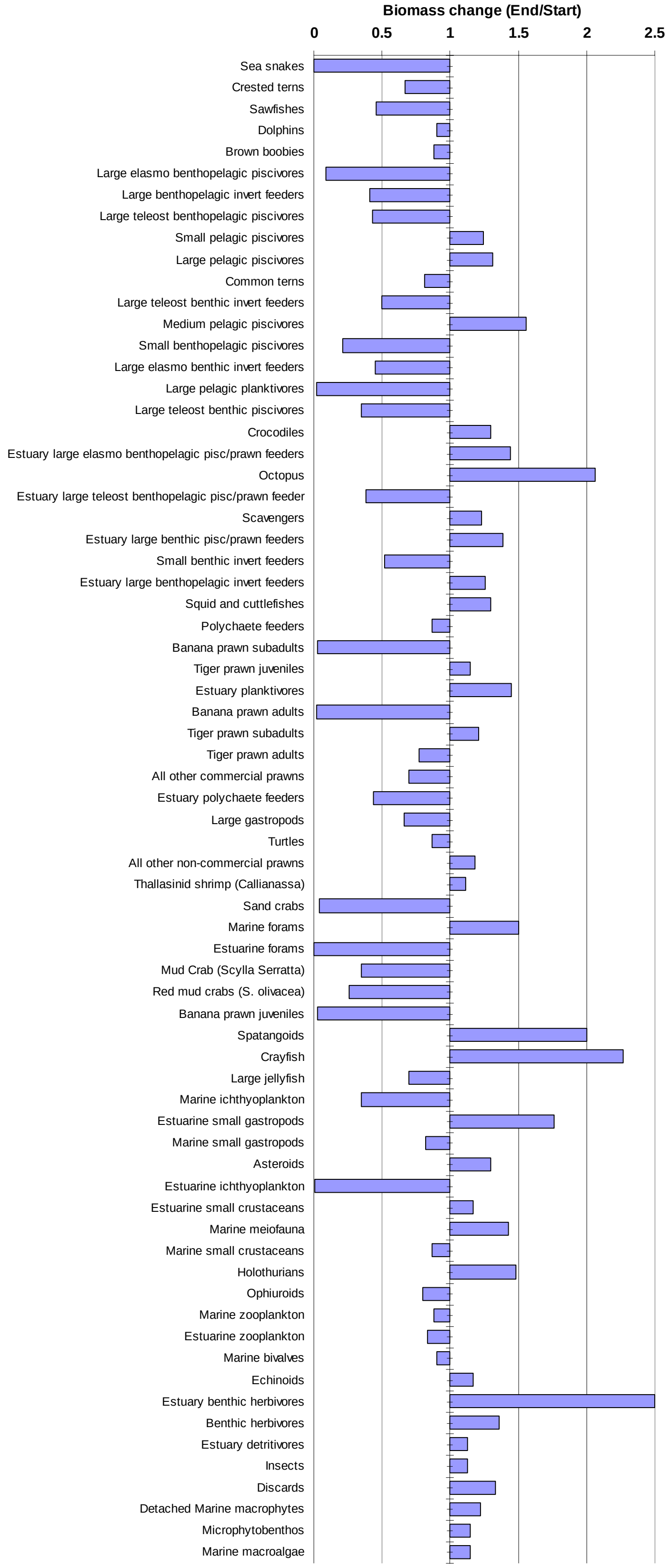

Figure 6-24. Predicted changes in each functional group in the Albatross Bay model 20 years after a gradual linear doubling of both banana prawn and tiger prawn trawling rate from 1986 levels (Scenario c in Figure 6-21). Groups are presented in order of descending trophic level and only those groups that were predicted to change greater than 10% are presented.

A closer examination of this broad pattern of community modification reveals predicted impacts that are consistent with the general life habits, life history characteristics, and bycatch rates of the various functional groups. For example, sea snakes, offshore sharks, and other large offshore benthic and benthopelagic piscivore and invertivore groups decreased, whereas some pelagic fish groups and cephalopods increased with increased prawn trawling. Crabs decreased, whereas less vulnerable and faster growing scavengers, herbivores, and planktivores increased.

In general, this simulation exemplifies the potential usefulness of this modelling approach. The present iteration of the Albatross Bay model produces simulations that provide qualitatively useful insights. Future refined iterations of the model can provide accurate and prescriptive simulations if further investments are made to continue developing and refining this model.

If these preliminary simulations are accurate qualitatively (e.g., considerably decreased banana prawn trawling decreases banana prawns) one implication is that prawn trawl fisheries are ‘productive’ because this form of fishing modifies the overall ecosystem to the benefit of prawns through, for example, the reduction of the predators and competitors of prawns through bycatch. The humans in this system reduce their own competitors non-selectively and this generally tends to increase prawn biomass until a ‘tipping point’ of fishing rate beyond which prawns begin to become overfished directly, or until the non-selective modification of the resident assemblage favours species that are effective predators of prawns, or until both effects manifest. This is indicated by the combination of direct and indirect effects revealed through the simplified scenarios, and by the evidence presented previously (and below) that certain apex predators, which are vulnerable to prawn trawling, facilitate banana prawns by controlling key vampires from the basement. Obviously, the 1986 Albatross Bay community was not ‘pristine’ or un-fished, and indeed it appears that the 1986 banana prawn trawling rate was higher than optimal for banana prawn biomass (Figure 6-22a and c), but simulations using this as a starting point still provide very useful insights.

It is not surprising that a fishery with high rates of bycatch, such as Australia’s Northern Prawn Fishery, would encounter unexpected and indirect ecological outcomes of fishing. Examination of preliminary Albatross Bay Ecopath model simulations indicates that the depletion of certain apex predators (e.g., via trawl bycatch) reduces banana prawn biomass by, for example, enabling the emergence (increase in biomass) of organisms that impose mortality on banana prawns. Such indirect trophic effects, or ‘trophic cascades’, might well be common in marine ecosystems, albeit difficult to see or detect without empirically-based trophodynamic models and empirical studies to evaluate their existence and strength. The present trophodynamic modeling approach is ideally suited to highlight such trophic cascades, especially those that are strong and conspicuous.

Vampires from the basement

Vampires from the basement are species that might compete with humans for food and whose populations increase unexpectedly when ecosystems are perturbed by fishing, thus causing ecological outcomes unwelcome to human users of the system (C. Walters, personal communication). If fishing reduces or removes biotic components in an ecosystem, other biota are likely to replace those that were removed because of the sudden availability of excess exploitable energy (e.g., prey biomass). The perturbation of complex ecosystems can result in surprising increases of sometimes unexpected species as energy flows are redirected through the modified ecosystem linkages.

Note that two versions of the Albatross Bay model were used for this series of simulations—one that does not include banana prawns in stomatopod diets (the following three subsections) and one that does (the Stomatopod subsection).

Octopus

Banana prawns decline in the Albatross Bay model if we simulate the removal of benthic sharks and rays (the 'Large elasmobranch benthic invertebrate feeders' functional group) by imposing high bycatch fishing mortality directly on that group (Figure 6-25). In this simulation, banana prawns declined because octopus increased as the result of removing this group.

It is important to note when interpreting Figure 6-25 that the bars represent relative change and do not indicate absolute biomass or consumption rates. Thus, one must examine the dynamics of both the relative changes in flows and the absolute flows in order to gain insights into emergent causality in these simulations. Examples of such diagnostics provided in the Ecosim routine include changes in mortality components, feeding time, consumption rates, predation mortality, and percent prey, in addition to changes in biomass, etc.

This trophic cascade manifests, not because rays are removed, but because the depletion of sicklefin weasel shark (*Hemigaleus microstoma)* a component of this functional group and a specialist octopus-eater enabled a considerable increase in octopus biomass, which in turn increased the mortality on banana prawns enough to cause a considerable decline. This mechanism of banana prawn biomass decline is quantitatively plausible based on the information in the model because prawn trawling is predicted to easily deplete benthic sharks and rays ('Large elasmobranch benthic invertebrate feeders') (Figure 6-24). This simulation reveals a plausible mechanism of banana prawn biomass declines driven indirectly by prawn trawling, an affect that could not be accounted for by single-species fisheries models.

The sicklefin weasel shark facilitates banana prawn populations by controlling an apparently important predator of prawns - even if this shark controls only one critical life stage of that predator – i.e. juvenile octopuses. When we simulate the removal of that shark species, banana prawns are predicted to decline as the result of increased predation pressure. Prawn trawling adversely affects this particular shark directly as bycatch, so at least in this one example the incidental capture of non-target species is indicated to reduce banana prawn populations indirectly and in a non-trivial way. Such simulations indicate possibilities, or hypotheses, that are plausible, thereby pointing the way toward approaches that can be developed to test these hypotheses. This indicates a trophic cascade that can be examined explicitly using this modeling framework, as opposed to simply speculating about its existence based on knowledge about the system, or as opposed to never thinking of this potentially real dynamic at all. Verification of such a mechanism could be accomplished through either experimental studies or field sampling designed to check the relative abundances and refine the modeling analyses.

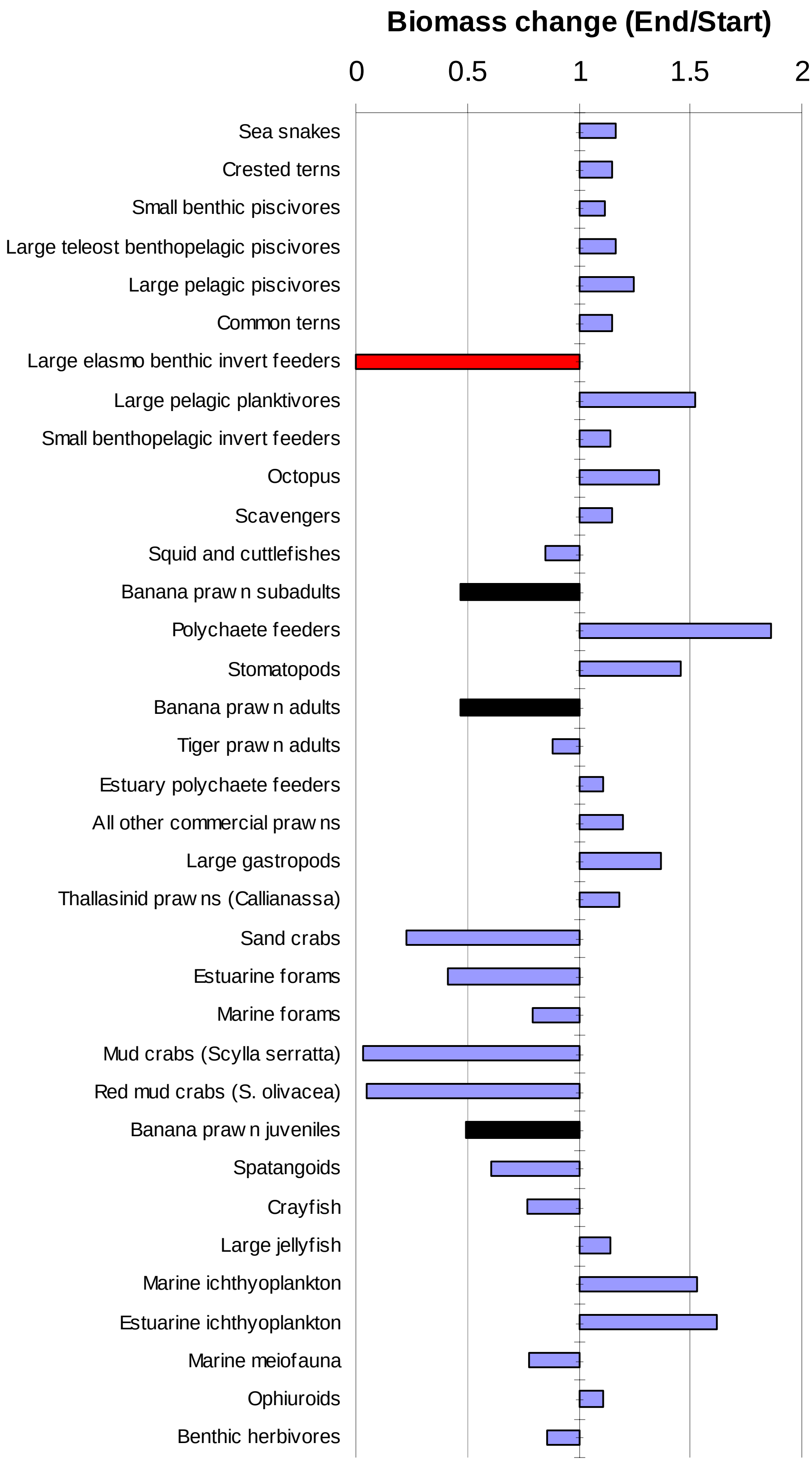

Figure 6-25. Simulated results of removing Large elasmobranch benthic invertebrate feeders from the Albatross Bay ecosystem. The red bar indicates the functional group that was removed; the solid black bars represent banana prawn life stages. Functional groups are presented in order of descending trophic level and only those groups that were predicted to change greater than ten percent are presented.

Octopuses of the Albatross Bay area presumably impose much of their banana prawn mortality on sub-adults during or just after movement of these prawns from the estuaries to the offshore areas, thus potentially explaining why January prawn “recruitment” surveys often indicate moderate to high prawn biomass while April catches have been very low during recent years. If octopuses have indeed been more abundant during these recent years, they would impose their increased prawn mortality on the fishing grounds between January and April of each year. The bycatch / shark / octopus explanation is plausible and should be evaluated further using simulation and direct empirical studies.

The removal of the Small benthopelagic invertebrate feeding fishes functional group - the other main predator of octopus - also causes a predicted collapse of all banana prawn life stages because its removal enables octopus to increase considerably, which imposes prolonged increased mortality on sub-adult and adult banana prawns, though slow increases in benthic sharks and rays (Large elasmobranch benthic invertebrate feeders) eventually begins controlling octopus in this simulation. However, the Small benthopelagic invertebrate feeding fishes functional group is not predicted or observed to have declined as the result of prawn trawling, so this simulation does not indicate a likely explanation for the recent declines in banana prawn catches. The starting fishing mortalities and predation mortalities of each bycatch functional group are specified for the ‘starting period’ in the Ecopath model and those mortality rates change over time during Ecosim dynamic simulations. During these simulations, there was never any indication that the ‘Small benthopelagic invertebrate feeding fishes’ functional group declined as the result of any of the simulations.

Simultaneous vampires

When we simulate the removal of Large teleost benthopelagic piscivores (trevallies, snappers, and barracuda) from the Albatross Bay model, banana prawn biomass is predicted to decline dramatically (by 90%). This decline manifests because of increases in three predators of juvenile and subadult banana prawns: Estuary large benthic fish/prawn eating fishes, octopus, and stomatopods. The removal of this functional group also enables increases of three groups that feed on adult prawns (Small benthic piscivores, small benthopelagic invertebrate feeders, and octopus), but the decline is caused principally by the aforementioned predation on the juvenile and subadult life stages. This simulation represents another plausible explanation for the recent observed declines in banana prawn catches, as the biomass of Large teleost benthopelagic piscivores is predicted to be affected strongly (decreased) by prawn trawling (Figure 6-24). The present simulation is also consistent with the observed moderate to high January biomasses of banana prawn recruits, since much of the predation on these prawns might occur between January and April given the life history of banana prawns.

Barramundi

Sharks are indicated by yet another simulation to facilitate prawns in the Albatross Bay area, in this case due largely to their control of barramundi. If we simulate the removal of the Estuary large elasmobranch benthopelagic pisc/prawn feeders (estuary carcharhinid sharks), banana prawn biomass is predicted to decline (by 70%) because of increases in barramundi biomass and subsequent mortality of juvenile and sub-adult life stages of banana prawns. This simulation indicates the importance of estuarine sharks in facilitating and maintaining prawn populations. However, the estuary sharks group is not indicated to have declined as the result of prawn trawling (because they reside principally in the protected estuaries). Other evidence indicates that estuary shark populations in the Albatross Bay region might be healthy for the time being due to inshore fishery restrictions. This estuary shark / barramundi explanation, therefore, should not be considered a highly plausible explanation for the recent observed declines in banana prawn catches, even though it does stand out as an issue for future management. Management that maximizes barramundi populations would, according to the current Albatross Bay model, tend to degrade banana prawn resources, and vice versa. All of the examples presented thus far indicate trade-offs between species, but the barramundi example is easiest to visualize: You can have lots of Barramundi, or you can have lots of prawns, but it might not be possible to have both.

Stomatopods

Early simulations using strawman versions of the Albatross Bay model indicated that stomatopod mortality might overwhelm other sources of banana prawn mortality (fishes and fishery), even when very low proportions of stomatopod diet is comprised of banana prawns (see Figure 6-19). This high mortality imposed by stomatopods on prawns is indicated by high biomasses of stomatopods from fish diet information, even when the high end of stomatopod production rate estimates are used in the model in order to minimize the estimated stomatopod biomass. The stomatopod sub-web is among the most complex functional group sub-webs in the Albatross Bay model (Figure 6-26). This sub-web shows the empirically-based high demand for stomatopods by fish predators, which necessitates the calculated high stomatopod biomass. The relative flows from prawn groups to stomatopods are very small, but the biomass of banana and other commercial prawn groups are specified to be small relative to that of stomatopods (Table 6-4) making the effect strong even though the flows are not large.

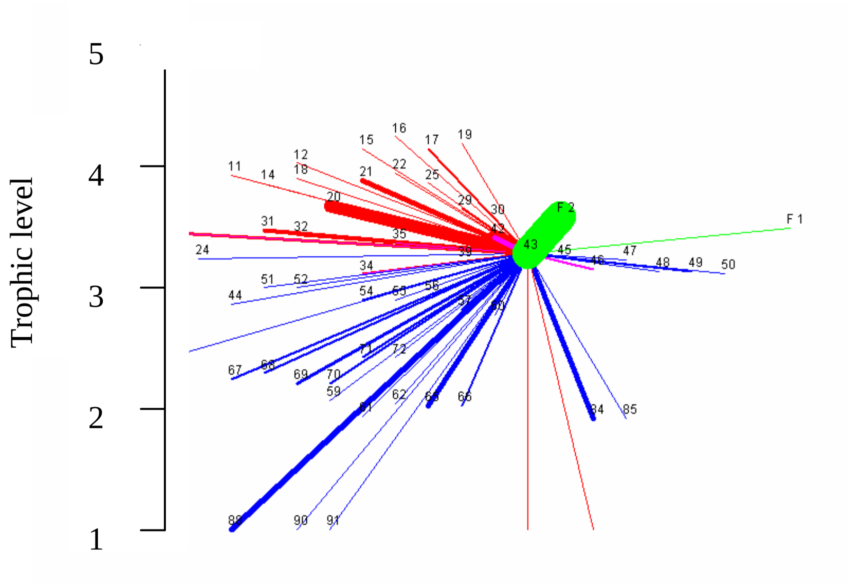

Figure 6-26. The stomatopod sub-web of the Albatross Bay area, Gulf of Carpentaria. Line thickness indicates relative magnitude of flows. Red lines are flows to predators (and detritus), blue lines are flows from prey, and the green lines are bycatch flows to the fisheries. F1 is the banana prawn trawl fishery and F2 is the tiger prawn trawl fishery. The flows of stomatopods to fish predators (red lines) is reasonably well known for the Albatross Bay area, whereas the stomatopod diet composition used here is borrowed from other systems and based on the author's judgement.

The simulations described in the previous sub-sections were conducted using a version of the Albatross Bay model in which stomatopods were not specified to consume banana prawns because of the high uncertainty of stomatopod diets in the Albatross Bay area, and in the Gulf of Carpentaria. Subsequent preliminary work has indicated that prawns might be the exclusive component of stomatopod diet, at least during some portions of the year (Robinson 2006). The simulations described in the present sub-section were conducted with a version of the Albatross Bay model in which 5% of the stomatopod diet consisted of adult banana prawns, 1% consisted of sub-adult banana prawns, and 1% consisted of juvenile banana prawns.

Banana prawns are predicted to decline by 60% when offshore carcharhinid sharks (Large elasmobranch benthopelagic piscivores) are removed from the system, and this is mediated ultimately by stomatopods (no figure). This decline is manifested in the model through a six-link trophic cascade (including humans). This cascade can be simplified as a chain of strong interactions. The removal of carcharhinid sharks causes an increase in the biomass of Small benthic piscivores (*Saurida* spp. and *Platycephalus* spp.), which causes a decrease in squid and cuttlefish, which in turn causes an increase in stomatopods, which then causes a decline in juvenile and sub-adult banana prawn biomass, which is finally predicted to cause adult banana prawn biomass to decline.

The plausibility of such an indirect (and seemingly unrealistically long) trophic cascade is justified because some of the predator functional groups are affecting their prey biomass by consuming early life stages of their prey, and this can be examined more explicitly in future iterations and refinements of the model. Other issues detract from the plausibility of this particular trophic cascade mechanism of banana prawn decline. For example, squid and cuttlefish might decline if the Albatross Bay system were bounded, but it is an open system in reality, and so the current iteration of the model might overestimate the impact of small benthic piscivores on squid and cuttlefish biomass, which in reality might typically replenish from a more oceanic meta-population, and this might be true for several other functional groups. These issues too can be adjusted and refined in future iterations of the model. Observed increases, rather than decreases, of squid and cuttlefish in this system might also discredit this simulation/hypothesis.

In addition to obvious implications about the critical role of carcharhinid sharks in structuring and regulating the Albatross Bay ecosystem (and potentially facilitating banana prawns), this simulation indicates the potentially central role of stomatopods in helping to structure and regulate this system, even if the entire cascade is qualitatively incorrect. Stomatopods influenced banana prawns very strongly in this simulation through only 2% of their diet at the most since the main effect manifested through juvenile and sub-adult banana prawns rather than adults (5% of the stomatopod diet was on adult banana prawns). It is very likely that banana prawns make up considerably more than 7% (2% + 5%) of the stomatopod diet, and that could mean that stomatopods (and sharks) are the key(s) to understanding banana prawn (and tiger prawn) dynamics.

Removal of Large teleost benthopelagic piscivores (trevallies, snappers, and barracuda) from this “Stomatopod feeding” version of the Albatross Bay model causes a predicted 99% decline in banana prawn biomass through the very same trophic cascade described above for the removal carcharhinid sharks. This indicates, as discussed previously in the context of the “non-stomatopod feeding”, that the trevallies-snappers-barracuda functional group is also a key facilitator of banana prawns. This could be wrong, but it is what the current versions of the Albatross Bay model indicates presently.

The removal of the Small benthic invertebrate feeding fishes functional group also causes banana prawns to decline (by ~20%), primarily by enabling increases in stomatopods, which impose increased mortality on juvenile and sub-adult banana prawns.

Time series fitting

In addition to driving the Ecosim simulations with the simplified fishing scenarios described above, simulations were also driven by quantitatively derived historical time series of effort in the seven fishing fleets as an attempt to reconstruct the past ecosystem and fishery changes more accurately and precisely than the simplified scenarios could. The goal of this effort was to impose these historical time series of effort to the existing catches and discards in the 1986 to 1992 base model (left hand panels of Figure 6-27 and Figure 6-29) in order to fit the resulting predicted biomass trajectories with observed catch trajectories and indices of biomass. Two different indices were used: the banana prawn index is the relative time required to capture 90% of the banana prawn catch; and the tiger prawn index is catch per unit effort (CPUE). To accomplish the best fit to the observed data, Ecosim uses an optimization routine to search for the combination of prey rates that will reduce the sum of squares of the divergences of predicted from observed (Christensen *et al.* 2004). The simulated banana prawn biomass trajectory followed index of biomass that was used, in the roughest sense, but the fit to the highly variable observations was poor (Figure 6-27).

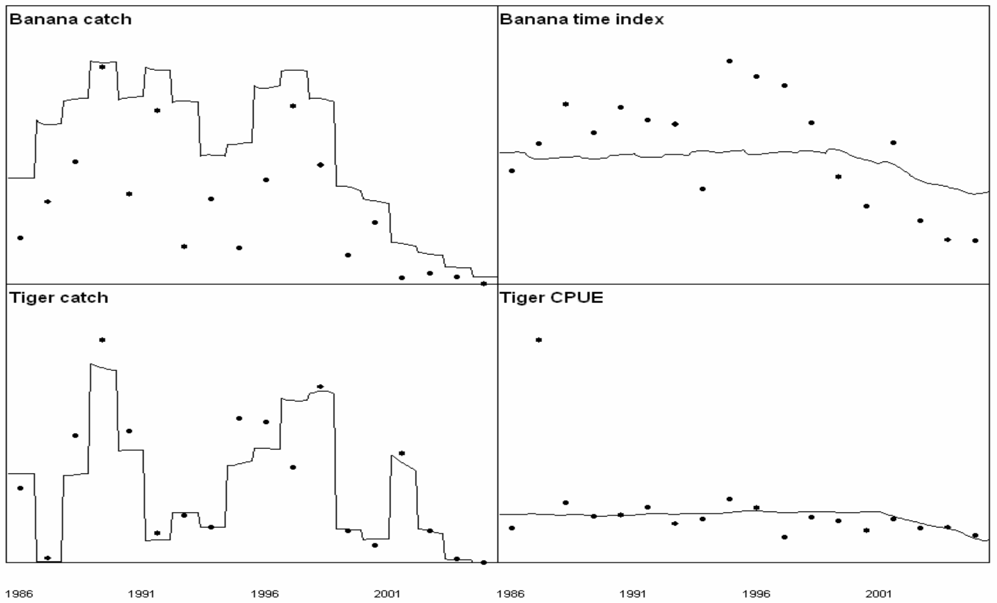

Figure 6-27. Predicted trajectories of catches and biomasses of banana prawns and tiger prawns (lines) fitted to historical observations of catches and biomass indices (dots), driven by historical changes in fisheries effort. The banana prawn index (upper right panel) is the relative time required to capture 90% of the banana prawn catch. The tiger prawn index (lower right panel) is catch per unit effort.

These results indicate that historical fishing effort, within the context of the trophodynamic interactions specified in this version of the Albatross Bay Ecopath model, can only partially explain the “observed” decline in banana prawn and tiger prawn biomass in recent years and in the very roughest of ways. The Ecosim fitting routine can also be set to search for anomalies of error in fitting, which could be considered anomalies of primary production (Figure 6-28), which can then be used to drive biomass trajectories in combination with the fisheries time series in order to improve the fit of those trajectories to the observed data. This is used as a big ‘error term’ that is called a production anomaly. This production anomaly error term improved this preliminary poor fit only slightly (Figure 6-29).

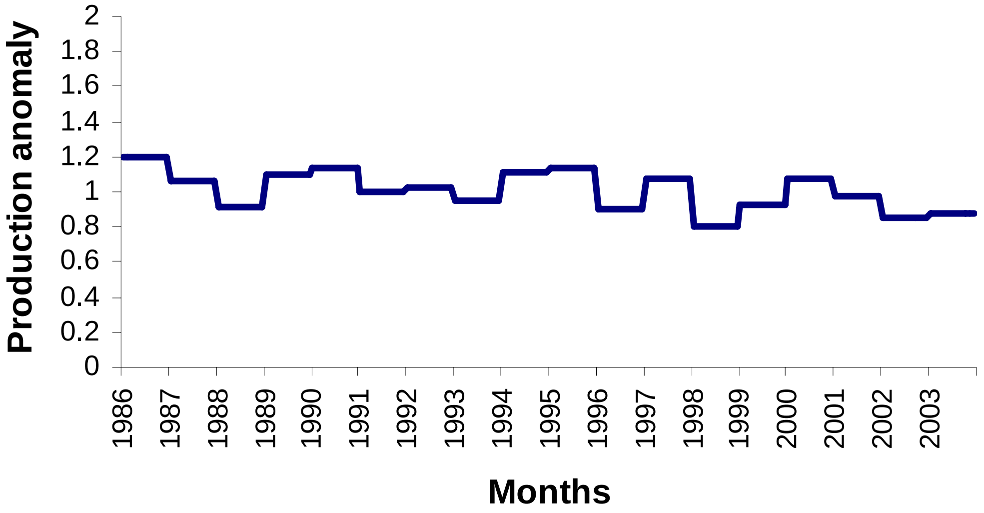

Figure 6-28. Anomaly produced during a search for error in fitting predicted biomass trajectories to observed biomasses in Albatross Bay using historical fisheries information. This error anomaly was used as an anomaly of production to try to improve this fit.

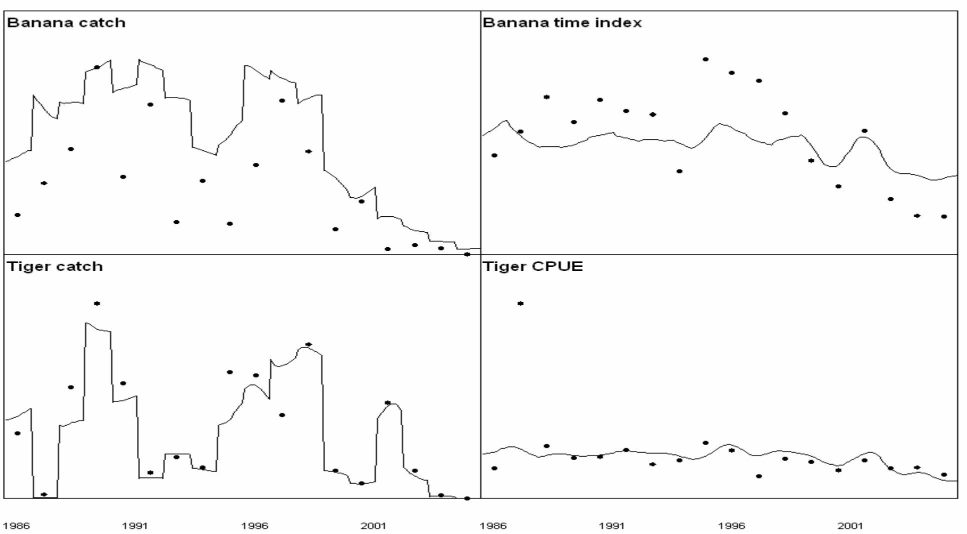

Figure 6-29. Predicted trajectories of catches and biomasses of banana prawns and tiger prawns (lines) fitted to historical observations of catches and biomass indices (dots), driven by a combination of historical fisheries effort and a produced anomaly of primary production error.

Ecological model refinement

It is challenging to construct a static trophodynamic model of a tropical marine ecosystem and to refine it to the point where it begins to provide useful and insightful results that relate to management of the human activities in the system, such as the predominant fisheries.

The existing Albatross Bay model is considered preliminary. Most parameters in the model need to be further reviewed, checked, and refined before the model can be used for rigorous quantitative prediction in the sense of reconstructing past ecosystem changes accurately. Nevertheless, the qualitative results of the preliminary quantitative simulations, e.g. the relative magnitudes of predicted changes, can be examined to: help understand the overall effects of fisheries and other stressors; to gain insights into the causes of recently observed catch declines; and to improve understanding of system structure, functions, and interactions.

It is even more challenging to reconstruct ecosystem changes in a complex tropical ecosystem such that the results of simulations are quantitatively accurate and precise. This was beyond the scope of the present study, which was designed to construct a preliminary trophodynamic model as a framework for understanding the food web and ecosystem and to conduct preliminary simulations to gain insights into the banana prawn dilemma at hand. A reconstruction of ecosystem changes was attempted nevertheless. Although considerable time was devoted to refining model input parameters to develop this analysis, the present author does not consider present results of the time series fitting analysis to be reliable. Rather, they serve here as an example of the types of analysis that can be conducted if investments are made to refine this simulation approach and the underlying model further. If such an investment is made the reliability of this approach to accurately reconstruct ecosystem changes can be improved considerably, though some basic problems are beyond the control of a desktop modeling exercise. Several problems prevent straightforward time series fitting simulations.

One major category of problems with the time series fitting is the apparent high temporal (e.g. inter-annual) variability in populations (e.g. prawn populations) and in fishery catch and effort. This high variability is difficult to simulate or reconstruct using the present iteration of the Albatross Bay Ecopath model. That is to say, high variability probably magnifies the effect of imprecision in the response speed of biotic groups to changes in fishing, predation, or resources. This problem could result from the underlying behavior of the Ecopath with Ecosim model formulation, but since the approach features variable speed splitting and other features that account for biological components that change at different speeds, the reliability of this model can probably be improved vastly by parameterizing the dynamics more carefully and correctly during future iterations of model refinement. Another major problem is the lack of reliable biomass indices (i.e. observed biomass) to fit the predicted biomass trajectories against. A third problem is the lack of adequate time series of primary production, river flow rates, and other important physical variables in the system that could be specified as a time series that forces selected biotic components in the model.

Fish biomasses and diet compositions are comparatively rigorous in the model as a result of comprehensive site-specific studies of the fish fauna of the Albatross Bay area. It is fortuitous that this information exists, as it provides the model with a good grounding of idea the predation pressure of fishes on prawns. The input parameters of other functional groups in the system – both at higher and lower trophic levels – are far less certain, and these parameters will need to be re-examined iteratively and prioritized so that research efforts on the system can be optimized to understand the whole Albatross Bay banana prawn ecosystem.

Other necessary refinements include improved estimations of fisheries catch and discard information for all the fleets, for the time period in question. Estimates of temporal (time series) changes in primary production, biomass, and fisheries information will also need to be refined continually. Information on habitats and spatial aspects of the system and functional groups will enable spatially-explicit explorations of potential future spatial policies. Finally, specification of economic and social parameters in the model will allow innovative explorations of alternative management strategies. Such capabilities of this approach will potentially be the foundation for an explicit and integrated decision support framework.

Conclusion

Given those caveats and limitations, the preliminary simulations and other analyses presented in this report indicate that the prawn trawl fisheries of the Albatross Bay region modify the resident biological community considerably, even without considering impacts on biogenic habitat. The simulations indicate that this considerable modification occurs through both direct impacts on populations of marine organisms and indirectly through trophic cascades. They also indicate that changes in catch rates of banana prawns and tiger prawns, within the magnitudes actually experienced over the past 20 y, can cause depletions of banana prawn biomass that would be severe enough to cause decreases in catch rates like those actually encountered during the last few years.

An intriguing result is that banana prawn biomasses were predicted to decrease considerably from 1986 levels with either increases or large decreases in prawn trawl catch rates, and the only apparent way to increase it marginally is by marginal decreases in prawn trawl catch rates, or with a complete reduction in tiger prawn trawl catch rates, or both. This result indicates that, up to a point, prawn trawling generally facilitates prawn biomass in this system, purely through the modification of the biological community in ways that benefit prawns-i.e. through trophic interactions. Beyond a certain point of fishing intensity, the effect of prawn trawling inhibits prawn biomass through both direct exploitation and indirect trophic effects.

An additional series of explorations and simulations indicates the presence of key banana prawn facilitators. The removal of these facilitating species/biotic groups causes the emergence of certain species (vampires from the basement) that cause considerable declines in banana prawns in the Albatross Bay ecosystem model. The presence of these trawler-facilitator-vampire-prawn cascades indicate plausible mechanisms for explaining how prawn trawling can indirectly cause sudden and persistent declines in banana prawn biomasses and catches that are surprising, in addition to direct impacts on prawn stocks. Other cascades and mechanisms might well exist in this system, and those highlighted might well be weaker than indicated by this preliminary series of analyses. Further refinement of the Albatross Bay model is needed to answer these questions with confidence.

It is nevertheless clear from this series of simulations that the present modeling approach holds considerable potential for: understanding the Albatross Bay marine ecosystem (and by extension more of Australia’s northern ecosystems); understanding the impacts of Australia’s prawn (and other) fisheries; and for informing fisheries and conservation policies. Although the present model and example simulations provide general insights about the impacts of Australia’s Northern Prawn trawl Fishery, they represent only the first step towards the development of a working trophodynamic Ecopath model that produces predictions that could be accurate and precise enough to be used explicitly for purposes such as quota setting.

Even though some lines of evidence that emerged from this modeling exercise support the notion that overfishing caused banana prawn declines, the present lack of quantitatively reliable reconstructions of ecosystem changes (i.e. explicit time series fitting using environmental variables or catch histories) prevents us from concluding whether or not the recent history of fishing actually did cause such biomass declines. Refinement of the present model might provide: Management Strategy Evaluation type bio-economic modelling; policy optimization routines based on trade-offs in maximizing disparate values in the system; spatially-explicit approaches to simulating fishery dynamics and the effects of closed areas; and other implications of human activities in these complex ecosystems.

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6.2.7 Weipa predator sampling – Steve Blaber *et al.*

Have prawn predators increased in the Embley estuary since 1990? A re-sampling of the Embley River estuary to assess changes in the fish fauna

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Introduction

Previous work (FRDC 86/13, 89/13) showed that in the Embley estuary, Norman estuary and the inshore waters of Groote Eylandt, about 50 fish species are significant predators of prawns. The diets of fish from the tropical Embley Estuary in the eastern Gulf of Carpentaria, Australia, were analysed with particular reference to piscivory and predation on juveniles of commercially important penaeid prawns from October 1986 until July 1988 (Blaber *et al.*, 1989; Salini *et al.* 1990). Of the 77 species caught, 52 were piscivorous and of these 37 ate penaeid prawns. The most numerous piscivores were *Scomberoides commersonianus* (Queenfish), *Arius proximus* (Arafura catfish), *Lates calcarifer* (Barramundi), *Polydactylus sheridani* (King salmon) and *Rhizoprionodon acutus* (Milk shark), the first four of which accounted for over 90% of all prawns eaten. Twenty species ate commercially important species of prawns. The proportions of penaeids in the diets varied seasonally, according to the density of penaeids in the estuary. The proportion was highest during the pre-wet period (November) and lowest during the dry period (July-August). Predation on prawns was highest in the lower and middle reaches of the river.

As part of the study of the reasons for declining banana prawn catches in the Weipa area, and in order to assess whether changes in predator numbers may be a factor influencing prawn numbers, the numbers of prawn eating fishes in the Embley estuary was re-examined in February 2005 for comparison with numbers in 1986 to 1990. This new study duplicated previous methods and used the same sampling sites and the same gear as employed during February sampling periods from 1986 to 1990.

Methods

Gill net sampling was undertaken from 7th to 11th of February 2005 to replicate sampling from 1986 to 1990, using a suite of nets. Areas in the lower, middle and upper reaches, with depths down to 5 m, were sampled with a fleet of 66 m monofilament gill nets of 50, 75, 100, 125 and 150 mm stretch mesh. Sampling was undertaken over all tides and day and night at each site (Table 6-9). All original sites were sampled: i.e. C1, SGB, Heinemanns Creek and Marmoss Creek. (See Blaber *et al.*, 1989 for further details).

All fish species were identified, measured and weighed. Catch rates are expressed as grams of fish per metre of net per hour fished. Fish lengths are expressed as standard length (SL), with the exception of sharks (total length) and rays (disc width).

Table 6-9: Gill net operations for the Embley estuary in February 2005 showing soak hours, gill net mesh sizes and net length per estuary reach. 1, 2, 3 refers to lower middle and upper

Operation no.	Date	Reach	Day/ night	hours	Mesh sizes (mm)	Total net length (m)
1217	07/02/2005	1	d	5	50,75	120
1218	07/02/2005	1	d	6	100,125,150	160
1219	08/02/2005	1	n	14.5	50,75,100,125,150	280
1220	08/02/2005	1	d	7	100,125,150	160
1221	09/02/2005	1	n	16	50,75,100,125,150	280
1222	09/02/2005	1	d	4	50,75,100,125,150	280
1223	10/02/2005	2	n	17	50,75,100,125,150	280
1224	10/02/2005	2	d	3	50,75,100,125,150	280
1225	10/02/2005	3	d	3	50,75,100,125,150	280
1226	11/02/2005	3	n	19	50,75,100,125,150	280

Results & Discussion

A total of 800 fish of 54 species were captured of which the most common were: *Scomberoides commersonnianus*, *Nematalosa erebi*, (Bony brim), *Lates calcarifer, Arius* sp.3, *Arius proximus*, *Valamugil buchanani* (Blue-tailed mullet) and *Carcharhinus tilstoni* (Australian black-tipped shark) (Table 6-10).

Table 6-10: Total weight and numbers of each species from gill net catches in the lower (1), middle (2) and upper reaches (3) of the Embley estuary 7 to 11 February 2005.

SPECIES	Total wt (g)	Number	Reach
Absalom radiatus	200	2	1
Acanthopagrus berda	3475	9	1
Acanthopagrus berda	2725	7	2
Alectis indicus	1050	2	1
Apogon hyalosoma	52	1	2
Apolectus niger	3700	4	1
Arius armiger	1975	3	2
Arius armiger	1050	3	3
Arius leptaspis	11525	15	1
Arius leptaspis	3600	4	2
Arius macrocephalus	1800	3	2
Arius macrocephalus	1900	4	3
Arius mastersi	17400	12	1
Arius proximus	10325	31	1
Arius proximus	450	1	3
Arius sp.2	3225	11	1
Arius sp.2	8050	30	2

SPECIES	Total wt (g)	Number	Reach
Arius sp.2	1650	7	3
Arius thalassinus	21350	5	1
Caranx bucculentus	4350	3	1
Caranx papuensis	1797	8	1
Caranx papuensis	3000	5	2
Caranx sexfasciatus	525	1	1
Caranx sexfasciatus	1225	1	2
Carcharhinus amblyrhynchoides	22000	1	1
Carcharhinus cautus	34050	9	1
Carcharhinus leucas	45000	1	1
Carcharhinus leucas	21475	5	2
Carcharhinus limbatus	20680	18	1
Carcharhinus sorrah	925	2	1
Chanos chanos	625	1	1
Chirocentrus nudus	250	1	1
Drepane punctata	750	2	1
Eleutheronema tetradactylum	11200	10	1
Elops machnata	500	1	1
Epinephelus suillus	30000	1	2
Gerres abbreviatus	875	5	1
Gnathanodon speciosus	23875	18	1
Hemiramphus far	200	1	1
Lates calcarifer	30500	31	1
Lates calcarifer	29000	14	2
Lates calcarifer	32700	14	3
Leiognathus moretoniensis	20	1	1
Liza subviridis	675	4	3
Liza tade	3675	15	1
Liza vaigiensis	3500	1	1
Lutjanus johni	2100	2	1
Lutjanus johni	725	1	2
Megalops cyprinoides	2650	2	2
Monodactylus argenteus	475	3	2
Negaprion acutidens	6900	3	1
Nematalosa come	131	3	1
Nematalosa come	54	1	2
Nematalosa erebi	22325	33	2
Nematalosa erebi	23825	39	3
Polydactylus sheridani	16450	4	1
Pomadasys kaakan	11000	7	1

SPECIES	Total wt (g)	Number	Reach
Pomadasys kaakan	4075	5	2
Pseudorhombus arsius	225	2	1
Scatophagus argus	14	1	1
Scomberoides commersonnianus	291655	259	1
Scomberoides commersonnianus	27550	18	2
Scomberoides commersonnianus	2600	1	3
Scomberoides tala	400	2	1
Scomberomorus semifasciatus	4150	9	1
Selenotoca multifasciatus	825	3	1
Strongylura leiura	1750	1	1
Thryssa hamiltonii	80	1	1
Toxotes chatareus	1175	10	1
Toxotes chatareus	770	5	2
Toxotes chatareus	855	5	3
Tylosurus crocodilus	650	2	1
Valamugil buchanani	28325	25	1
Valamugil cunnesius	750	7	1

The overall catch rates for the lower, middle and upper reaches and are not significantly different from those of 1986 to 1990 (Table 6-11).

Table 6-11: Overall gill net catch rates (g m^{-1} h^{-1})

Reach/yr	1986 to 1990	2005
Lower	51.9	52.2
Middle	30.0	28.8
Upper	19.9	10.7

The catch rates of major prawn eaters were as follows:

Scomberoides commersonnianus 28 g m^{-1} h^{-1}

Range 1986 – 1990 for wet season: 19 to 47 g m^{-1} h^{-1}

Lates calcarifer 6 g m^{-1} h^{-1}

Range 1986 – 1990 for wet season: 2 to 8 g m^{-1} h^{-1}

As with the overall catch rates those of all the prawn predators were not different from those of 1986 to 1990.

There is therefore no evidence based upon wet season sampling that the numbers of prawn predators in the Embley estuary is any different from the 1986 to 1990 period.

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6.2.8 Stable isotope analysis – Michele Burford *et al.*

Determining food web dynamics in the context of sustaining prawn populations the Gulf of Carpentaria

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A study is currently underway to examine the trophic community in the Gulf of Carpentaria in the context of factors affecting prawn productivity. It is funded by CSIRO Marine and Atmospheric Research and Centre for Riverine Landscapes, Griffith University in Brisbane. This study involves using stable isotope markers ($^{13}C/^{12}C$-carbon and $^{15}N/^{14}N$-nitrogen ratios) of a range of fish, crustacean, infaunal and plant groups to determine the trophic linkage between groups and the connectivity between the marine and freshwater environments. The theory is that predator $\delta^{13}C$ ratios will closely resemble prey ratios, so that the food sources assimilated by predators can be determined. Additionally, freshwater environments have a distinctly different $\delta^{13}C$ signature from marine environments. These differences can be used to determine the effect of freshwater inputs on coastal ecosystems. In the case of $\delta^{15}N$, predator ratios are typically 2 to 4 % higher than their prey. The combination of $\delta^{13}C$ and $\delta^{15}N$ ratios therefore provides a powerful tool for assessing trophic linkages.

The study was conducted at five prawn trawling regions in the Gulf of Carpentaria: Weipa; Karumba; Mornington Island; the Vanderlins; and Groote Eylandt; and three river systems: Embley River in the northeast Gulf; Nicholson and Flinders Rivers in the southeast Gulf. The trophic groups (grinners, pony fish, flounder, prawns, crabs, zooplankton, infauna, particulate organic matter) in the Weipa prawn fishery had similar $\delta^{13}C$ and $\delta^{15}N$ ratios to the other prawn trawling areas in the Gulf, and were consistent with infauna providing a major food source for adult prawns and demersal fish such as grinners, pony fish and flounder feeding on prawns (Figure 6-30). Crabs and stomatopods had a similar signature to prawns suggesting that they are likely to be eating the same food source as prawns. Stomatopods had a slightly higher $\delta^{15}N$ signature than prawns so it is conceivable that they are gaining a small proportion of their diet from feeding on prawns.

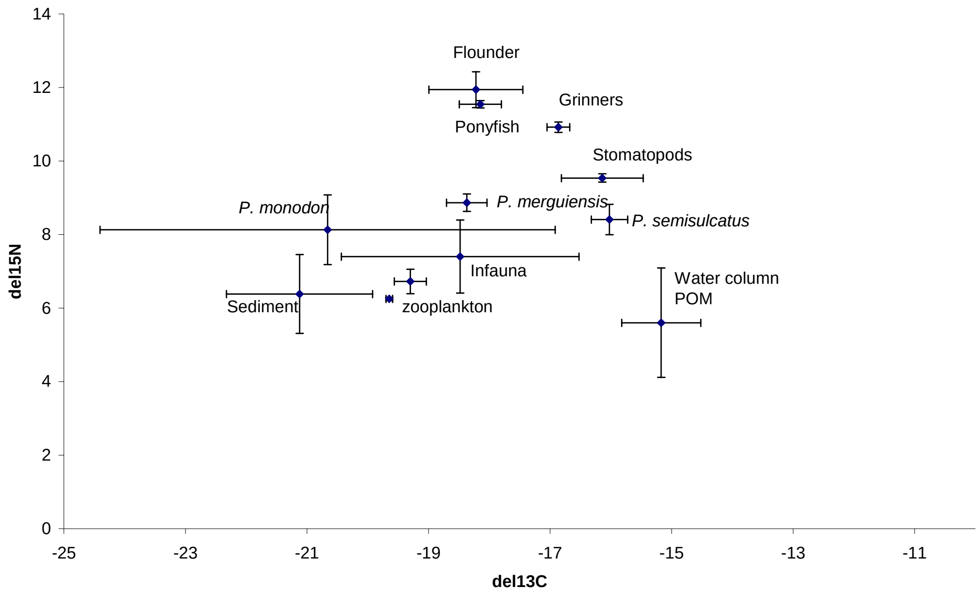

Figure 6-30: Example δ13C and δ15N ratios (± SD) of trophic levels in Albatross Bay off Weipa.

The degree of effect of freshwater carbon and nitrogen sources on coastal processes was also examined in the wet season in the Embley River. A distinct gradient of freshwater to marine signals was seen in a number of trophic groups with a shift towards a less depleted ^{13}C signal. The effect of freshwater was more pronounced in the water column that the sediment (Figure 6-31).

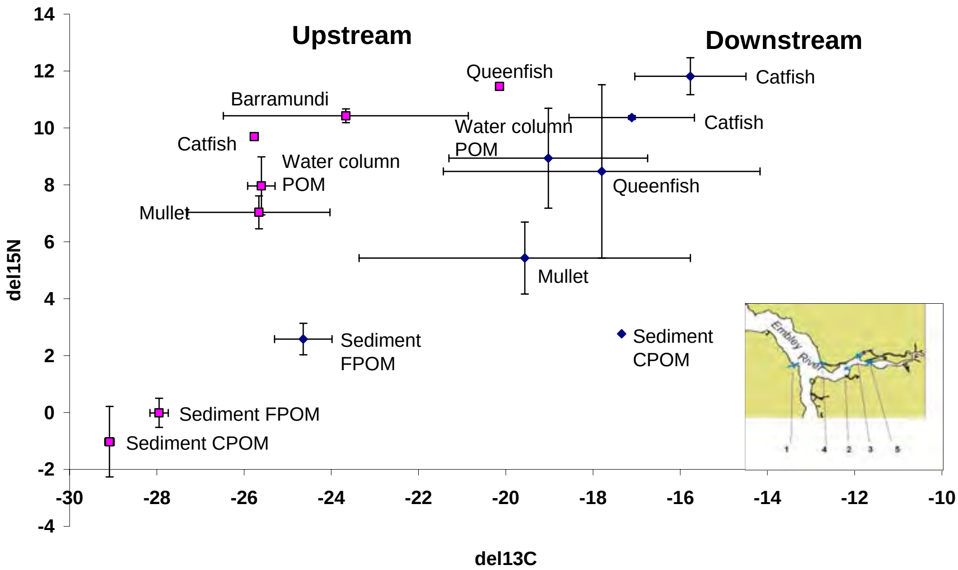

Figure 6-31: Mean δ13C and δ15N ratios (± SD) of trophic levels in an upstream and downstream site in the Embley River near Weipa.

As prawns have an estuarine juvenile phase, their estuarine food signal continues to be seen for some time after prawns migrate offshore into the fishery. *Penaeus monodon* is an example of this with individual animals showing a high degree of variability in their ^{13}C signal (Figure 6-30). Additionally the effect of estuarine food sources on different prawn species can be seen. The banana prawn, *P. merguiensis*, is known to feed in mangrove areas in the juvenile phase while the juvenile phase of the grooved tiger prawn, *P. semisulcatus* is known to feed in seagrass areas. Therefore, banana prawns would have a stronger freshwater signal than the grooved tiger prawns (Figure 6-32).

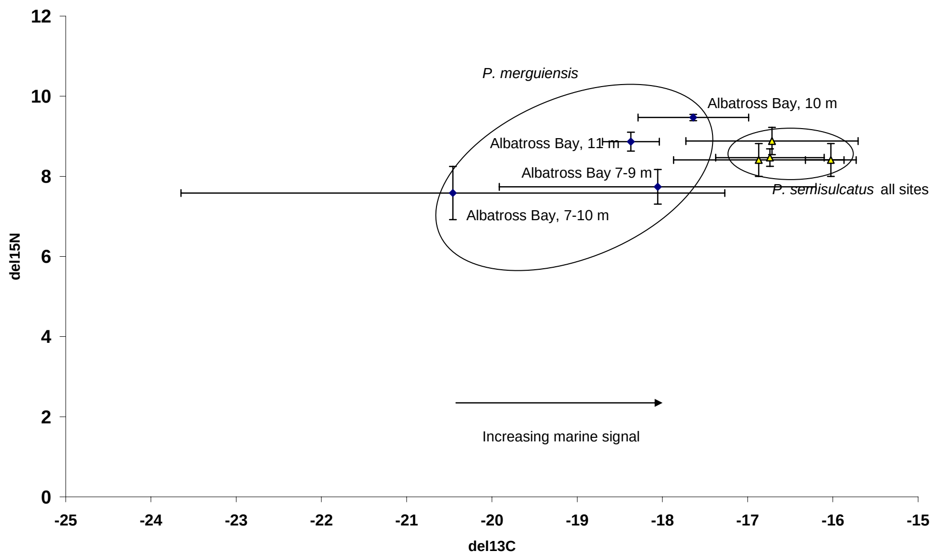

Figure 6-32: Mean $\delta^{13}C$ and $\delta^{15}N$ ratios (± SD) of *P. merguiensis* and *P. semisulcatus* in Albatross Bay.

Analysis of the stable isotope dataset continues and it is planned to use the stable isotope data in the Ecopath model as an independent dataset to verify the outputs based on biomass and productivity estimates for trophic groups. Ultimately this study should provide key information about prawn prey and predators across the juvenile and adult life history stages both in the Weipa fishery and the Gulf of Carpentaria generally.

6.2.9 Environmental predictors of abundance – Bill Venables & Elvira Poloczanska

Possible environmental and other external influences on the annual banana prawn catch at Weipa, Guld of Carpentaria[7].

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One possible explanation for the apparent decline in catchable banana prawn abundance at Weipa is that there has been an environmental change. This contention presumes that the annual efflux of prawns onto the fished areas is either triggered or promoted by some environmental driver and that in Weipa at least there has been a recent decline in the driver. Environmental triggers have been suggested for behavioural changes in *Penaeus merguiensis* (Staples 1980, Owens 1981) and considerable attention has been given in the past to predicting the catch of banana prawns in the Gulf of Carpentaria using various environmental predictors (Staples *et al.* 1982, Vance *et al.* 1983a,b, Staples *et al.* 1984, Vance *et al.* 1985, Staples and Vance 1986, Long *et al.* 1992, Staples *et al.* 1995, Vance *et al.* 1998).

In this study we examine links between environmental predictors and aspects of the commercial catch in Weipa and in two nearby stock regions for comparison. In using only observational data, as we must do here, it is not possible to establish causality but any associations we can uncover between environmental measures and Catch may suggest new hypotheses or refute possible scenarios.

Although this is intended to be a re-examination of questions studied in the past, we will nevertheless be guided by the considerable experience that has been built up in the past to focus the search, in particular to guide our choice of possible predictors and abundance indicators.

Abundance indicators

The banana fishery is a pulse fishery, with a peak of activity confined to a few weeks after the beginning of the season (usually 1st April) so annual Catch within any stock area is an appropriate response to consider. Trying to build prediction models to the Catch at finer temporal scales with only the data available is impracticable. An alternative is to use Catch within a short period after the start of the season, for example 6 weeks within each stock region, but the results are not materially different from using the annual Catch.

Catch generally varies proportionally with influences, so we use log(Catch) as the response. This has several advantages. Firstly it stabilises the variance, transforming a distribution with (approximately) constant coefficient of variation to one with constant variance. Secondly it simplifies the mean structure, transforming multiplicative relationships to additive, and therefore linear ones. It also likely obviates the need to consider most interactions between possible predictors.

If log(Effort) is used as an offset in the model, that is a component of the mean with coefficient unity, the model is essentially focused on log (Catch/Effort) that is log (CPUE). Alternatively if log(Effort) is used as just another explanatory variable, the model cannot be used for prediction prior to the season opening – since Effort is not known in advance – but such a model may allow more subtle relationships with environmental variables to be uncovered, as it allows for a

[7] The complete manuscript is in Appendix IV-7.

relationship between Catch and Effort that is either super- or sub-proportional, as well as exactly proportional (other factors remaining constant).

Clearly in any fishery Effort partially determines Catch, since without Effort there is no Catch. But for pulse fisheries, such as this one, a critical question is the extent to which this link is reflexive, with initial signs of a good Catch in an area inducing higher Effort and conversely poor signs causing fishing Effort to be reduced or even abandoned. This possibility of at least a partially reflexive nature of the link between Catch and Effort would result in a relationship between Catch and Effort that was not strictly proportional, but such an outcome of a model fitting exercise with observational data alone cannot be taken as hard evidence of such reflexivity. If Catch is a major influence on Effort then the total Catch would be the appropriate abundance index, whereas if Effort is a major influence on Catch, the appropriate index would be CPUE.

For these reasons, we consider models both excluding log(Effort) as a predictor (or offset) and fixing log(Effort) in as a predictor. Environmental predictors that show up as important in both cases are then presumably established as unequivocally important.

Explanatory variables and environmental drivers

We will use linear regression as the primary exploratory technique. Variables will be included in the equation either as primary predictors, or to act as an 'explanatory' variable, or covariate. That is, to allow for a correlation between response and predictor in order to unmask other more subtle relationships. As we have noted above, log(Effort) will in some cases be considered as an explanatory variable. Another explanatory variable that will be considered is the Year itself, which will act as a surrogate for unmeasured variables that cause a consistent proportional change in annual Catch.

Caution must be applied when interpreting the results of the regression in this observational study as the predictors and covariates may themselves be correlated. For example, a variable may be an important predictor when there is a causal link driving the relationship with Catch or it may appear to be an important predictor because it is correlated with another variable, possibly measured or unmeasured, which has the causal link. In observational studies the most that can be shown is an association between response and predictors, not a causal relationship. Their value comes from their ability to generate useful hypotheses, or to counter existing hypotheses by failing to find key expected associations.

Environmental covariates

Previous studies, in particular those cited in the opening paragraph of this chapter, have shown links between some environmental variables and the banana prawn catch. These environmental predictors are most notably various rainfall measures, but measures of Air temperature and Wind were also applied as well as the previous year's annual catch and log(Effort). The work of D. Vance and his colleagues generally started with rainfall measured at some point location, usually on a daily basis, and aggregated to form measures such as monthly totals. We opt here to use measures aggregated over river catchments obtained from the standard SILO data sources, available at http://silo.eoc.csiro.au/html/grids/griddata.htm.

Four environmental predictors were considered: daily rainfall; daily average evaporation; daily average maximum and minimum air temperatures. The measures are first averaged over the catchment on a daily basis, and then suitable aggregate measures formed from them (Table 6-12). These fall into 3 groups:

- Mean and standard deviation of the daily measurement of variable for the 6 months prior to the opening of the season on 1st April.

- The mean time at which events occurred, measured as a time lag prior to the 1st April, and the standard deviation of this time difference. These represent the 'time location and spread' of events relative to the start of the season.
- Mean and standard deviation of the daily measurement of variable for each of the 6 months prior to the opening of the season on the 1st April.

Table 6-12: Environmental variables explored as predictors for catch of banana prawns *P.merguiensis* for different fishing regions in the Gulf of Carpentaria and number of (N) models in which they were selected.

Description	Rainfall	N	Evaporation	N	Maximum Air Temperature	N	Minimum Air Temperature	N
Daily mean for 6 months prior to opening of the season on 1st April	Rain. Mean	45	Evap.Mean	2	MaxT.Mean	6	MinT.Mean	9
Standard deviation for 6 months prior to opening of the season	Rain.Stdev	16	Evap.Stdev	3	MaxT.Stdev	2	MinT.Stdev	7
Weighted mean time lag of events in the 6 months prior to opening of the season	Rain.MDev	0	Evap.MDev	3	MaxT.MDev	0	MinT.MDev	0
Weighted standard deviation of the time lag of events during 6 months prior to opening of the season	Rain.SDev	0	Evap.SDev	5	MaxT.SDev	0	MinT.SDev	0
Daily mean for October prior to opening of the season	Rain.MMean.Oct	0	Evap.MMean.Oct	4	MaxT.MMean.Oct	10	MinT.MMean.Oct	3
Daily mean for November prior to opening of the season	Rain.MMean.Nov	8	Evap.Mmean.Nov	0	MaxT.MMean.Nov	8	MinT.MMean.Nov	0
Daily mean for December prior to opening of the season	Rain.MMean.Dec	6	Evap.MMean.Dec	9	MaxT.MMean.Dec	6	MinT.MMean.Dec	1
Daily mean for January prior to opening of the season	Rain.MMean.Jan	2	Evap.MMean.Jan	2	MaxT.MMean.Jan	1	MinT.MMean.Jan	0
Daily mean for February prior to opening of the season	Rain.Mmean.Feb	0	Evap.MMean.Feb	0	MaxT.MMean.Feb	3	MinT.MMean.Feb	3
Daily mean for March prior to opening of the season	Rain.MMean.Mar	4	Evap.MMean.Mar	1	MaxT.MMean.Mar	2	MinT.MMean.Mar	4
Standard deviation for October prior to opening of the season	Rain.MStdev.Oct	1	Evap.MStdev.Oct	0	MaxT.MStdev.Oct	0	MinT.MMean.Oct	0
Standard deviation for November prior to opening of the season	Rain.MStdev.Nov	1	Evap.MStdev.Nov	3	MaxT.MStdev.Nov	6	MinT.MStdev.Nov	1
Standard deviation for December prior to opening of the season	Rain.MStdev.Dec	2	Evap.MStdev.Dec	0	MaxT.MStdev.Dec	0	MinT.MStdev.Dec	0
Standard deviation for January prior to opening of the season	Rain.MStdev.Jan	7	Evap.Mstdev.Jan	0	MaxT.MStdev.Jan	13	MinT.MStdev.Jan	12
Standard deviation for February prior to opening of the season	Rain.MStdev.Feb	1	Evap.MStdev.Feb	33	MaxT.MStdev.Feb	1	MinT.MStdev.Feb	2
Standard deviation for March prior to opening of the season	Rain.MStdev.Mar	1	Evap.MStdev.Mar	10	MaxT.MStdev.Mar	4	MaxT.MStdev.Mar	0

In addition, the Southern Oscillation Index (SOI) monthly measures for each of the 9 months prior to the start of each season were also used. Data were obtained from http://www.bom.gov.au/climate/current/soihtm1.shtml. As the Southern Oscillation is a wide-scale event, influencing weather over all of Australia, these measurements will not reveal direct causal links with catch but may help confirm climate is influencing catch.

Classification of catchments based on rainfall

The suite of possible predictors we consider from a single catchment is very extensive, especially compared with the number of observations we have available to build a prediction model (i.e. just 35 years). However most of the environmental predictors are correlated with each other and most can be at least partially related to rainfall. To look for links between environmental predictors and catch indices it would be useful to restrict the search to those predictors coming from just one catchment for each stock region. There is a natural catchment to choose, as the fished areas for Weipa, Mitchell and Karumba are in each case mostly concentrated near the outlet of a major river, namely the Embley, the Mitchell and the Norman rivers.

It is of some independent interest to show that the catchments themselves cluster into three main groups, using a distance measure based on similarities between their daily rainfall patterns for the 35 years for which we have fishery logbook data. This clustering is shown in Appendix IV-7, but also in Figure 6-33 below.

Not surprisingly, the Embley and the Watson, the two main candidates for Weipa, are seen to be very closely grouped. This is also true of the Mitchell and the Staaten (Mitchell area), and of the Gilbert and the Norman (Karumba area). These close associations to some extent confirm for us that choosing just one catchment for each stock region is likely to uncover any links between environmental variables and catch, if such exist and can be established with the limited data we have available.

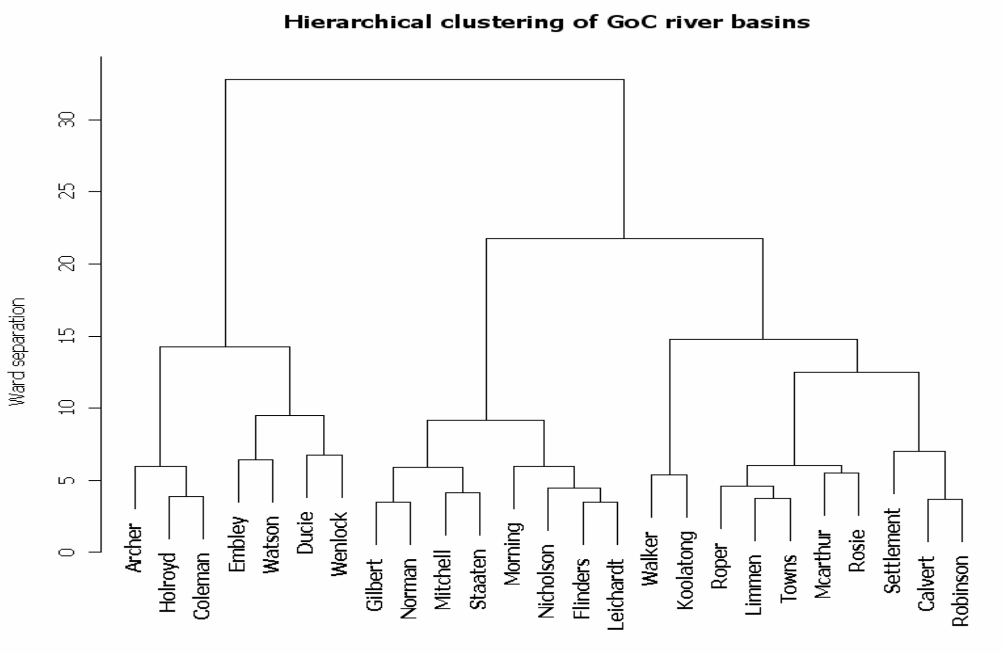

Figure 6-33: Hierarchical clustering of Gulf of Carpentaria catchments based on covariances between de-seasonalised, de-trended time series of daily rainfall.

Has there been a change in the rainfall at Weipa?

If there is an environmental explanation for the decline in the banana prawn catch at Weipa it is mostly to be associated with a long-term change in the rainfall. We examine the evidence for a link with rainfall and associated measures further down in the report, but at this point we looked for any evidence of a change in the rainfall pattern, but using point source data from a rainfall recording station in Weipa itself rather than with catchment averages. For comparison we also look at the rainfall from the weather station at Normanton.

We were unable to show any convincing evidence of a change in either the timing or the amount of rainfall at either location. There is, of course, large variability in the rainfall, both in timing and in the amount, but no clear evidence of a systematic departure from a well established pattern in recent years.

Model building and inference

Our primary aim is to build prediction equations for Catch using the available predictors. For reasons outlined above we use log(Catch) as the actual response and consider fitting models first excluding log(Effort) and then with log(Effort) fixed in the equation.

With effectively only 35 observations, which we optimistically regard as independent, fitting regression models by choosing from a large suite of possible predictor variables which are themselves linked in complex ways poses a difficulty for the traditional stepwise methods, for example. We adopted the following strategy:

For regression models with up to six predictor variables, (realistically about the maximum we might expect to include with such a small sample), we found the three best fitting regression models of each size by exhaustive search. By the ‘best three’ we mean the three regressions of each size with lowest residual sum of squares,
This is done first excluding log(Effort) and then fixing log(Effort) in the equation. In this latter case there is only one equation with one predictor, of course.

Conventional inference with optimal regression is problematical, particularly with so few observations. Rather than rely on simple significance tests, our plan is to use ‘leave-3-out’ cross-validation (as explained in the report) to check for the predictive capacity of the model, as measured by the multiple correlation coefficient.

As a check on the cross-validation method itself for this collection of predictors, we also did a dummy run with a randomly generated variable in place of the actual log(Catch) response.

Models were fitted to catch data for Weipa and to catch data for Mitchell and Karumba using the protocol outlined above.

Results

The cross-validation results on the multiple correlation coefficients are summarised below (Figure 6-34). Several conclusions are clear from this exercise, namely:
Without log(Effort), log(Catch) is only weakly predictable in Weipa and Mitchell. Cross-validated estimates of the multiple correlations suggest that only about 50% of the variability can be explained by environmental predictors alone. For prediction, normally a model explaining at least 80% would be required, so although there is a significant effect of environmental influences, it is not strong enough for confident predictions of catch.

Including log(Effort) as a predictor – which cannot be taken as a real predictor as it is unknown before the season begins, but it can be used as an explanatory variable – the catch becomes highly predictable in Weipa and reasonably well predictable in Mitchell.

In the case of Karumba, the catch is reasonably predictable with or without log(Effort). Since the predictability of Catch is high even without log(Effort) it is a clear indication that environmental influences are strong and well established by the data.

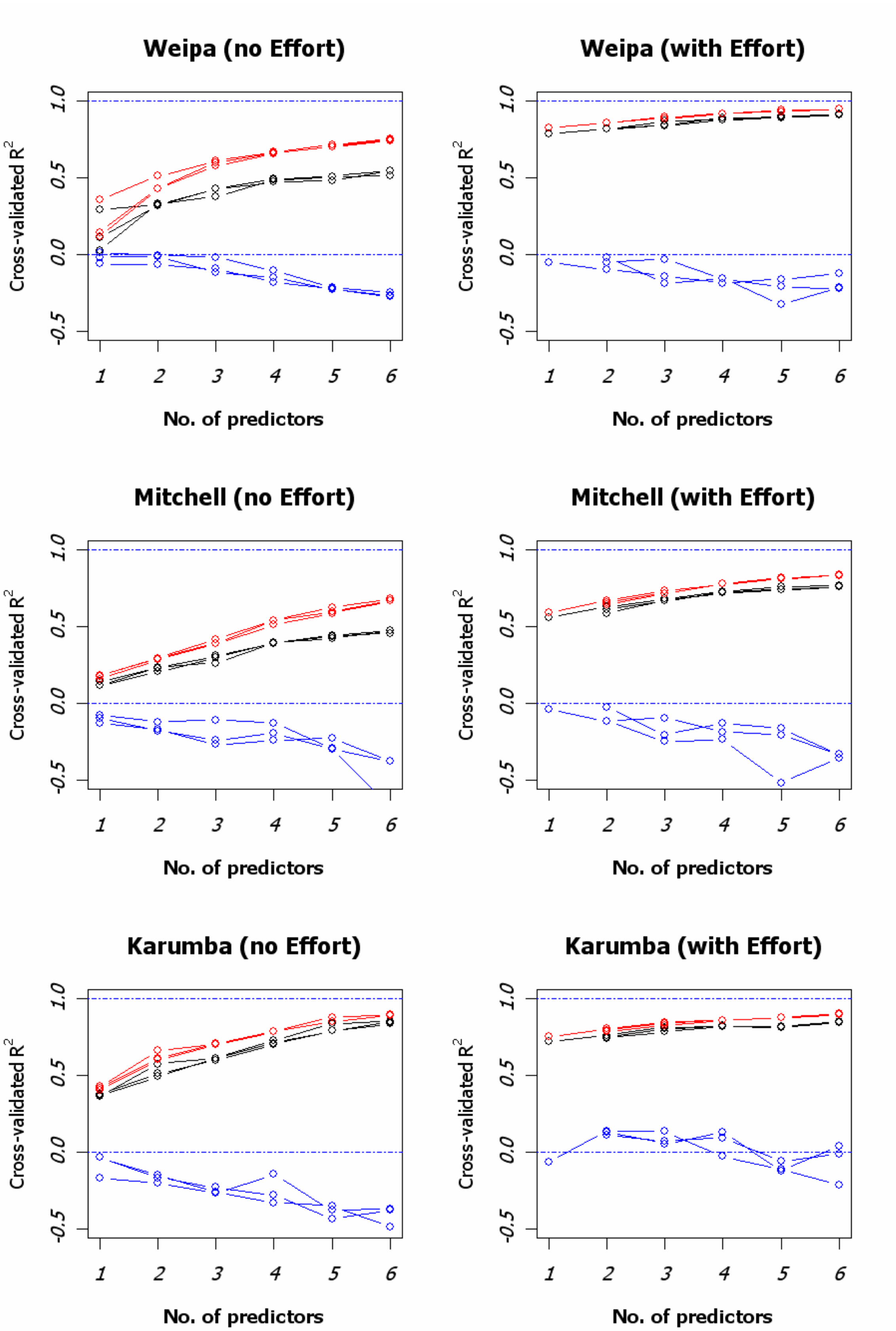

Figure 6-34: Standard (red lines), and cross-validated (black lines) estimates of the multiple correlation coefficient as a function of the number of predictors in the model. The blue lines show a comparison with a dummy response of independent normal variates, i.e. statistically a 'pure noise' signal. The left panels exclude log(Effort) as a predictor and the right panels include it.

Environmental predictors selected by the optimal regression models

Certain consistencies were noted in the signs of the coefficients for the predictor variables selected by the optimal regressions, namely

- As shown in Table 6-12 rainfall means were the predictors most often selected and in the clear majority of cases these had positive estimated coefficients. In general, the more rainfall the higher the catch of banana prawns.
- Evaporation and Minimum Temperature means, where selected, also generally show positive coefficients so in general, so years with higher temperatures in certain months are generally followed by a higher the catch of banana prawns that autumn. However, Maximum Temperature means are often given a negative coefficient so years where certain months had extreme high temperatures are generally associated with a smaller banana prawn catch the following season.
- In some cases standard deviation measures are chosen, and in these cases Rainfall, Evaporation and Minimum Temperature measures are usually given a negative coefficient. Standard deviation represents the spread in the variable data, for example does the rain fall over a period of a few days or over a few weeks. In general, banana prawn catch is higher if monthly rain falls in shorter bursts. Maximum Temperature standard deviation measures are often given a positive coefficient so higher banana prawn catches are associated with higher temperatures that occur over a long period of time.
- The year itself (or more precisely, 'Year – 1970', the elapsed time since the start of the fishery) is allowed as a predictor along with the true environmental predictors, but only in one stock area, Weipa, was it selected with any regularity.
- ***SOI*** measures were not often selected as useful predictors, but where they were the ***SOI*** for a month early in the period, say for the preceding July, usually attracted a negative index, whereas SOI measures for months closer to the start of the season generally had a positive index. High SOI in certain months of the year are generally associated with warmer sea temperatures off northern Australia and a high probability of high rainfall during the wet season.

Some specific comments about the selected regressions themselves now follow.

Weipa. Where log(Effort) is excluded as a predictor, the Year predictor is by far the most commonly selected, and it generally has a negative coefficient. One explanation of this is that environmental predictors play little part in determining the Weipa catch, but Year is strongly correlated with 'Effort**'** over the latter part of the period, particularly, and Year is therefore acting as a partial surrogate for Effort. Note that there has been a strong decline in the absolute level of Effort in all three regions over a considerable time period, but this is strongest and most consistent in Weipa (Figure 6-35). The other predictors chosen along with Year are generally rainfall or evaporation measures, with coefficient signs adhering closely to the general patterns noted above.

Where log(effort) is fixed in the regression, Year is not as often selected as a predictor, but when it is it usually has a slightly *positive* coefficient, suggesting somewhat paradoxically that after allowing for Effort, the catch rate in Weipa is actually *improving*, if only slightly!

One consistent and very interesting feature of the Weipa results is that where log(Effort) is included it usually has a coefficient of about 1.4 to 1.5. This suggests that Catch is 'over responsive' to Effort, that is, to the extent that the model represents a causal relationship between Catch and Effort. The marginal effect of an increase in Effort actually rises with the total Effort. This is clearly not entirely a correct implication, but does suggest that Catch and Effort are in some kind of feedback loop – an initially promising CPUE seems to result in a persistence of Effort but an initially unpromising CPUE rapidly results in a cessation of Effort, or rather a transfer of

Effort to other stock regions. The multiple correlations, which will be strongly biased upwards because of the selection effect, only rise to 0.75 if log(Effort) is not included and to 0.94 when it is. In the first case even discounting the selection effect, this relationship would not be considered useful enough for effective prediction. This indicates that links between total Catch and environmental variables (or at least those which might be used prior to the opening of the season for catch prediction) are very weak or obscured by a Catch-Effort feedback loop.

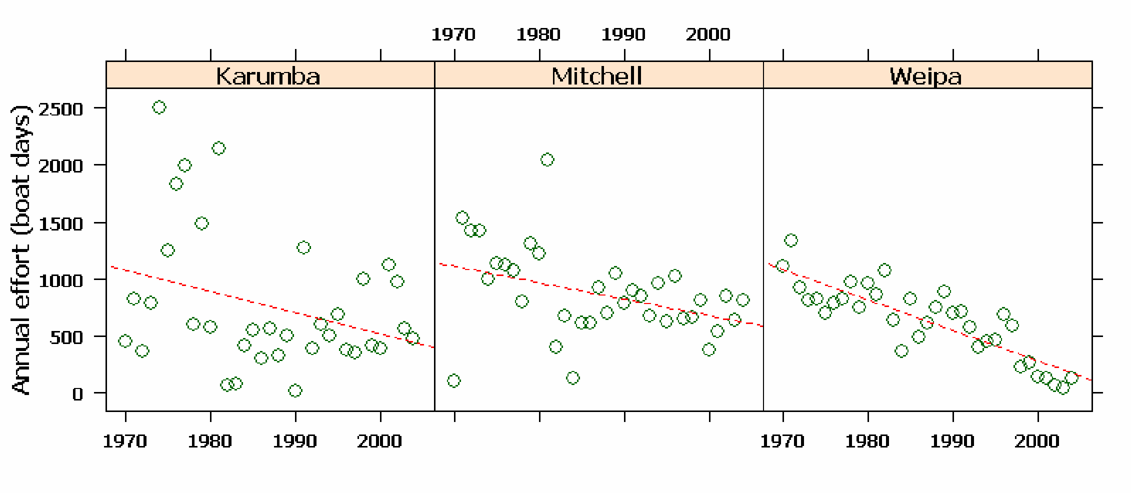

Figure 6-35: Annual banana prawn fishing Effort at Karumba, Mitchell and Weipa with year of the fishery, with simple least squares line.

Mitchell. When log(Effort) is excluded, the catch is even less predictable than in Weipa. The Year predictor is not selected at all, possibly due to the weaker connexion between Effort levels and Year (Figure 6-35). Although there is some evidence of a decline in recent years, it is by no means as consistently tight a relationship as with Weipa. The environmental variables that are selected are again either rainfall mean measures or putative surrogates of them, and have the pattern of signs in their coefficients outlined in general above. Without log(Effort) allowed as a predictor the multiple correlation coefficient remains less than 0.7, indicating a relationship probably not useful for prediction and hence somewhat uncertain for interpretation purposes as well. When log(Effort) is fixed in the regression, predictability increases considerably, as would be expected, but even then the multiple correlation coefficient remains below 0.9. The coefficients of $\log(\text{Effort})$ are now very close to 1 in all cases, indicating a close proportionality relationship between Catch and Effort for Mitchell. Any interpretation of this feature would be somewhat speculative, but clearly the "over proportional" aspect of the Weipa stock area (as explained below) is not replicated in Mitchell.

Karumba. The catch in the Karumba, by contrast, appears to be predictable by environmental variates, and annual pre-season mean rainfall appears to be the dominant environmental predictor both when log(Effort) is excluded and when it is included. Other environmental predictors tend to be either rainfall measures or partial surrogates. The Year predictor is not selected, as in the case of Mitchell. When log(Effort) is excluded, there appears to be some evidence of a slight relationship with SOI, particularly the contrast between the previous July and November mean values. This may be spurious in the sense that it could be accidentally correlated with other predictors. In the case of Karumba, the coefficient of log(Effort) is nearly always in the range 0.3 to 0.5, which suggests that the dependency of Catch on Effort is much weaker than in the other two regions. This is underscored by the fact that the multiple correlation coefficients start from quite high levels even for just one predictor, and approach 0.9 in both cases.

The three stock areas provide an interesting contrast in the way that they show different patterns of dependency on environmental predictors and Effort. In the case of Weipa, a simplistic interpretation of this is that it is a local fishery that requires more searching time and hence has a stronger dependence on Effort than either of the other two. Mitchell is intermediate and Karumba has the weakest dependence on Effort and a stronger environmental signal than the others. This may imply that Karumba is the more attractive fishing area particularly, given the dependence on environmental variables, if the industry can have a higher confidence level in knowing what stock might be available prior to the start of fishing than in the other two areas.

Dependence on log(Effort)

Our main reason for fitting models both with and without log(Effort) as a predictor was to allow the existence of environmental drivers, independent of and in addition to Effort to be established. This seems to have been established most clearly in the case of Karumba, where rainfall measures clearly play an important part in predicting banana prawn catch. In the case of Mitchell environmental predictors are clearly present but are less effective than for Karumba, and for Weipa the evidence of links with environmental drivers is still strong, even though those links themselves appear to be weak and fairly ineffective for prediction when used alone.

One curious outcome of this study is to show that the relationship between Catch and Effort is itself somewhat different in the three areas. For Weipa it seems to be 'over proportional' with, roughly $Catch \propto Effort^{1.5}$. In Mitchell it is very close to strict proportionality $Catch \propto Effort$, and for Karumba is 'under-proportional' with $Catch \propto Effort^{0.5}$.

These approximate relationships may only reflect the different degrees of importance given to environmental drivers in the three areas. They could also suggest that the catch in Weipa is much more sensitive to changing Effort levels than either of the other two and recent decline in catch at Weipa is partly the result of a decline in Effort mediated by the Catch-Effort feedback loop.

Opportunities for future research

Drivers for other phases of the banana prawn life cycle

Despite all the research attention given to Weipa during the history of the NPF we still seem to have substantial questions left unanswered. It is profoundly worrying from a scientific point of view that a once-thriving area of the fishery could decline so drastically without any real scientific explanation. It raises the real question of whether our scientific view of the banana prawn life cycle and its main drivers in the Gulf of Carpentaria is anywhere near complete.

Given our conceptual model of the life cycle (Figure 6-36), our attention in this study has been to focus on the possible environmental drivers for the emigration cycle. In the case of Karumba these seems to be strong and clear, but for Mitchell and Weipa the picture remains somewhat obscure. Nevertheless further studies along the lines of what we have been doing here would appear to have limited value without collection of extra data.

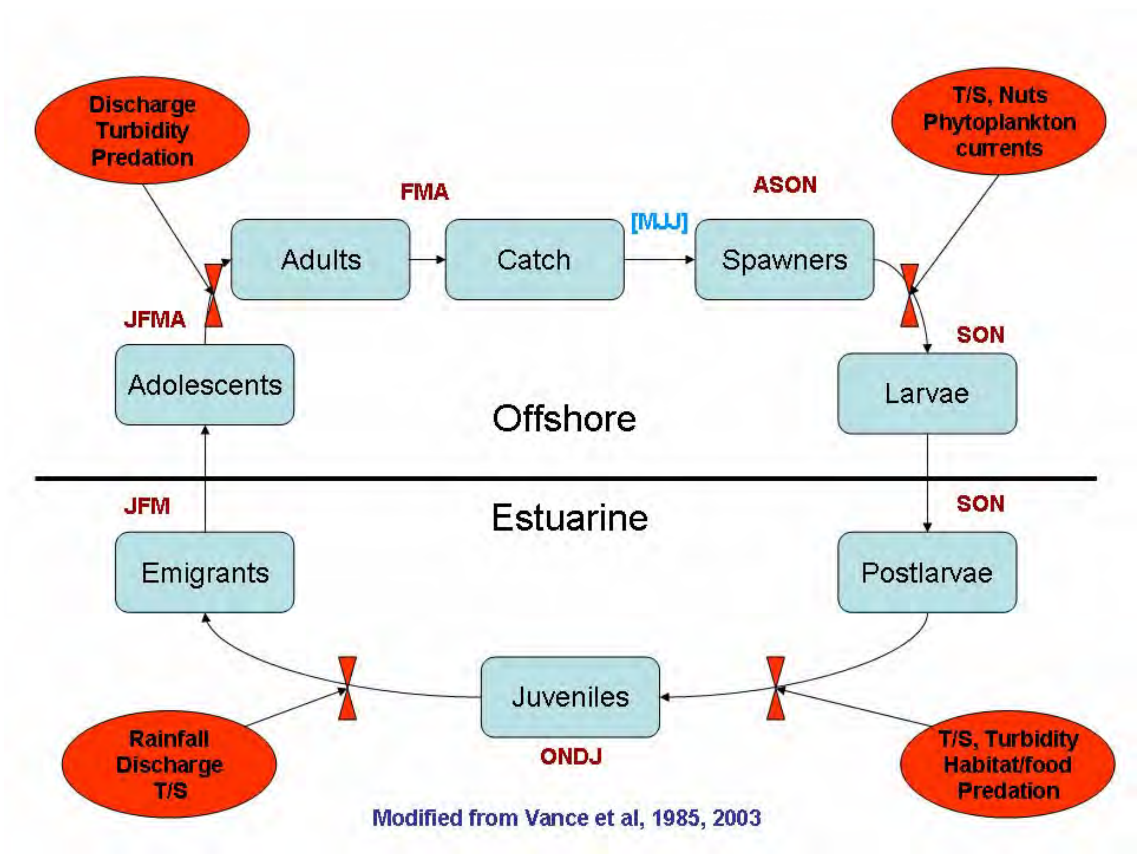

Figure 6-36: Schematic diagram of the life stages of *Penaeus merguiensis*. The animal is spawned in the near offshore by the survivors of the commercial catch and natural mortality. As larvae the animals then migrate to the estuarine areas where they mature. Later in the life cycle they migrate to the offshore areas again where they develop into adults. Environmental influences are seen to be important in at least four stages, as indicated by the red ellipses.

The most promising way forward, we suggest, is to consider the drivers for the other crucial phases of the entire cycle and substantiate and quantify the suggestions implicit in the diagram above. The data sources for this are limited, but not entirely absent. The substantial Weipa study done between 1986 and 1992 still has considerable unused data that may well through light on these key questions. It is unlikely to answer the question of what has been the cause of the decline in the banana prawn catch in Weipa in any definitive way, but it should provide a clearer understanding, both quantitatively and qualitatively of what really drives the banana prawn life cycle, and possibly suggests the crucial directions for further field work to elucidate these important issues.

A Catch and Effort feedback loop?

The curious, but clear, difference in the degree to which log(Catch) depends on Effort allowed in the three regions also warrants some substantial scientific investigation. One possible interpretation is that there is a feedback loop between Catch and Effort which operates differently in the three stock areas, presumably for reasons which have a lot to do with the way the fleet operates. We suggest that establishing some light on this may well be crucial to understanding the extent to which the decline in Catch can be explained by a decline in Effort. This is likely to be a challenging exercise. It will need collection of additional information with Catch and Effort data.

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6.3 Hypothesis analysis

In the original project proposal for the present project, four potentially interacting factors (≅Hypotheses) were suggested to explain low catches of banana prawns in the Weipa area:

1. Overfishing – a recently completed project showed that banana prawns do exhibit a stock-recruitment relationship and therefore can become overexploited (Vance *et al.*, 2003);
2. Too little fishing time in a season to adequately search for prawns in an area where spotter planes can not be used;
3. Changes in the ecosystem such as the predator-prey balance; and
4. Environmental changes in the Weipa region:
    a. The rainfall pattern or run-off to the estuary due to drought or changes in the catchment;
    b. Greater extraction of water from the water table.

This list of potential hypotheses was extended to seven hypotheses during the second workshop (see Table 6-13, Table 6-14), and the final number of hypotheses was expanded to nine in light of preliminary results of trophodynamic modelling (presented here in the order that they were originally listed):

1. Overfishing caused recruitment collapse;
2. Fleet cannot find prawns because the reduced fleet has less searching power;
3. An environmental change has drastically reduced recruitment;
4. Prawns are staying inshore;
5. Prawns are no longer schooling;
6. Groundwater pumping reduced runoff;
7. A pollutant killed off the prawn stock;
8. Indirect trophic effect of fishing;
9. Indirect trophic effect of an environmental change.

This hypothesis analysis section includes a summary discussion of how these alternative hypotheses were narrowed down based on the results of this project and an overview of the nine hypotheses and how they would express themselves and could be evaluated.

Fishing-related changes

There was insufficient power in the fishery analysis to diminish the plausibility of the recruitment overfishing hypothesis (H1). In addition, the analysis of spatial contraction of prawn fishing effort in the Weipa area provided a plausible and compelling mechanism for overfishing as a cause of the observed spatial contraction of the fishing and the decline in catch. It is also possible, however, that the patterns emerging from this analysis reflect the limited searching time available during the shortened season (H2). The effort analysis tends to support the hypothesis that effort reductions have contributed to the very low catches in Weipa since 2000 (H2).

Trophodynamic changes

The trophodynamic modelling indicated that increases in fishing rate since the late 1980s could decrease the biomass of banana prawn populations considerably (and that small decreases in fishing rate can increase the biomass). However, an accurate reconstruction of banana prawn declines has not yet been possible using real time series of catch, because of the inherent problems of temporal variability in this system. This trophic analysis indicates the possibility that the prawn fisheries can adversely affect prawn stocks by both direct and indirect means (H8).

Behavioural changes

The notion that adult prawns stayed inshore in recent these years (H4) and were thus not available for capture is somewhat discredited by the annual recruitment surveys, which have indicated that sub-adult prawns have been moving offshore in a normal fashion (Dichmont *et al* 2006, FRDC 2002/14). The most reasonable mechanism for the sudden lack of schooling in adult prawns (H5) would be that overfishing reduced the abundance of prawns. Failure to school would therefore presumably be unlikely without reduced biomass from overfishing. The likelihood of these explanations is thus diminished to low because failure to school would not be the ultimate cause of the change.

Environmental changes

The Tuned VPA used in the fishery analysis offered no support for the hypothesis that recruitment estimates had been affected by rainfall, thus diminishing the plausibility of the environmental hypotheses (H3, H9) (see Section 6.2.3 and Appendix IV-3). The further exhaustive exploration of the relationship between the observed banana prawn catch decline and environmental variables revealed no evidence for such a relationship, thus providing an additional line of evidence to diminish the plausibility of these hypotheses (see Section 6.2.9. and Appendix IV-7). These analyses were further hampered by the lack of a consistent prawn biomass estimate other than catch or CPUE. Further, regional variations in effort were seen to affect the predictive capacity of environmental variables. The environmental change hypotheses were therefore given a low likelihood ranking for explaining the observed banana prawn catch decline.

Other anthropogenic-induced changes

The notion that recruitment has collapsed due to a pollutant (H7) and that pumping of groundwater has lowered the water table and reduced run-off (H6) were dismissed because there is no evidence for a decline of the estuarine populations of banana prawns (anecdotal information from cast net fishers), and because there have been no reports of mortality or declines in estuarine fishing – indicating that other estuarine species have not been affected). Furthermore, a fishery-independent empirical field study undertaken during this project indicated stable populations of estuarine fish populations over time. In addition, other evidence indicates that pollutants are not the explanation for prawn catch declines (D. Vance, CSIRO Marine and Atmospheric Research, unpublished data).

These two hypotheses were dismissed during this project because there is little evidence for a decline of the estuarine populations of banana prawns (e.g. Dichmont *et al.* 2006; and anecdotal information from cast-net fishers), because there have been no reported declines in estuarine fisheries (i.e. indicating that other estuarine species have not been affected), and because a fishery-independent empirical field study undertaken during this project indicated stable populations of estuarine fish populations over time (Blaber *et al.*, this volume Section 6.2.7).

Overall, nine hypotheses were considered during the project (Table 6-13). The three hypotheses that emerge as the most likely explanations for the observed catch declines in banana prawns over the last several years are all fishing-related explanations. They include recruitment overfishing, indirect effects of fishing, and a loss of searching power resulting from a reduction of boats and searching power in this region.

Table 6-13. Ranking of the likelihood of each explanation (hypothesis) for the observed decline in banana prawn catch, based on the analyses conducted during the course of the present study.

Likelihood	Hypothesis
High	Recruitment overfishing (H1)
	The fleet has lost searching power (H2)
Medium	Indirect trophic effects of fishing (H8)
Low	Adult prawns are staying inshore (H4)
	Adult prawns are no longer schooling (H5)
	Direct effects of environmental change on banana prawns (H3)
	Indirect trophic effects of environmental change (H9)
Discredited	Pumping of groundwater has reduced run-off (H6)
	Recruitment has collapsed due to a pollutant (H7)

Thus, the analyses presented here provide insights that allow us to narrow down alternative hypotheses as well as a framework for future refinements in understanding the system. For example, the working hypotheses can be ranked in order of their likelihood given the information that is currently available (Table 6-13). Moreover, the lack of reliable abundance indices over the whole distribution of the species, and the paucity of other important information highlighted by the study leads to the conclusion that direct empirical studies (see Section 6.4) are necessary to discern the nature of the decline with a confidence that will allow effective management action in a reasonable time frame.

Although available information was generally inadequate to evaluate these hypotheses rigorously, the hypotheses were ranked on best professional judgement in the context of the analyses conducted during this project.

6.3.1 Detailed analysis of the nine hypotheses

An overview of the nine hypotheses is presented in this section with population trends (Table 6-14) that would be expected if each hypothesis was correct and with any relevant indices and analyses (Table 6-15) that could be used to evaluate each hypothesis.

Hypothesis 1. Overfishing caused recruitment collapse

The Hypothesis

Catches have declined because a long history of heavy fishing pressure has depleted the spawning stock of banana prawns to low levels causing a large decline in available recruitment.

The fishery has monitored this decline and has reduced effort proportionally. However, the current low effort levels may still be generating enough fishing pressure to continue to deplete stock levels.

Expected Population Trends

A. Biomass – is declining in parallel with catch and will not rebuild without management action.

B. Spawning Stock – is declining in parallel with catch and will not rebuild without management action.

C. Recruitment – is declining in parallel with catch and will not rebuild without management action.

D. Survival Through Year – is low and declining in parallel with catch. There is not enough escapement of prawns from the fishery. It will not improve without management action.

E. Area of Stock – is declining in parallel with catch, and catchability is increasing proportionally negating the effect of declining effort levels. The situation will not be reversed without management action.

F. Area of Fishery – is declining in parallel with catch and the area covered by the stock. The trend will continue without management action.

Relevant Indices & Analyses

If this hypothesis is correct, the results of standard fishery models are valid. CPUE trends accounting for the effect of the spatial contraction will also be valid and is proportional to biomass. Fishery Independent indicators of sufficient precision should also indicate a similar trend. It should be noted that under this hypothesis, catchability is expected to have escalated as the stock contracted and consequently the recent decline in effort may not have resulted in reduced fishing mortality. Current low effort levels may still be producing historically high fishing mortality. If this hypothesis is valid, analysis of within season CPUE declines will show recent trends in catchability are a continuation of long-term trends, and the size structure of survey catches late in the season should show very low and probably declining survival of prawns through the season.

The analysis of appropriate environmental covariates should explain some of the variability observed around historic and recent trends, but no unusual anomaly is required to explain the recent collapse in catches.

Assuming sufficient measurement precision, this hypothesis might be distinguished from Hypotheses 2, 4, 5 & 6 by comparing densities of juveniles in estuaries with previously measured densities, the latter of which should be significantly higher.

Hypothesis 2. The reduced fleet has less searching power and cannot find prawns

The Hypothesis

Catches have declined because management has reduced the size of the fleet and the length of the season to such an extent that it can no longer effectively search the area of the fishery off Weipa and consequently the fleet has been unable to find the prawns in recent years.

Recent low levels of fishing effort will reflect low fishing pressure and the stock should be rebuilding as a result, although this will not be reflected in catch and catch rates until the fishery discovers the stock again. At some time and without management action, the catch will increase rapidly when the fleet rediscovers the stock and renewed fishing and searching pressure is attracted back into the area.

Expected Population Trends

A. Biomass – was probably declining until recent years but should be rebuilding now effort is very low.

B. Spawning Stock – was probably declining until recent years but should have been rebuilding since effort fell to very low levels.

C. Recruitment – was probably declining until recent years but should have been rebuilding since effort fell to very low levels.

D. Survival Through Year – was probably declining until recent years but is much higher now because fishing effort and pressure is low (probably similar to levels of the late 1980s and early 1990s).

E. Area of Stock – was probably declining until recent years but should now be rebuilding since effort and fishing pressure is at very low levels.

F. Area of Fishery – has declined because of the lack of searching success but has a growing probability of a rapid and spontaneous increase, because the stock and the area it covers is rebuilding, steadily improving the chance it will be found. Once found it will again attract searching and fishing effort.

Relevant Indices & Analyses

Under this hypothesis, fishery dependent data (CPUE) will be invalid in recent years because of the loss of searching power. Fishery independent indicators of sufficient precision would reveal a different and actual trend and could be used in standard fisheries model if the time series were sufficiently long. The surveyed size structure of prawns should suggest relatively high survival of prawns during the season because fishing mortality has declined, unless natural predators of prawns have increased in abundance due to fishing or some other cause. Analysis of appropriate environmental covariates would explain some of the variability observed around trends in fishery independent data.

Increasing stock abundance resulting from low effort will reduce the possibility of the stock remaining hidden and with each season that passes without significant fishing the probability diminishes that this hypothesis is primarily responsible for recent trends, unless other fishing areas always remain better for fishing even after a recovery.

This hypothesis could be distinguished from the other hypotheses by implementing a thorough search of the Weipa grounds by the northern prawn fleet. Significant catches in the Weipa area would prove this hypothesis correct.

Hypothesis 3. An environmental change has drastically reduced recruitment

The Hypothesis

Catches have declined because some change in the environment has occurred that has had a catastrophic effect on survival of banana prawns at one or more stages in the life cycle at Weipa, leading to a collapse in stock size.

Under this hypothesis current trends will be reversed without management intervention if and when the environmental change reverses.

Expected Population Trends

A. Biomass – has declined in parallel with catches. This will be reversed without management intervention when the environmental change reverses.

B. Spawning Stock – has declined in parallel with catches. This will be reversed without management intervention when the environmental change reverses.

C. Recruitment – has declined in parallel with catches. This will be reversed without management intervention when the environmental change reverses.

D. Survival Through Year – Although stock levels are low because of reduced survival at one or more life history stages, low fishing effort should mean higher survival through the year.

E. Area of Stock – has declined in parallel with catch this will be reversed without management intervention when the environmental change reverses.

F. Area of Fishery – has declined in parallel with the catch and the area occupied by the stock this will be reversed without management intervention when the environmental change reverses.

Relevant Indices & Analyses

Standard fishery models will be valid in analysing trends. CPUE trends accounting for the effect of spatial contraction will be valid. Fishery Independent indicators of sufficient precision should indicate similar trends.

Analysis of appropriate environmental covariates would explain some of the variability observed around trends in fishery independent data including the recent collapse in catches.

Hypothesis 4. Prawns are staying inshore

The Hypothesis

Catches have declined because there has not been sufficient flooding in recent years (since 2001) to push the juveniles from the nursery grounds and/or the sub-adult prawns offshore into water deep enough for the fleet to catch prawns. This hypothesis relies on the notion that river flow has changed such that a sufficient emigration cue is not provided. Rainfall could be reduced or spread too evenly over time, changes in cloud cover and evaporation could have changed runoff regimes, or something else about the watershed may have changed.

Under this hypothesis, the low catch and effort reflects a period of low fishing pressure for the stock, which should be producing effective recruitment and increasing in abundance. The prawns are simply remaining concentrated near shore (i.e. in the effective spawning area and inshore of the fishing area).

Expected Population Trends

A. Biomass – was probably declining until recent years but should be rebuilding now effort is very low.

B. Spawning Stock – was probably declining until recent years but should be rebuilding now effort is very low.

C. Recruitment – was probably declining until recent years but should be rebuilding now effort is very low.

D. Survival Through Year – should now be high reflecting low effort and fishing pressure.

E. Area of Stock – currently low because the prawns are not being forced out onto the grounds by flooding and are remaining concentrated in shallow inshore areas. This situation will be reversed without management intervention, by a return to historic flooding levels.

F. Area of Fishery – currently low because the prawns are not being forced out onto the fishing grounds by flooding. This situation will be reversed without management intervention, by a return to historic flooding levels.

Relevant Indices & Analyses

Under this hypothesis the stock should be growing but remaining concentrated inshore and unavailable to the fishery. Recent trends in fishery dependent data will not reflect actual population trends although fishery independent data of sufficient precision and with appropriate inshore coverage might provide a reliable index of abundance and should show the concentration of the growing stock at inshore sites. Conversely fishery independent index with insufficient inshore coverage will not reveal this trend.

Size structure data from inshore surveys should also show relatively high survival of prawns through the year because fishing pressure is low.

Analysis of appropriate environmental covariates (rainfall, river flow, salinity anomalies) should support this hypothesis by revealing some recent and continuing explanatory anomaly in rainfall or runoff.

Hypothesis 5. Prawns are no longer schooling

The Hypothesis

Catches have declined because, for some unknown reason, the prawns are no longer schooling, thus preventing the fleet from deploying its normal searching and fishing techniques. The function of and mechanisms for schooling are not understood making the analysis of this hypothesis problematic. However, it would be expected that either declining stock density or some environmental change cause such a breakdown in schooling behaviour, unless they have stopped schooling because of lower predator abundances.

Under this hypothesis, the stock is probably rebuilding as a result of recent low levels of fishing effort and fishing mortality, although this might not be reflected immediately in catch and catch rates. It would be expected that schooling will resume either through rebuilding stock abundance or a reversal of environmental conditions, and that this would lead to a rapid escalation of catches.

Expected Population Trends

A. Biomass – was probably declining until recent years but should be rebuilding now effort is very low.

B. Spawning Stock – was probably declining until recent years but should have been rebuilding since effort fell to very low levels.

C. Recruitment – was probably declining until recent years but should have been rebuilding since effort fell to very low levels.

D. Survival Through Year – was probably declining until recent years but should be much higher now because fishing effort and pressure is low (probably similar to levels of the late 1980s and early 1990s).

E. Area of Stock – was probably declining until recent years but should now be rebuilding since effort and fishing pressure is at very low levels.

F. Area of Fishery – has declined because lack of searching and fishing success but has a growing probability of a rapid and spontaneous increase when schooling resumes, either because of stock rebuild or the ending of the environmental anomaly responsible.

Relevant Indices & Analyses

Under this hypothesis fishery dependent data from recent years will not reflect actual population trends because of the sharp decline in searching efficiency and catchability caused by the cessation of schooling. However, fishery independent data of sufficient precision would provide a reliable index of abundance and show that the growing stock is remaining dispersed across the fishing grounds throughout the year. However, the structured monitoring cruises, very low effort and seasonality of the survey may not be appropriate to measure the degree of schooling.

Size structure data from surveys should also show relatively high survival of prawns through the year because fishing pressure is low.

The phenomenon of schooling is probably not sufficiently well understood to allow a meaningful analysis of the factors that should have driven the change in schooling behaviour. If environmentally driven, some environmental anomaly should be associated with the recent collapse in catches. If density dependent (i.e. schooling stops at low density) schooling should resume as stock abundance grows due to current light fishing.

Hypothesis 6. Groundwater pumping reduced runoff

The Hypothesis

Catches have declined because there has not been sufficient flooding in recent years (since 2001) to induce emigration of juveniles and adults into the fishery. This is at least partially due to the extraction of groundwater and thereby lowering the water table in the catchment, thereby requiring larger rainfall events to result in flooding.

Under this hypothesis, current trends could be reversed without management intervention by a return to strong flooding conditions. However, under this scenario stronger flooding conditions will be needed than for Hypothesis 4 (adult prawns staying inshore) as flooding is required to overcome the impact of lower water tables.

Expected Population Trends

A. Biomass – was probably declining until recent years but should be rebuilding now effort is very low. This situation will be reversed without management intervention, by a return to strong flooding conditions.

B. Spawning Stock – was probably declining until recent years but should be rebuilding now effort is very low. This situation will be reversed without management intervention, by a return to strong flooding conditions.

C. Recruitment – was probably declining until recent years but should be rebuilding now effort is very low. This situation will be reversed without management intervention, by a return to strong flooding conditions.

D. Survival Through Year – should now be high reflecting low effort and fishing pressure. This situation will be reversed without management intervention, by a return to strong flooding conditions.

E. Area of Stock – currently low because the prawns are not being forced out onto the grounds by flooding and are remaining concentrated in shallow inshore areas. This situation will be reversed without management intervention, by a return to strong flooding conditions.

F. Area of Fishery – currently low because the prawns are not being forced out onto the fishing grounds by flooding. This situation will be reversed without management intervention, by a return to strong flooding levels.

Relevant Indices & Analyses

Fishery dependent data from recent years will not reflect actual population trends. Fishery independent data of sufficient precision and with appropriate inshore coverage might provide a reliable index of abundance and should show concentration of the stock at inshore sites. Size structure data from surveys should also show relatively high survival of prawns through the year because fishing pressure is low. However, insufficient inshore coverage will invalidate fishery independent data. Analysis of appropriate environmental covariates (water table height, rainfall, river flow, salinity anomalies) should support this hypothesis.

Simple analysis of the area impacted by groundwater pumping relative to the area of the catchment (i.e. a measure of water table depth) would test this hypothesis. Lateral movement of groundwater is normally extremely low producing localised impacts on groundwater height. So if the historical and current bore field is limited compared to catchment area an insignificant impact on run-off would be expected.

Hypothesis 7. A pollutant killed off the prawn stock

The Hypothesis

Catches have declined because some pollutant has had a catastrophic toxic effect on juveniles in the estuary. Because this impact has been a multi-year impact it can be assumed that the pollutant is still being released or is persisting in the environment.

Under this hypothesis a fishery management change or a return to strong flooding will not reverse this trend, it will be necessary for the pollutant to be removed from the environment.

Expected Population Trends

A. Biomass – has declined in parallel with catch and will not be reversed until the pollutant is removed from the environment.

B. Spawning Stock – has declined in parallel with catch and will not be reversed until the pollutant is removed from the environment.

C. Recruitment – has declined in parallel with catch and will not be reversed until the pollutant is removed from the environment.

D. Survival Through Year – probably low due to the toxicity of the environment. However, if the pollutant acted on a single life history stage (i.e. juvenile stage) low fishing effort and pressure could allow for the higher survival of other life history stages (i.e. adult and spawners) during the year.

E. Area of Stock – has declined due to declining stock abundance and will not be reversed until the pollutant is removed from the environment.

F. Area of the Fishery – has declined due to declining stock abundance and area covered by the stock. This will not be reversed until the pollutant is removed from the environment.

Relevant Indices & Analyses

CPUE trends accounting for the effect of spatial contraction will be valid. Fishery Independent indicators of sufficient precision should also indicate similar trends. Analysis with fishery models should show recent negative trend in recruitment residuals that would correlate with the release of toxins. Because the impact is continuing analysis of toxins in the environment and prawns should reveal significantly higher levels at Weipa than in other areas. Similar mortality increases in other crustaceans (e.g. other prawn species and crabs) would also be expected.

Knowledge of processing techniques used by Comalco and toxicants released by dredging should identify a possible toxic agent that should still be present in the environment. It should be expected that any such toxic agent should have impacted a suite of related species similarly. It would be unlikely that only a single species, or single type of species, would be impacted.

Hypothesis 8. Indirect trophic effects of fishing

The Hypothesis

Fishing activities such as prawn trawl fishing in the Weipa area has modified the overall biological assemblage such that trophic conditions are no longer favourable for fishery-sized banana prawns to persist long enough during the austral autumn to be found or captured in high numbers. Prawn trawling modifies biological communities considerably through the removal of large numbers and biomasses of ‘bycatch’ species and this changes the living assemblage and habitats that are encountered by prawns, thereby changing natural mortality and survivability. The removal of certain higher predators from prawn trawling would cause population increases in important prawn predators such as stomatopods and octopods thereby increasing predation on prawn sub-adults between the time of migration from nursery areas and the April opening of the prawn fishing season.

Expected Population Trends

A. Biomass – has declined in parallel with catch and will not be reversed until a trophic structure that favours prawn survival is restored (i.e. until certain higher predators are restored) either through management action or by chance.

B. Spawning Stock – is declining in parallel with catch and will not be reversed until a trophic structure that favours prawn survival is restored either through management action or by chance.

C. Recruitment – is declining in parallel with catch and will not improve until a trophic structure that favours prawn survival is restored either through management action or by chance.

D. Survival Through Year – is low and declining in parallel with catch. It will not be improved until a trophic structure that favours prawn survival is restored either through management action or by chance.

E. Area of Stock – is declining in parallel with catch, and catchability is increasing proportionally negating the effect of declining effort levels. The situation will not be improved until a trophic structure that favours prawn survival is restored either through management action or by chance.

F. Area of Fishery – is declining in parallel with catch and the area covered by the stock. The trend will continue until a trophic structure that favours prawn survival is restored either through management action or by chance.

Relevant Indices & Analyses

This hypothesis emerged as a predicted result of whole food-web trophodynamic (Ecopath with Ecosim) simulations of the prawn fisheries in the Albatross Bay area, based on the best ecological and fisheries information available.

If this hypothesis is correct, CPUE trends accounting for the effect of spatial contraction will also be valid. Fishery Independent indicators of sufficient precision should also indicate a similar trend. As in the overfishing hypothesis, catchability is expected to have escalated as the stock contracted and consequently the recent decline in effort may not have resulted in reduced fishing mortality. Current low effort levels may still be producing historically high fishing mortality. If this hypothesis is valid, analysis of within season CPUE declines will show recent trends in catchability are a continuation of long-term trends, and the size structure of survey catches late in the season should show very low and probably declining survival of prawns through the season.

The analysis of appropriate environmental covariates should explain some of the variability observed around historic and recent trends, but no unusual anomaly is required to explain the recent collapse in catches.

Hypothesis 9. Indirect trophic effects of environmental change

The Hypothesis

Some environmental change has modified the overall biological assemblage such that conditions are no longer favourable for fishery-sized banana prawns to persist due to increases in predators, decreases in prey, or some other indirect factor.

Catches have declined because some change in the environment has occurred that has had a catastrophic effect on survival of banana prawns at one or more stages in the life cycle at Weipa, leading to a collapse in stock size.

Under this hypothesis current trends will be reversed without management intervention if and when the environmental change reverses.

Expected Population Trends

A. Biomass – has declined in parallel with catches; this will be reversed without management intervention if and when the environmental change reverses.

B. Spawning Stock – has declined in parallel with catches; this will be reversed without management intervention when the environmental change reverses.

C. Recruitment – has declined in parallel with catches; this will be reversed without management intervention when the environmental change reverses.
D. Survival Through Year – has declined in parallel with catches; this will be reversed without management intervention when the environmental change reverses.
E. Area of Stock – has declined in parallel with catch this will be reversed without management intervention when the environmental change reverses.
F. Area of Fishery – has declined in parallel with the catch and the area occupied by the stock this will be reversed without management intervention when the environmental change reverses.

Relevant Indices & Analyses

Whole food web trophodynamic models would produce anomalies that indicate some trend in production or biomass of prawns. The decline would not be adequately explained by simulating changes in fisheries pressure alone in these whole food web trophodynamic models. CPUE trends accounting for the effect of spatial contraction will be valid. Fishery independent indicators of sufficient precision should indicate similar trends.

Analysis of appropriate environmental covariates would explain some of the variability observed around trends in fishery independent data including the recent collapse in catches.

Table 6-14: Population trends (A to F), Relevant analyses (G) and Comments (H) related to the Hypotheses (1 to 7) affecting the abundance of banana parawns (*P. merguiensis*) in the Weipa region of the Gulf of Carpentaria.

	1. Fishing pressure drives recruitment collapse	**2. Loss of searching power drives decline in catch because fishers can't find them**	**3. Change in environment has collapsed recruitment**	**4. Prawns are staying in Inshore and are not available to fishery**	**5. Prawns are no longer schooling so that the fishery cannot find or fish them**	**6. Pumping of groundwater has lowered water table reducing freshwater input**	**7. A pollutant has killed off the prawn stock**
A. Biomass Trend	Declined like catch	Less decline than catch probably now rebuilding	Declined like catch	Less decline than catch probably now rebuilding	Less decline than catch probably now rebuilding	Less decline than catch probably now rebuilding	Declined like catch
B. Spawning Stock	Reduced to very low levels	Less decline than catch probably now rebuilding	Reduced to very low levels	Less decline than catch probably now rebuilding	Less decline than catch probably now rebuilding	Less decline than catch probably now rebuilding	Declined like catch
C. Recruitment Trend	Declined to very low levels	Less decline than catch probably now rebuilding	Declined to very low levels	Less decline than catch probably now rebuilding	Less decline than catch probably now rebuilding	Less decline than catch probably now rebuilding	Declined like catch
D. Survival Through Year	Now Very Low	Higher – similar to late 1980s	Now very low	Higher – similar to late 1980s	Higher – similar to late 1980s	High – because the stock is not vulnerable to the fishery.	Could be low if toxins act on all life stages, or high if toxins only act on larval stages and fishing pressure is low

	1. Fishing pressure drives recruitment collapse	2. Loss of searching power drives decline in catch because fishers can't find them	3. Change in environment has collapsed recruitment	4. Prawns are staying in Inshore and are not available to fishery	5. Prawns are no longer schooling so that the fishery cannot find or fish them	6. Pumping of groundwater has lowered water table reducing freshwater input	7. A pollutant has killed off the prawn stock
E. Area of the Stock	Greatly reduced, still contracting and will need management intervention to reverse.	Greatly reduced - but should be increasing rapidly because of the low fishing pressure.	Greatly reduced, still contracting will slowly rebuild when conditions reverse.	Greatly reduced - but should increase rapidly when Environmental condition reverses and rebuilt prawn biomass become available again.	The growing stock is remaining dispersed across the same large area.	Reduced because population remains concentrated inshore will increase if flooding sufficient to overcome effects of pumping.	Greatly reduced because most of the population has been killed off will only increase when toxins removed from environment.
F. Area of the Fishery	Greatly reduced, still contracting and will need management intervention to reverse.	Greatly reduced - but should increase rapidly when fishers get lucky and stumble across the rebuilding prawn biomass.	Greatly reduced, still contracting will slowly rebuild when conditions reverse.	Greatly reduced - but should increase rapidly when Environmental condition reverses and rebuilt prawn biomass become available again.	Greatly reduced - but should increase rapidly when conditions change and prawns begin aggregating again.	Reduced because population remains concentrated inshore will increase if flooding sufficient to overcome effects of pumping.	Greatly reduced because most of the population has been killed off will only increase when toxins removed from environment.

	1. Fishing pressure drives recruitment collapse	2. Loss of searching power drives decline in catch because fishers can't find them	3. Change in environment has collapsed recruitment	4. Prawns are staying in Inshore and are not available to fishery	5. Prawns are no longer schooling so that the fishery cannot find or fish them	6. Pumping of groundwater has lowered water table reducing freshwater input	7. A pollutant has killed off the prawn stock
G. Relevant Analyses	Standard fishery models valid. CPUE trends accounting for the effect of spatial contraction will be valid. Fishery Independent indicators of sufficient precision should indicate similar trends. If this hypothesis is valid analysis of within season CPUE declines will show recent trends are a continuation of longer term trends and the size structure of survey catches late in the season should show very low and probably declining survival of prawns through the season. Analysis	Fishery dependent data (CPUE) will be invalid in recent years because of loss of searching power. Fishery independent indicators of sufficient precision would reveal a different and actual trend and could be used in standard fisheries model if time series were sufficiently long. The surveyed size structure of prawns should suggest relatively high survival of prawns during the season because fishing mortality has declined. Analysis of appropriate environmental covariates would explain some of	Standard fishery models valid. CPUE trends accounting for the effect of spatial contraction will be valid. Fishery Independent indicators of sufficient precision should indicate similar trends. Analysis of appropriate environmental covariates would explain some of the variability observed around trends in fishery independent data including recent collapse.	Recent trends in fishery dependent data will not reflect actual population trends. Fishery independent data of sufficient precision and with appropriate inshore coverage might provide a reliable index of abundance and should show concentration of the stock at inshore sites. NB. Insufficent inshore coverage will invalidate fishery independent data. Size structure data from surveys should show relatively high survival of prawns through the year because fishing pressure is low. Analysis of appropriate	Fishery dependent data from recent years will not reflect actual population trends. Fishery independent data of sufficient precision should provide a reliable index of abundance and show the stock remains dispersed across the fishing grounds as normal in non-aggregating times of year. Size structure data from surveys should also show relatively high survival of prawns through the year because fishing pressure is low. The phenomenon of schooling is probably not sufficiently understood to allow a meaningful analysis of the factors that should have driven the change in schooling behaviour. If environmental driven some environmental anomaly should be associated with the recent collapse in catches. If density dependent (i.e. schooling stops at low density) schooling should resume as stock abundance grows due	Fishery dependent data from recent years will not reflect actual population trends. Fishery independent data of sufficient precision and with appropriate inshore coverage might provide a reliable index of abundance and should show concentration of the stock at inshore sites. Size structure data from surveys should also show relatively high survival of prawns through the year because fishing pressure is low. NB. Insufficent inshore coverage will invalidate fishery independent data. Analysis of appropriate environmental covariates (water table height, rainfall, river flow, salinity anomalies) should support this hypothesis.	CPUE trends accounting for the effect of spatial contraction will be valid. Fishery Independent indicators of sufficient precision should also indicate similar trends. Analysis with fishery models should show recent negative trend in recruitment residuals that would correlate with the release of toxins. Because the impact is continuing analysis of toxins in the environment and prawns should reveal significantly higher levels at Weipa than in other areas.

	1. Fishing pressure drives recruitment collapse	2. Loss of searching power drives decline in catch because fishers can't find them	3. Change in environment has collapsed recruitment	4. Prawns are staying in Inshore and are not available to fishery	5. Prawns are no longer schooling so that the fishery cannot find or fish them	6. Pumping of groundwater has lowered water table reducing freshwater input	7. A pollutant has killed off the prawn stock
	of appropriate environmental covariates should explain some of the variability observed around trends but no unusual anomaly is required to explain recent trends.	the variability observed around trends in fishery independent data.		environmental covariates (rainfall, river flow, salinity anomalies) should support this hypothesis.	to current light fishing.		

	1. Fishing pressure drives recruitment collapse	2. Loss of searching power drives decline in catch because fishers can't find them	3. Change in environment has collapsed recruitment	4. Prawns are staying in Inshore and are not available to fishery	5. Prawns are no longer schooling so that the fishery cannot find or fish them	6. Pumping of groundwater has lowered water table reducing freshwater input	7. A pollutant has killed off the prawn stock
H. Comments	Here, fishing pressure has continued increasing as stock contracted and recent decline in effort may not have resulted in reduced fishing mortality. Assuming sufficient measurement precision this hypothesis might be tested by comparing densities of juveniles in estuaries with previously measured densities which should be significantly higher.	Increasing stock abundance will reduce the possibility of the stock remaining hidden. Could be tested by constraining industry to thoroughly search the Weipa grounds.	Analysis of environmental covariates in recent years should reveal some extraordinary recent conditions.	Stock should be growing but remaining concentrated inshore - this might be supported by analysis of recent survey data if coverage and precision sufficient.	Stock should be growing but remaining dispersed across the normal area this might be evident in recent survey data if coverage and precision sufficient.	Simple analysis of the area impacted by groundwater pumping relative to the area of the catchment might suggest this hypothesis is infeasible. Lateral movement of groundwater is normally extremely low producing localised impacts on groundwater height. So if histoirical and current bore field is limited compared to catchment area an insignificant impact on run-off would be expected.	Knowledge of processing techniques used by Comalco and periodic dredging should identify possible toxic agent that should still be present in te environment. It should be expected that any such toxic agent should have impacted a suite of related species similarly. It would be unlikely that a single species would be impacted.

Table 6-15**.** Assumptions, weaknesses, strengths and techniques of various fishery dependent and fishery independent indices used to address Hypotheses regarding the abundance of banana prawns (*P. merguiensis*) in the Weipa region of the Gulf of Carpentaria.

Indices/Analyses	Assumptions	Weaknesses	Strengths	Techniques
Fishery Dependent				
A. CPUE	CPUE tracks abundance. Hypotheses 1, 3 & 7 must be correct for recent trends to be valid.	Imprecision early (poor reporting) & late (too few data) in time series. Depending on technique used spatial contraction of fishing area may not be captured in index. Recent data cannot be used to analyse Hyp. 2, 4, 5 & 6.	Long time series of data. Variance in data can be estimated.	Filter for Lunar phase. Restrict analysis to early part of first season (Banana prawn fishery only). Daily or weekly data? Improve measure of effort. Explore index reliability at low effort. Account for missing spatial zeros to capture spatial contraction.
B. VPA	Growth and mortality estimates are accurate. Hypotheses 1,3 & 7 must be correct for recent trends to be valid.	Imprecision early (poor reporting) & late (too few data) in time series. Needs reliable estimates of growth and mortality. Being based heavily on catch rate care required to ensure spatial contraction captured within index or else bias will result. Difficulty of estimating variance. Recent data cannot be used to analyse Hyp. 2, 4, 5 & 6	Long time series of data, not biased by spatial depletion	
C. Depletion	Declining CPUE through season reflects biomass decline through season. Hypotheses 1, 3 & 7 must be correct for recent trends to be valid.	Imprecision early (poor reporting) & late (too few data) in time series. Ignores growth and mortlaity. Difficulty of estimating variance. Recent data cannot be used to analyse Hyp. 2, 4, 5 & 6	Long time series of data. Not biased by spatial depletion as this the slope of the depletion curve is influenced by the spatial extent of the stock.	Leslie-Deluury technique

Indices/Analyses	Assumptions	Weaknesses	Strengths	Techniques
Fishery Dependent				
D. Catch	High and relatively consistent F through history of fishery. Hypotheses 1,3 & 7 must be correct for recent trends to be valid.	Very crude index that does not account for varying exploitation rates or within season processes of growth and mortality. Recent data cannot be used to analyse Hyp. 2, 4, 5 & 6.	Long time series of data, not biased by spatial depletion as catch is influenced by spatial extent of fishery.	
E. Area Index	There is a relationship between stock size and the area occupied by the stock. Hypotheses 1,3 & 7 must be correct for recent trends to be valid.	Relatvely crude index based only on catch and distribution of catch. Does not account for varying exploitation rates or within season processes of growth and mortality. Imprecision early (poor reporting) & late (too few data) in time series. Difficulty of estimating variance. Recent data cannot be used to analyse Hyp. 2,4, 5 & 6	Long time series of data, not biased by spatial depletion which is explicitly incorporated in the index.	Use indices calculated by Venables
F. Area	There is a relationship between stock size and the area occupied by the stock. Hypotheses 1, 3 & 7 must be correct for recent trends to be valid.	Very crude Index only based on area. Does not account for varying exploitation rates or within season processes of growth and mortality. Imprecision early (poor reporting) & late (too few data) in time series. Imprecision early (poor reporting) & late (too few data) in time series. Difficulty of estimating variance. Recent data cannot be used to analyse Hyp. 2,4, 5 & 6.	Long time series of data, not biased by spatial depletion which is the sole basis of the index.	
Fishery Independent Surveys				
G. Density	Survey estimates reliably and precisely track abundance	Only 9 years of survey data over a 35 year time series. Two separate survey periods with some changes in technique. Initial visual inspection suggests high variance of estimates.	Fishery Independent data that are capable of precisely tracking abundance is not impacted by hypothesised changes in commercial catchability proposed by Hyp. 2,4, 5 & 6.	

Indices/Analyses	Assumptions	Weaknesses	Strengths	Techniques
Fishery Dependent				
H. Size Structure	Survey estimates reliably track size structure of stock.	Only 9 years of survey data over a 35 year time series. Two separate survey periods with some changes in technique.	Additional data set that might allow testing hypotheses that predict differing (high or low) survival rates through the year.	
I. Juvenile Surveys	Survey estimates reliably and precisely track absolute abundance	Only one period of data and no recent data - would require repeat surveys. Sampling regime designed for biological sampling program - and has not yet been proven to reliably track abundance.	Additional Fishery Independent data that if capable of precisely tracking abundance might allow testing hypotheses that predict differing recruitment trends.	

6.4 Decision support framework for the fishery

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A decision support framework was developed during and after the third project workshop to accomplish two main goals: (1) to provide empirical data that would further narrow down the alternative explanations for the recently observed declines in banana prawn catches; and (2) to try to ensure the best management decisions in the context of the results of the present study and the new information arising from three types of surveys:

- An experimental fishing survey - opening the fishery prior to the first season (in the Weipa area only);
- An inshore juvenile prawn sampling program; and
- A January recruitment survey (already underway).

The results of these surveys are designed to be used in the decision support framework to allow decisions on whether fisheries should be closed and for how long, even if these alternative explanations of catch declines go unresolved. For example, strong management action such as a complete 5-year closure would be required when prawns are deemed to be scarce in most of their habitats (using this framework), regardless of the causes of the deemed low abundance. A critical aspect of this framework is that the participating fishing industry would commit to the management outcomes of the framework *a priori*. Another critical aspect of this framework would be the explicit recognition of risks associated with this management experiment (Okey and Harrington 1999). Finally, the various alternative hypotheses can be re-tested or verified by subjecting the new information from these surveys to the statistical and dynamical analyses developed during the current project. Seven hypotheses (excluding the two discredited ones) are included in the framework. Figure 6-37 shows the complete decision support framework, while Figure 6-38 shows a modified framework with an expensive juvenile survey sacrificed.

Because there is not presently enough information to determine the primary cause of banana prawn declines, the decision support framework was developed so that optimal and appropriate management decisions can be made in the face of information that does arise during the course of management and additional research.

Note that the framework expressed in Figure 6-37 represents the latest thinking and results of the present project, and it is therefore slightly different (updated) from the framework that emerged from the third project workshop and that went through the NORMAC approval process (shown as Figure 6-39). The difference between the updated framework (Figure 6-37) and the NORMAC approved framework (Figure 6-39) is that the updated framework specifies a fisheries closure when the experimental fishing survey result is “low” and the “juvenile” and “recruitment” survey results indicate “high” prawn biomasses. The previous framework specified no management action in this situation.

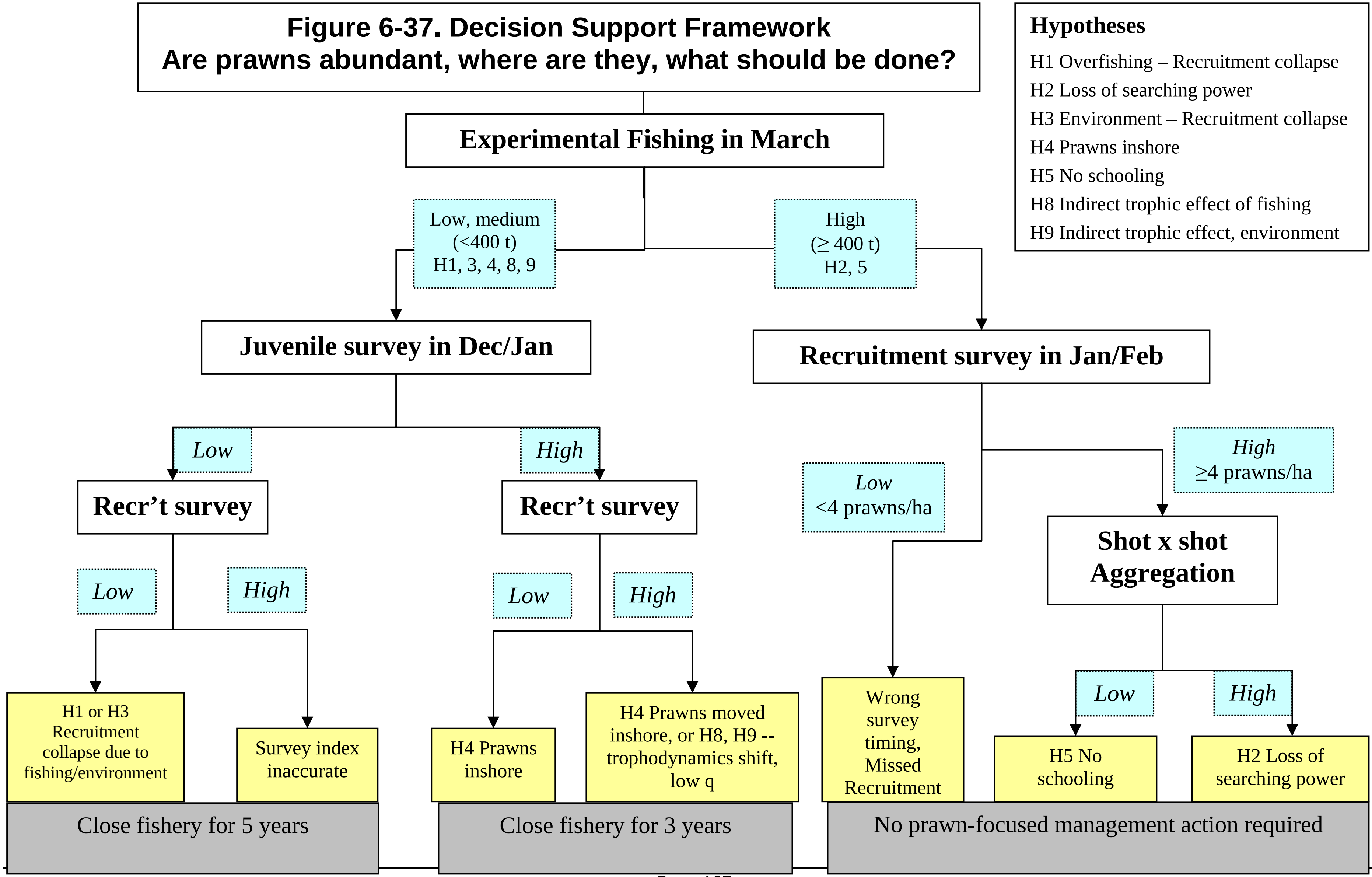


Figure 6-37. Decision Support Framework
Are prawns abundant, where are they, what should be done?

Figure 6-38. Simplified Decision Support Framework (Sacrifice of juvenile survey)

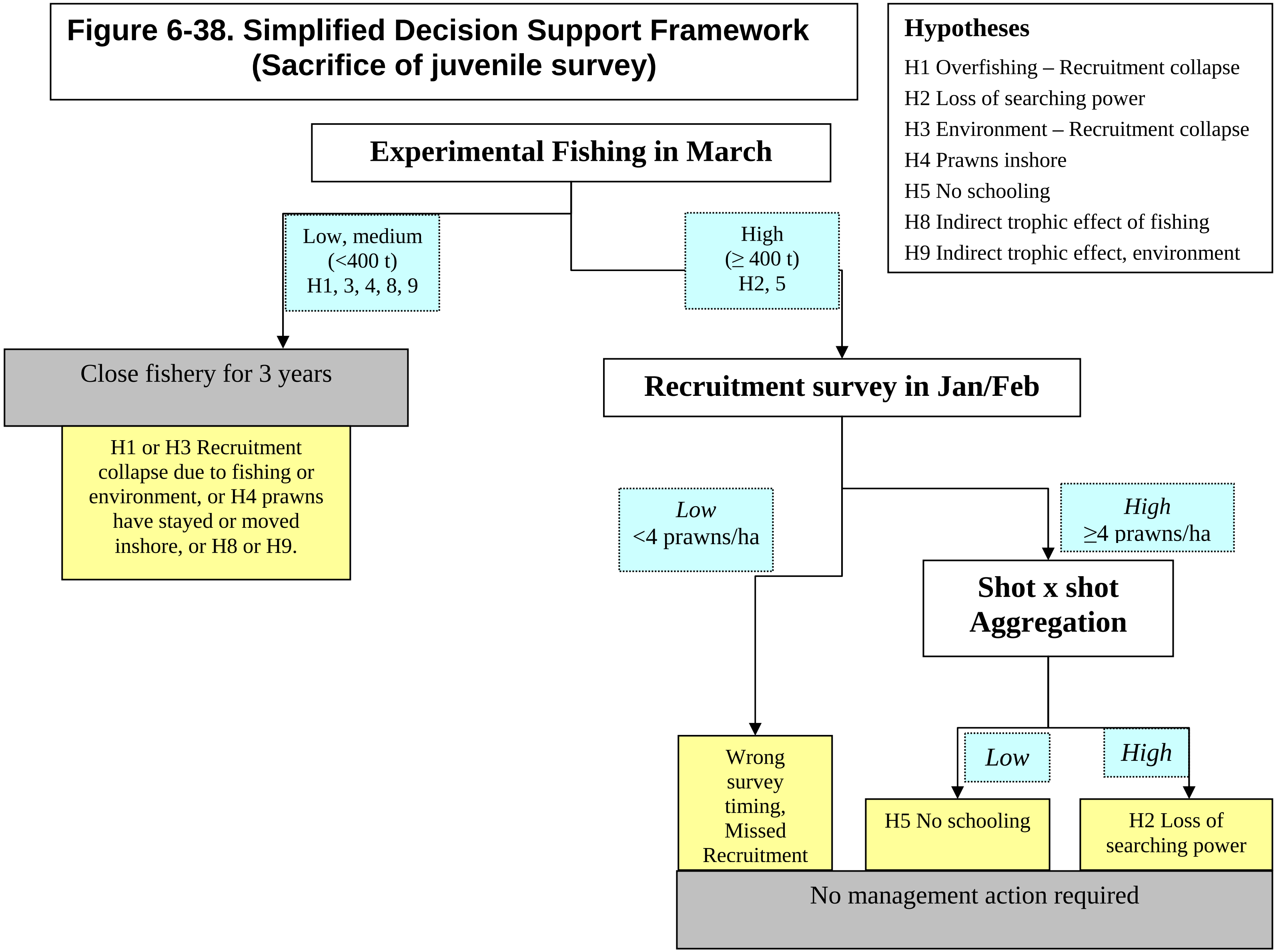
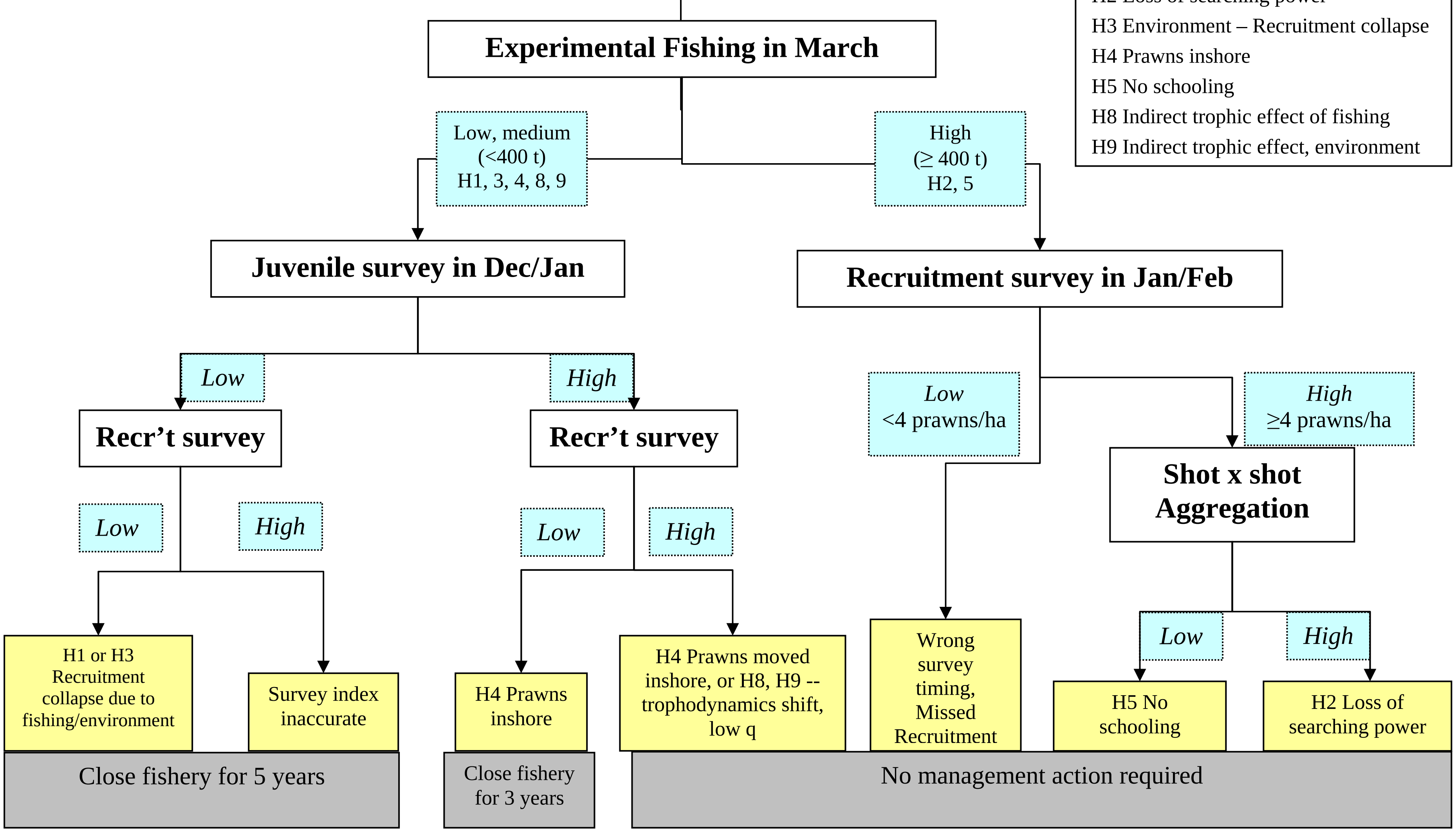


Figure 6-39. Original Decision Support Framework (now superceded by Figure 6-37 & 6-38)



6.4.1 The proposed experimental fishing survey

The experimental fishing survey uses the Northern Prawn Fishing fleet to estimate the abundance or biomass of banana prawns in the Weipa prawn fishing region. In this section we articulate the survey methodology. Information about the January recruitment survey is found elsewhere (Dichmont *et al.* 2004). Further, the inshore juvenile surveys are less likely to be implemented immediately (sensu Figure 6-38). The main aim of the experimental fishing survey is to determine the presence and abundance of banana prawns at the time of the opening of the fishing season.

This experimental fishing survey in Weipa is designed with four proximate goals:

1. Increase the searching power of the fishery beyond that normally observed;
2. Sample the period between the January recruitment survey and the April opening;
3. Offset the costs entailed in additional fishery-independent surveys; and
4. Achieve involvement of the fishing industry in management decisions.

General approach

Opening the Weipa commercial prawn trawling region for 1 week before the start of the first season (e.g. 21 to 27 March 2006) would allow a large proportion of the fleet to trawl in the Weipa area, whereas most boats might normally start the season in another location. Participants of the third project Workshop suggested three reasons for this particular period:

1. These 2 weeks would capture adequately representative phases of a lunar cycle[8];
2. The period accommodates the shift to daytime-only fishing in the 1st season; and
3. Many current fishers would be unfamiliar with this region and they need that many days to orient themselves.

One way to ensure a management decision result, irrespective of whether or not fishers participate, is for the Northern Prawn Fishery Management Advisory Committee (NORMAC) to consider that lack of participation by the fleet constitutes a general belief amongst fishers that prawns are economically depleted in the region. This lack of participation is considered equivalent to a determination of “low” biomass in the experimental fishing survey (see Figure 6-37) and would therefore lead to closures in the fishery for durations determined by the implementation of additional surveys specified by the framework. Workshop participants attempted to define what constitutes a “low” abundance result, but it was determined that this role is more appropriate for the Northern Prawn Fishery Resource Assessment Group (NPFRAG). In addition, detailed shot-by-shot information would be a desired output of the experiment so that the ‘loss of searching power’ hypothesis (H2) could be distinguished from the ‘no schooling’ hypothesis (H5)(Figure 6-37). The least expensive option is for these data to be collected by the industry as they fish, with once-off data sheets to be developed by CSIRO, checked by the NPFRAG, and provided to the fishers.

We note that the results of these potential surveys would apply to questions of abundance only in the particular circumstance of banana prawns at Weipa, and not to other species or areas in the Northern Prawn Fishery. The finding of abundant prawns in the pre-season experimental banana prawn opener poses the risk of misplaced justification to escalate effort in the tiger prawn fishery. Furthermore, the pre-season experimental opener poses potentially serious risks to the banana prawn population, especially if abundance/biomass is indeed at very low levels for whatever reason. Closures and marine protected areas with monitoring are an alternative type of management experiment that is protective rather than destructive, and just as informative if adequate monitoring is implemented (Okey and Harrington 1999).

[8] The full moon in March 2006 is on March 15th (0935 in Cairns).

The following sections are examples of how this decision support framework (Figure 6-37 and Figure 6-38) can be implemented.

“Low” biomass indicated by the experimental fishing survey

If the experimental fishing indicates “low” prawn biomass, then the ‘loss of searching power’ and ‘no schooling’ hypotheses (H2, H5) would be discarded (see Figure 6-37). A “low’ result from an additional inshore juvenile survey (which needs to be undertaken in Oct-Dec) would allow discarding of the hypothesis that prawns are abundant but moved inshore (H4) (the ongoing recruitment survey already allows distinction between the ‘no schooling’ and ‘loss of searching power’ hypotheses). A “low” result from the recruitment index would then indicate that that recruitment has collapsed in both the inshore and offshore areas, and that the cause of low catches is overfishing or environmental change (H1, H3) (possibly mediated indirectly through the food web in either case). Although the cause of low prawn biomass would still be strictly indiscernible, a 5-year closure would be recommended.

If the recruitment survey result indicates “high” biomass after both the experimental fishing and the juvenile survey indicated “low” biomass, then the recruitment survey is not a good predictor of biomass at the start of the fishing season. This would point to recruitment collapse in both the inshore and offshore areas and again the decision tree indicates that the Weipa fishery be closed for 5 years.

If we go back up the decision tree, to where the experimental fishery result is “low” but the juvenile survey result is “high”, then a “low” recruitment index would indicate that the prawns are inshore and have not moved offshore. In this case, the fishery would be closed for 3 years as there is some evidence that prawns that remain inshore do not spawn. A recruitment survey would be recommended in Weipa during this 3 year closure. Alternately, a “high” recruitment index in this case would mean that the prawns that were inshore in December successfully moved offshore in January/February but then either moved back inshore by March or were consumed by predators. The fishery would be closed for three years in this case because of the possibly that decreased numbers of adult prawns on the fishing grounds at the opening of the fishing season during the recent low catch years was caused by an increased abundance of predators that consume the pre-adult prawns after the “recruitment survey” or the possibility that moving inshore is density related.

This latter case requires management action because, for example, the Ecosim simulations indicate that prawn trawling may have indirect adverse effects on prawns by decreasing apex predator populations thereby increasing the biomass of the predators of prawns and in turn either reducing the biomass of adult banana prawns or initiating a change in their distribution.

“High” biomass indicated by the experimental fishing survey

If the “experimental” opener indicates “high” pre-season biomass, the recruitment index and the shot-by-shot data from the experimental fishing can be used to distinguish a lack of schooling from loss of searching power. If the January “recruitment” index is “low” in the case of high adult biomass, then the recruitment survey timing was wrong—it must have missed the recruitment pulse. No fisheries closures or other prawn-focused management actions are required in this case since sufficient adult prawns occur offshore.

If the January “recruitment” survey results indicate “high” biomass then we deduce that low catches would not be an indicator of poor January “recruitment.” Analyses of the shot-by-shot data collected during the experiment will help us separate whether an observed low catch is due to the prawns no longer schooling or the lack of vessels entering the fishery and a resultant loss of searching power (i.e. fishers tend to miss the schools). Again, no management action in terms of closures is required (for achieving prawn recovery) since prawns do occur offshore at recruitment sizes and adult sizes.

6.4.2 Implementation of the Decision Support Framework

The decision support framework was developed before, during, and after the third workshop of the current project with key input from members of the core project team, but also with key input from a variety of contributors and participants in both the project and the workshops, including members of the commercial fishing community. Refinements to this system have been continual throughout the process, and some of these are described in the previous section. The current section describes the steps taken both inside and outside of the present project to implement this decision support framework. Additional refinements were made during this implementation process, and these are described in the subsections that follow.

Implementation of the decision support framework to date has undertaken several steps, or milestones. These are shown in Table 6-16 and they are used as section headers for the remainder of this chapter. In general, NORMAC was divided on the prospect of implementation and so made no action, partly because the 2006 survey indicated high recruitment and it rained, making the NORMAC comfortable for the time being.

Table 6-16. Milestones in the implementation of the Decision Support Framework developed in the present project (FRDC 2004/024)

Milestone	Date
Presentation to the NPRAG/REC by project staff on Weipa workshop 3 and the Decision Support Framework ('the framework')	30 November 2005
NPRAG/REC discussion and recommendation to NORMAC 60	1 December 2005
NORMAC 60 discussion of experimental fishing survey	5-6 December 2005
Endorsement of the framework by the AFMA Board	16-17 February 2006
NPRAG actions and recommendations to NORMAC 61	14 February 2006
Refined proposal to NORMAC 61 with RAG/REC recommendation	23-24 February 2006
NORMAC 61 resolutions and actions regarding the framework	23-24 February 2006
Specification of the agreement on implementing the framework	

Threshold – experimental fishing

Table 6-17. Commercial catch data used to calculate experimental fishing threshold

Year	Total catch of bananas in first week of season	Average catch per day per boat (tonnes)	Total days fished by fleet in first week	No of boats fishing in first week of season
1990	237.2	0.577	411	123
1991	673.1	1.580	426	90
1992	131.9	0.502	263	76
1993	228.0	1.118	204	64

Year	Total catch of bananas in first week of season	Average catch per day per boat (tonnes)	Total days fished by fleet in first week	No of boats fishing in first week of season
1994	174.9	0.717	244	80
1995	498.3	1.786	279	60
1996	974.5	2.383	409	94
1997	641.1	1.955	328	89
1998	166.8	0.864	193	71
1999	349.2	1.819	192	78
2000	29.6	0.259	114	55
2001	63.0	0.750	84	47
2002	41.7	1.096	38	33
2003	2.8	0.176	16	16
2004	118.3	2.151	55	30

The average catch per boat per day for the first 7 days of the banana season at Weipa for the years 1990 to 1999 is 1.33 tonnes. The average catch per boat for the first 7 days of the season is therefore 9.31 tonnes (1.33 x 7).

Table 6-18. Expected total catch for the first seven days of the banana season at Weipa using an average catch per boat of 9.31 tonnes.

No of boats	Expected total catch for the first 7 d of the banana season (tonnes)
1	9.31
40	372.41
50	465.51
60	558.61
70	651.71
80	744.81

We have calculated the experimental fishing threshold in Table 6-17 and Table 6-18 by the following.

If we assume that:

1. catches at the start of the banana season at Weipa are around the average for the years 1990 to 1999;
2. that up to 70 boats may take part in the experimental fishing for seven days; and
3. each boat catches the average daily catch of 9.31 tonnes then,

we would expect a total fleet catch of about 651 tonnes (Table 6-18). We have rounded this total down to a **threshold of 600 tonnes** in the Figures.

The allowable fishing area for this experiment would be the Weipa area as designated in the AFMA NPF data summary; i.e. the area bounded by 12° S, 13° S, 140° E and the coast of Cape York.

Threshold – recruitment survey

The threshold for the recruitment index is based on CSIRO survey data from Weipa for the years 1987 to 1992 (January survey) and from 2003 to 2005 (January/February survey).

Catches from all surveys have been converted to the number of subadult banana prawns caught per hectare of seabed. Subadult prawns were defined as ≤ 30 mm carapace length for males and ≤ 33 mm carapace length for females.

Table 6-19. January survey index for scientific recruitment surveys carried out in Albatross Bay.

Year	**Survey index** (prawns/ha)
1987	5.6
1988	30.4
1989	2.3
1990	0.7
1991	8.5
1992	0.1
2003	1.9
2004	2.3
2005	10.4

In calculating a threshold for the recruitment surveys, we have removed the very high survey index for 1988 from calculations.

The average index for all surveys without 1988 is 3.98. In all the survey years when the recruitment index was above 3.98 prawns/ha, the subsequent commercial catch was at least 490 tonnes. We have therefore decided on a **threshold level of 4**.

Presentation to the NPRAG/REC

This section is extracted and modified from the NORMAC REC/RAG report of 5 December 2005.

On 30 November 2005, Dr. Tom Okey presented the results of the October 2005 Workshop on the FRDC/CSIRO-funded project “Variation in banana prawn catches at Weipa…” (FRDC 2004/024) to the NPRAG/REC. The presentation included an outline of the remaining hypotheses for recent declines in banana prawn catches, and it described the approaches of the working groups that examined the hypotheses. Working group analyses were presented in seven categories:

- Qualitative modeling
- Environmental correlates
- Fisheries stock assessment modeling
- Spatial contraction of the Weipa banana prawn fishery
- Ecosystem – Ecopath & Ecosim modeling
- Stable isotope analysis
- Qualitative model

It was explained that industry input to the workshop was extremely effective and that one of the outcomes of the project was the decision support framework.

It was requested the NPRAG/REC provide feedback on the decision support framework presented, and also requested an approval or endorsement of the process explained in the framework. The Chair requested that Dr. Okey present to the meeting on the next day a succinct list of requests for the RAG/REC that include definitions of reference points for the decision framework as well as resource and costing details.

On the second day of the RAG/REC meeting, Dr. Okey presented a proposal and three explicit questions for the RAG:

(1) Does the RAG support the decision support framework?

(2) Which survey approach is the RAG prepared to support?

(3) Can the RAG recommend or provide advice in determining the triggers and thresholds for the framework?

RAG/REC members asked a few questions about the implications of the framework, and after some discussion agreed that the framework is appropriate.

Two alternative approaches (Figure 6-37 & Figure 6-38) were discussed, keeping in mind the benefits of collecting information at various prawn life history stages. The full decision framework includes a juvenile survey in November/December followed by a recruitment survey in January and finally the experimental fishing survey in March/April.

Due to resources, imminent timing, and cost factors, members agreed that it was best to rule out a juvenile survey, with the proviso that industry would not at a later time argue to keep fishing open because of the possibility that prawns were abundant inshore. Discussion about the possible need to survey and sample the 1 to 8m depth range inshore Albatross Bay noted that sampling had never been conducted there before, and would require a beam trawl, and further that this is a large area requiring considerable effort. There was a concern that the proposed process might not distinguish fishing effects from environmental effects.

All agreed with the need to determine the reasons for recent low catches and that this is a one off approach. Discussion then centered on the criteria and triggers for the experimental fishing (i.e. 300 t and the 5 t/h) and ways to ensure that a sufficient number of boats and searching time. It was agreed the trigger would be total catch. It was also agreed CSIRO would calculate the triggers for the experiment based on logbook CPUE data and assume about 60 to 80 vessels would participate. The recommendation below details the length of the experimental fishing and the linkage of the timing of the survey to the lead up to the first quarter moon.

All members indicated their unanimous support for the framework and noted the considerable risk of using destructive sampling methods that might severely affect the remaining prawn population in the case of proving a recruitment failure would. However, it was felt that this option was being undertaken for the greater good of the NPF.

NPRAG/REC discussion and recommendation to NORMAC 60

This Section is extracted and modified from the Northern Prawn Fishery Management Advisory Committee (NORMAC) 60 Research and Environment Committee (REC) and Northern Prawn Fishery Resource Advisory Group (NPRAG) Report.

The REC/RAG considered two decision support frameworks that would help to determine the status of the banana prawn catches in the Weipa area, narrow down causes of low catches in recent years, and specify appropriate management responses. The REC/RAG recommended that the framework depicted in Figure 6-38 be adopted, given the logistical unlikelihood of successfully undertaking a juvenile survey over the coming few weeks. This is the lower cost option, but also the one that supplies less information. The REC/RAG thus recommended that the Weipa region be opened from 21 to 27 March 2006 as a once-off opportunity to search for banana prawns in the region with an adequate number of participating boats. The REC/RAG also explicitly acknowledged that this experimental fishing survey could be detrimental to the banana prawn stocks if they are indeed depleted at the Weipa area. The REC/RAG considered the survey to be worthwhile compared with the *status quo* because obtaining confirmation of stock depletion at Weipa might indicate the possibility of stock depletion in other regions throughout the Northern Prawn Fishery.

The REC/RAG also recommends that NORMAC note and discusses the appropriateness of the trigger points in the framework. The proposal shown later (and the figures shown previously) includes the framework and associated costs ($15 to 20k without juvenile survey).

The minimum requirement for participation was that the fishers provide detailed shot by shot data (using an extra log sheet provided by the RAG out of session by end January 2006) and also to provide full plotter data so that catch distributions and searching patterns could be analysed.

Recommendation of the NPRAG/REC to NORMAC 60:

Two decision support frameworks were discussed by the REC/RAG that would progress the debate on why the catches are low in Weipa. Given that it would be logistically impossible to undertake a juvenile survey over the next few weeks, the REC/RAG recommends that the Figure 6-38 decision support framework option be adopted. This is the lower cost, but also the low information, option. The REC/RAG therefore recommends that the Weipa region be opened 7 days earlier once-off (from 21 to 27 March 2006) in order to provide the fleet numbers to search for and survey the banana prawns in the region. The REC/RAG acknowledges that, if there is recruitment failure at Weipa, this experiment may be detrimental to that resource. However, it is worthwhile obtaining this information rather than remaining at *status quo,* as a recruitment failure at Weipa would indicate the possibility of recruitment failure in other regions of the NPF.

The REC/RAG also recommends that NORMAC note and discusses the appropriateness of the trigger points in the framework.

A minimum requirement of participation should be that the fishers provide detailed shot by shot data (using an extra log provided by the RAG out of session by end January 2006) and also to provide full plotter data so as to record the catch distributions and searching patterns.

NORMAC 60 discussion of the experimental fishing survey

This section was extracted and modified from the NORMAC 60 Chair’s summary of 12 December 2005.

Weipa Fishery

Catches of banana prawns in the Weipa fishery have been at an all time low for the last 5 years (with 2006 now a possible exception) and serious concerns were held about the stocks in that fishery. Opinions on Weipa vary from the possibility that the area may be suffering from recruitment failure to views held by some NPF operators that there are insufficient vessels searching for banana prawns due to the short season length and the need to quickly locate aggregations of banana prawns. The NPRAG organized a series of workshops to specially address concerns about Weipa and produced a range of options to investigate those theories. These included an experimental fishing program to be undertaken by the fleet prior to the commencement of the season, and juvenile surveys to ascertain whether prawns are in the inshore areas but are not getting out to the fishing grounds. NORMAC noted that it is logistically impossible to undertake a juvenile survey before the start of the 2006 banana prawn season, and the REC/RAG recommended that the Weipa region be opened 7 days earlier than the rest of the fishery to allow the fleet to undertake a once-off experimental fishing program to search for and survey the banana prawns in the region. The REC/RAG acknowledged that, if there is recruitment failure at Weipa, this experiment may be detrimental to that resource. However, it was considered worthwhile obtaining this information rather than remaining at *status quo* as a recruitment failure at Weipa would indicate the possibility of recruitment failure in other regions of the NPF. NORMAC noted advice from the RAG is that the experimental approach should only be adopted for one year and it would be too risky to do it more than once.

[Editor's note: Some of the details in the statement above are inaccurate. The CSIRO organized the series of workshops referred to as part of FRDC project 2004/024. This project articulated a range of alternative explanations (hypotheses) for banana prawn catch declines, it explored the plausibility of these hypotheses using a range of analytical approaches, and it developed a management decision support framework to guide AFMA with further research and management decisions that would both narrow down the alternative hypotheses and protect the banana prawn stocks.]

NORMAC agreed to implement the industry-based one-off experimental fishing program from the 21 to 27 March 2006. NORMAC agreed that a minimum of 400 t must be caught by the fleet in the experimental fishing program if the fishery is to remain open. NORMAC agreed that if the fishery does not produce the results required to meet the survey specifications (400 t) the Weipa fishery (area of the statistical region of Weipa) will be closed for the duration of the banana prawn seasons for 3 years. NORMAC noted that a minimum requirement of participation would be that the fishers provide daily log sheets and full plotter data so that catch distributions and searching patterns can be identified.

Endorsement of the framework by the AFMA board

The AFMA board met on 16 to 17 February 2006, and the following paragraph regarding AFMA's endorsement of the experimental fishing survey is excerpted from the NORMAC 61 minutes:

"…the AFMA Board recently endorsed the implementation of a proposed one-off industry-based experimental fishing program to be conducted from 21 to 27 March 2006 to search for and survey banana prawns in the statistical region of Weipa in accordance with agreed survey specifications as recommended by NORMAC [61]. The Board also agreed that if the fishery did not produce the results required to meet the survey specifications, the Weipa fishery (area of the statistical region of Weipa) should be closed for the duration of the banana prawn seasons for three years."

NPRAG actions and recommendations to NORMAC 61

The Northern Prawn Resource Assessment Group (NPRAG) resolved the following action (excerpted from the 14 February NPRAG meeting minutes) relating to the experimental fishing survey for recommendation to the NORMAC 61 at their 23 to 24 February 2006 meeting:

Chair to report to NORMAC with a recommendation from the RAG that (given daily catch reporting to AFMA) NORMAC should adhere to the decision-tree frame work that underpins the Experimental Fishing: if the catch obtained during the experimental fishing is < 400 t, then the Weipa region is closed for first-season 2006, 2007 and 2008; if the catch obtained during the experimental fishing is > 400 t, then the Weipa region opens again in 2006 simultaneously with the NPF-wide first-season. The RAG notes that the decision will be made based on un-verified data provided to AFMA on a daily basis.

Discussion at this 14 February 2006 NPRAG meeting focused on: the risk that this experimental fishing survey might cause damage to this stock given the potential interest in participating in this survey throughout the fleet (and the potential breech of AFMA management objectives); the reason for choosing 21-27 March 2006 (determining presence and abundance rather than immediate economic optimisation); questions about when the fishery would be closed if 400 t was not reached (rules of the game); and the justification for the threshold (400 t is the 25th percentile of the historical catches examined).

The original (more detailed) action items from the RAG meeting are presented in Table 6-20.

Table 6-20. Action items agreed on during the 30 November-1 December NPRAG meeting related to the decision support framework

Action	Person and deadline
Cathy Dichmont to report to NORMAC with a recommendation from the RAG that (given daily catch reporting to AFMA) NORMAC should adhere to the decision-tree framework that underpins the Experimental Fishing: if the catch obtained during the experimental fishing is < 400 t, then the Weipa region is closed for first-season 2006, 2007 and 2008; if the catch obtained during the experimental fishing is > 400 t, then the Weipa region opens again in 2006 simultaneously with the NPF-wide first-season. The RAG notes that the decision will be made based on un-verified data provided to AFMA on a daily basis.	Chair; by NORMAC 61, February 23/24, 2006.
Develop separate log sheets for the Weipa experimental fishing survey and provide them to the NPF fleet so that the requirement for extra data is clear (extra data such as date, shot #, time of shooting away, time of winch up).	Wade Whitelaw; distribution prior to survey
Cathy is to seek NORMAC endorsement for measures to support the Weipa Experimental Fishing survey: • The VMS polling frequency be increased to 1 hour or less for the duration of the Weipa experimental fishing survey. • It be a requirement of participation that all Skippers provide GPS position data in the form of their C-Plot files created during the experiment to CSIRO to support their analysis of the results of the experiment. CSIRO's Rob Kenyon will be responsible for collecting the GPS data on USB drive or CD.	Chair; NORMAC 61

Action	Person and deadline
• AFMA highlight the legal requirement that, in conjunction with the logsheets targeted to the experiment, skippers must complete the regular NPF logsheets as per usual. • All 'experimental logsheets' will be sent to AFMA. AFMA to telephone Industry and/or vessels on a daily basis to obtain catch statistics for that day.	
Collect C-Plot files from Skippers participating in the Weipa experimental fishing survey	Rob Kenyon; after the end of the survey

NORMAC 61 meeting resolutions and actions on the framework

On 23 to 24 February 2006, the NORMAC 61 voted unanimously to defer the experimental fishing survey (presumably to the following season), and that the 2006 season should open at the same time as the rest of the fishery (15 April).

Industry members expressed concern that the proposed experimental fishing survey might constitute "severe pulse fishing in an area which appeared to be showing signs of stock recovery." The NORMAC concurred that the proposed experimental fishing survey might pose "considerable potential risks to the banana prawn population," which might already be depleted, but the NORMAC considered these risks to be acceptable. Industry members also expressed concern about the negative economic ramifications of potentially catching and marketing large quantities of small prawns prior to the season

Several specific resolutions about the decision support framework were made by the NORMAC 61:

- That NORMAC unanimously agrees that the experiment should be deferred, and that the Weipa area should open at the same time as the rest of the fishery, to spread the fishing effort and minimize potential negative impacts on the area;
- That, to assist in obtaining data on catch and effort in the area, operators who fish in the Weipa area will be required to provide shot by shot information, in addition to their daily log sheets;
- That AFMA will develop and distribute specific separate log pages on which operators are to record shot by shot information;
- That the VMS polling rates in the Weipa area will be increased for the duration of the banana prawn season to provide better information on fleet dynamics and grounds searched;
- That [these] data will be reviewed by the RAG and the MAC after the 2006 banana season;
- That the Scientific Member will provide a discussion paper for consideration at the next MAC meeting on the principles for defaulting to a precautionary approach if there appears to be recruitment overfishing of a stock.

Four specific actions arose from NORMAC 61 related to the experimental fishing survey. These are shown in Table 6-21.

Table 6-21. Actions related to the experimental fishing survey arising from the NORMAC 61 meeting

Action	Responsible person
Develop and distribute specific shot by shot log pages for operators fishing Weipa banana season	AFMA Management
Increase polling in Weipa area during 2006 banana prawn season	AFMA Management
Review Weipa data and next steps for Weipa after banana prawn season	NPRAG/NORMAC
Provide paper to NORMAC 62 on the principles for defaulting to a precautionary approach if there appears to be recruitment overfishing of a stock	Cathy Dichmont

Three changes were made to the Decision Support Framework after the NORMAC 61 meeting:

- The "high/low-medium" catch threshold was reduced from 600 t to 400 t because of the notion that below average catch should not be considered an indicator of "low" biomass;
- If low-medium decided to close fishery for 3 years;
- An indication of "low" biomass from the experimental fishing survey following indications of "high" biomass from both the juvenile surveys and January "recruitment" survey is now specified to require a 3 year fishery closure rather than no management action (compare Figure 6-37 with Figure 6-39). This change was made because prawns might be depleted in March-April because prawn trawl fisheries have reduced the apex predators that control the predators of banana prawns, thus leading to an indirect depletion of the banana prawns by the prawn trawl fisheries.

These changes are reflected in the 'original' decision support framework (Figure 6-39), but more changes have been added to the latest modified framework (Figure 6-37) as discussed previously.

References

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Okey, T. A., and Harrington GA. 1999. Criteria for designing ecosystem-based, experimental management programs: Bottom trawling and the Bering Sea ecosystem. pp. 425-446 *In:* Ecosystem approaches for fisheries management. University of Alaska Sea Grant, AK-SG-99-01, Fairbanks.

6.5 Synthesis

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This Chapter summarises the major findings of the four Working Groups (Qualitative Modelling, Fisheries Dynamics, Ecological Modelling, and Environmental Factors Affecting Recruitment) and other individual contributions to the Project. We present elements of common understanding and future research needs to determine the factors affecting recruitment variability in the banana prawn *Penaeus merguiensis*.

The present exploration of the causes of banana prawn catch declines was designed with five parallel analytical approaches that were independent of each other methodologically. The synthesis of these results into a more refined and improved explanation of the catch declines benefited from the sharing of the results that emerged from the working groups. This interfacing of results was achieved through ongoing communication during each of the project workshops, working interactions between workshops, and a thorough examination of the results at the conclusion of the project. This synthesis stage allowed us to narrow the set of alternative explanations and provide useful insights into some likely causes. Perhaps more importantly, the results point toward additionally needed research and management actions to resolve the banana prawn catch decline dilemma by highlighting uncertainties related to critical gaps in information about banana prawns (*Penaeus merguiensis*) and the Albatross Bay ecosystem.

An unavoidable aspect of this project is that the analyses carried out by each team were conducted simultaneously and not sequentially. This inhibited the effectiveness of each analysis to some extent by limiting the opportunity to conduct iterations of analyses that were based on each working group's results. Opportunities for continued analyses along the present lines is thus likely to produce true breakthroughs in understanding questions such as why banana prawn catches declined so suddenly and considerably, and why the catches apparently rebounded in 2006.

This synthesis chapter contains four elements: (1) A discussion of the overall results from each working group and how these results reconcile with, or contradict, each other; (2) A logical discussion of how the initial set of hypotheses was narrowed and organised into themes for conceptual clarity; (3) A 'Decision Support System' framework that was developed during the third project workshop and refined subsequently, including a discussion of the science and management benefits, and risks of this framework; (4) A history of the implementation of this Decision Support System by fisheries management authorities, up to the present.

6.5.1 Reconciling the results of each working group

Life cycle and reproductive dynamics

In the early part of the project we reviewed past research on each of the life history stages of the banana prawn. The banana prawn life cycle is complex with offshore spawning and inshore/estuarine nursery phase. Reproduction as measured by a population fecundity index (PFI) is seasonal with a large peak in late Summer-Autumn (Jan-Mar) and a smaller peak in Spring (Aug-Nov). The Summer-Autumn peak is made up of a large number of 6-month old females before the season's fishing commences and the Spring peak is comprised of a small number of 12-month old females that escaped from the season's fishing. The smaller sized Spring peak supplies most of the eggs, larvae and postlarvae that give rise to the following season's fished stock. The differential in contribution of the peaks reproductive output to postlarval recruitment is due to the location of the spawning stock (the "effective spawning population") close to shore (the "effective spawning envelope"), the suitability of the juvenile habitat during Spring, and the stimulus for offshore migration during the Summer wet season.

Future research

Interannual variation in spawning magnitude and location, and the subsequent variation in PL recruitment, needs to be quantified to refine the spatial extent of effective spawning envelope and the size of the effective spawning population.

Better understanding of factors affecting egg survival and hatching rate as well as factors affecting larval growth and survival would strengthen the relationship between the PFI and subsequent PL numbers.

Qualitative Modelling

The Qualitative Model was developed for and used as both a Conceptual Framework for the project and a guide to interactions among the various impacts on the banana prawn population and fishery for the purpose of providing general insights into the interactions and possible dynamics in the system. The full model incorporated the impacts of the fishery and the market, as well as effort trade-offs and effects of environmental and habitat factors on all life history stages of banana prawns.

Key findings of the qualitative model include *inter alia*:

1. Instability in the prawn-based system will arise when discarded bycatch promotes relatively high predation pressure on prawns;
2. CPUE was not a reliable indicator of stock abundance;
3. High early season rainfall should increase all prawn life history stages and CPUE;
4. Late season rainfall should suppress all life history stages, but the effect on CPUE is ambiguous; and
5. Reduced catch in Weipa reinforces a shift in effort away from Weipa.

Because the qualitative model was constructed and specified based on general and common ideas about how the Weipa banana prawn fishery system works, it was very useful in evaluating interconnections amongst physical, biological and anthropogenic factors, but it could not be used to evaluate the relative likelihood of the various hypotheses listed. For example, it could not be used to eliminate or rank the likelihood of the overfishing, environmental, or searching power explanations. Like other Working Groups the qualitative analysis could not find a reliable correlation between CPUE and the size of the catch in the Weipa region.

Future research

The current model needs to be enhanced to include the new findings of this report and provide guidelines for future research. Likely areas of enhancement would include more detailed analysis of environmental effects on all life history stages, and the dynamics of effort trade offs between regions – e.g. searching efficiency, opportunity costs and the relationship between management objectives and measures.

Fishery Modelling

The aggregating behaviour of *P. merguiensis* has made biomass very difficult to estimate historically because of their high variability in space and time. It was hoped that more refined estimates would be possible, based on available data identified during the present project, but this was not possible. Pooling of data over vessels, time and space was not fruitful because of the very limited season and lack of daily CPUE observations. Neither the Tuned VPA nor the Depletion Model demonstrated a clear relationship between recruitment and associated spawning biomass, but there appears to be no downward trend in spawning biomass. The Tuned VPA offered no support for the hypothesis that recruitment estimates had been affected by the environmental variables examined (principally rainfall timing and amount).

There was insufficient power in the analysis to conclude that recruitment was **not** affected by a reduction in spawning biomass resulting from fishing, or the effect of environmental factors, or both. In the absence of such evidence, it remains appropriate to manage the fishery in accordance with the precautionary principle – assume that recruitment is affected by a reduction in spawning biomass induced by fishing. It is therefore suggested that management strategies should be put in place to allow recruitment in Weipa to recover to levels in the mid-1970s and mid-1990s. The Decision Support Framework constructed in Workshop 3 recommended a pre-season controlled-fishing experiment to test this hypothesis prior to management actions.

Future research

To add power and predictability to the fishery models, a more precise and accurate index of abundance for banana prawns is needed. This would be further enhanced by estimates of abundance and characteristics of aggregations such as prawn abundances inside and outside aggregations. This information could be incorporated into refined logbook information. In addition, a better understanding of effort in the banana prawn fishery is needed; i.e. the dynamics of the searching process. This might be achieved with a combination of a refined logbook or detailed GPS track data. These enhancements would lead to a better understanding of the changes in the overall spatial distribution of both prawns and fishing boats.

Contraction of Fishing Area

Penaeus merguiensis is an aggregating species during the fished part of its life cycle. Catchability (q) of the prawns is sensitive to the ability of fishers to target and search for these aggregations. The ability of fishers to predict and find aggregations increases catchability and vulnerability, especially as the stock size declines. According to this analysis, catchability in the Albatross Bay region increased by 5 to 10 times from the early 1970s to late 1990s.

This increase in catchability, which is probably exponentially shaped, occurred because the observed distribution of the catch (if not the stocks) has contracted and concentrated over the years to the centre of the historically widespread fishing area – a “hotspot”. This increased catchability occurred in spite of declines in the nominal effort of the fishery in the overall Weipa area. This analysis provides a very plausible mechanism explaining how catchability increased and biomass declined in the Weipa area, based on data on historical fishing patters from the area. The analysis also indicates that similar concentration trends are occurring in other regions of the NPF.

This spatial contraction analysis clearly indicates either a fisheries explanation for the decline in banana prawn catch in the Weipa area or the limited searching time available during the shortened season, which makes them focus their efforts only on the historical hotspot in the Weipa region, as they have a higher likelihood of finding aggregations in the southern Gulf due to the presence of spotter planes and a larger fleet there.

Future research

To understand the impact of these trends we need to:

- establish the relationship between distribution of catch and distribution of stock; and
- establish the relationship between catchability and effort (real or nominal).

Effort Analysis

There has been a steady decline in fishing effort (boat days) at Weipa from the 1970s (600 to 1400) to the 1990s (400 to 800); with fewer than 100 boat days since 2000. There has been a similar trend at Karumba, but not the continued falloff since 2000. The trends reflect both the diminishing size of the fleet and the increased restrictions on length of season.

Mean decadal catches in the Weipa region increased from the 1970s, to the 1980s and to the 1990s and then dropped precipitously from 2000 on. This trend is less apparent in Karumba, where the mean catches in the 2000s are comparable or slightly higher than previous decades

The proportion of Weipa catch explained by effort was highly variable from 23 to 73%. In Karumba effort explained more of the variation and was more consistent (70 to 95%). Over the decades there has been an increase in catchability at Weipa. Currently the small effort (few boats for short time) in Weipa is in contrast with Karumba where effort has been maintained and is aided by spotter planes.

These analyses tend to support the hypothesis that effort reductions have contributed to the very low catches in Weipa since 2000.

Future research

There is a need to reconcile this analysis with Venables and Poloczanska (this report) which stated that effort (as an explanatory variable, not a predictive one) was more closely related to catch in Weipa than in Karumba.

Ecological Modelling – Ecopath with Ecosim

The results of the trophodynamic modelling analyses indicate that changes in fishing effort within the range of changes observed during the last 20 y is capable of causing very large declines in banana prawn biomass through both direct and indirect effects. They also indicate that small decreases in prawn fishing rate from the 1986 to 1992 levels can cause moderate increases in prawn biomass, but that large decreases in trawl prawn fishing rate can cause large decreases in prawn biomass, indicating an optimum fishing rate for prawn production that is less than the average 1986 to 1992 fishing rate.

Simulations of changes in trawl fishing effort indicated that banana prawn populations are sensitive to prawn trawl fishing effort, and that the effects of prawn trawling on banana prawns manifested both directly through removals of biomass and indirectly through trophic cascades. For example, the simulated removal of shark functional groups often enabled increases in the biomasses of species (functional groups) that prey on banana prawns, thus decreasing banana prawn biomass. Given the information at hand for this trophodynamic ecosystem model it is therefore plausible that the recently observed large declines in banana prawn catches is a reflection of large declines in banana prawn biomass in the Albatross Bay area, and that these declines were caused by prawn trawl fishing either directly or indirectly.

In general, the trophodynamic simulations indicated that prawn trawling in the Albatross Bay area modifies the biological assemblage of the region in ways that sometimes have a net beneficial effect on prawns and sometimes are adverse to prawn persistence. Increased prawn fishing levels from the late 1980's, for example, is predicted to remove high trophic level predators thus enabling predators of prawns (e.g. stomatopods and octopus) to become more abundant and exert higher natural mortalities on prawns. Low levels of prawn trawling seem to have net beneficial effects on prawns by reducing the overall predation pressure on them.

A more sophisticated simulation to accurately reconstruct community changes caused by fishing or the environment by comparing predicted time series to observed changes in functional group biomass was not reliable or robust at the current level of model refinement, mostly because of the lack of reliable observed time series of prawns or other functional groups, and perhaps also because the analytical tool is not ideally suited to dealing with the high interannual variability of these prawn populations. Notwithstanding such concerns, additional refinements to this trophodynamic model is expected to be profitable with respect to understanding the causes of prawn catch and biomass fluctuations in the context of fisheries, environmental changes, and other disturbances, as well as understanding the broader ecosystem impacts of bycatch.

Future research

Refinement of the stability, reliability and predictability of the model is possible with more time and increased collaboration with experts in various functional groups. The model points to possible key drivers and controllers to banana prawn populations dynamics that warrant further study. These include collection of basic biological information in the following areas:

- Some further key banana prawn biology;
- Reliable time series of abundance and trends;
- Improved estimates of the predators and prey of banana prawns (e.g. stomatopods);
- Focussed studies on key predators (e.g. stomatopods, octopuses and other cephalopods);
- Improved information on primary and secondary production rates and fates (e.g. production of detritus);
- Improved oceanographic and climatological trend information; and
- Improved fisheries information.

Ecological Modelling – Estuarine fish predation studies

A short field study in the Embley-Hey estuary in February 2005 was undertaken to compare the current suite and abundance of juvenile prawn predators to an earlier 1986 to 1992 study. This is a partial test of the changes in predation pressure element of Hypothesis 8.

In the 1980s, 77 species were caught and 54 were piscivorous. The most numerous piscivores were: *Scomberoides commersonianus* (Queenfish), *Arius proximus* (Arafura catfish), *Lates calcarifer* (Barramundi), *Polydactylus sheridani* (King salmon) and *Rhizoprionodon acutus* (Milk shark), the first four of which accounted for over 90% of all prawns eaten. In 2005, 54 species were captured of which the most common were: *Scomberoides commersonnianus, Nematalosa erebi,* (Bony brim), *Lates calcarifer, Arius sp.3, Arius proximus, Valamugil buchanani* (Blue-tailed mullet) and *Carcharhinus tilstoni* (Australian black-tipped shark).

The overall fish predator catch rates from the lower, middle and upper reaches of the Embley estuary were not significantly different between the 1980s and 2005. The overall catch rates of the major prawn predators (fishes) were not different between the 1980s and 2005

Future research

The comparative sampling in the 2005 sampling episode was limited to a single wet season survey. Further, no fish gut content analyses were undertaken to compare to the 1980s. The sampling only covered potential fish community changes in the estuary and does not address changes that may have occurred offshore where the trawl fishery operates. To test the indirect predation effect of bycatch reduction, as proposed in the Ecosim simulations, offshore sampling of the fish community and its predation impact will also have to be re-examined.

Ecological Modelling – Isotope studies

A short field trip to the Embley-Hey estuary in February 2005 was undertaken to study trophic linkages and the effect of freshwater inputs on coastal ecosystems using stable isotopes.

Infauna provided the major food source for adult prawns and demersal fish. Crabs and stomatopods are likely to be eating the same food source as prawns. The stomatopod's isotope signal was slightly higher than prawns indicating a portion of their diet is prawn, and their diet is probably opportunistic and varied during the weeks or months preceding this February sampling.

The study also found distinct gradients of freshwater to marine signals in a number of trophic groups. The signal was more pronounced in the water column than the sediment. The estuarine juvenile phase of the prawn's life history can be seen in their ^{13}C signal – this is more apparent in *P. monodon* and *P. merguiensis* than in *P. semisulcatus*.

Future research

Stable isotope analysis continues and will be used in the Ecopath model as an independent dataset to verify biomass and productivity estimates of different trophic groups. Ultimately this study should provide information about prawn predators and prey across the juvenile and adult life history stages in both Weipa and the Gulf of Carpentaria

Environmental Factors Affecting Recruitment

An exhaustive study of the relationship between a suite of environmental variables (rainfall, evaporation, air temperature) and banana prawn catch and effort in the Weipa, Mitchell and Karumba regions was undertaken. There has been no long-term change in timing of or downward trend in rainfall, and so changes in banana prawn catch cannot be explained by changes in rainfall. In terms of interannual variability, log(Catch) is only weakly predictable in both Weipa and Mitchell based on rainfall data. With log(Effort) added as an explanatory variable, the catch is highly correlated with environmental variables in Weipa and reasonably correlated in Mitchell. In Karumba the environmental signal is the strongest – catch is reasonably correlated with or without log(Effort) – pre-season rainfall (or surrogates) is the dominant environmental predictor there. The effect of the decline in effort on catch in all three regions is strongest and most consistent in Weipa, relative to the effects of environment. Despite the exhaustive and rigorous nature of this analysis, environmental variables could not explain the observed multi-year trend in banana prawn catch in the Weipa area probably because the prawn abundance estimates (catch and CPUE) are confounded by dramatic changes in effort since 2000.

Future research

To enhance the predictability of environmental factors we need to examine environmental drivers of other (earlier) phases of the life cycle. Using a Bayesian approach, the potential feedback loop between catch and effort (i.e. opportunity costs) which operates differently in the three stock areas, should also be examined.

6.5.2 Hypothesis analysis

Overall, nine hypotheses were considered during the project (Table 6-22). The three hypotheses that emerge as the most likely explanations for the observed catch declines in banana prawns over the last several years are all fishing-related explanations. They include recruitment overfishing, indirect trophic effects of fishing, and a loss of searching power resulting from a reduction of boats in this region.

Table 6-22. Ranking of the likelihood of each explanation (hypothesis) for the observed decline in banana prawn catch, based on the analyses conducted during the course of the present study

Likelihood	Hypothesis
High	Recruitment overfishing (H1)
	The fleet has lost searching power (H2)
Medium	Indirect trophic effects of fishing (H8)
Low	Adult prawns are staying inshore (H4)
	Adult prawns are no longer schooling (H5)
	Direct effects of environmental change on banana prawns (H3)
	Indirect trophic effects of environmental change (H9)
Discredited	Pumping of groundwater has reduced run-off (H6)
	Recruitment has collapsed due to a pollutant (H7)

Although available information was generally inadequate to evaluate these hypotheses rigorously, the hypotheses were ranked on best professional judgement in the context of the analyses conducted during this project.

The analysis of life cycle and reproductive dynamics and the qualitative modelling exercise, which integrated current knowledge about the system, established the plausibility of all the listed hypotheses.

Fishing-related changes

There was insufficient power in the fishery analysis to diminish the plausibility of the recruitment overfishing hypothesis (H1). In addition, the analysis of spatial contraction of prawn fishing effort in the Weipa area provided a plausible and compelling mechanism for overfishing as a cause of the observed spatial contraction of the fishing and the decline in catch. It is also possible, however, that the patterns emerging from this analysis reflect the limited searching time available during the shortened season (H2). The effort analysis tends to support the hypothesis that effort reductions have contributed to the very low catches in Weipa since 2000 (H2).

Trophodynamic changes

The patterns revealed in the spatial contraction analysis and the fishery analysis also do not diminish the possibility that fishing impacts on prawns manifest indirectly thorough trophic cascades (H8). The trophodynamic modelling indicated that increases in fishing rate since the late 1980s can decrease the biomass of banana prawn populations considerably (and that small decreases in fishing rate can increase the biomass). However, an accurate reconstruction of banana prawn declines has not yet been possible using real time series of catch, because of the inherent problems of temporal variability in this system. This trophic analysis indicates the possibility that the prawn fisheries can adversely affect prawn stocks by both direct and indirect means (H8).

Behavioural changes

The notion that adult prawns stayed inshore during these years (H4) and were thus not available for capture is somewhat discredited by the annual recruitment surveys, which have indicated that sub-adult prawns have been moving offshore in recent years. The most reasonable mechanism for the sudden lack of schooling in adult prawns (H5) would be that overfishing reduced the abundance of prawns. The likelihood of these explanations is thus diminished to low.

Environmental changes

The Tuned VPA used in the fishery analysis offered no support for the hypothesis that recruitment estimates had been affected by rainfall, thus diminishing the plausibility of the environmental hypotheses (H3, H9). The further exhaustive exploration of the relationship between the observed banana prawn catch decline and environmental variables revealed no evidence for such a relationship, thus providing an additional line of evidence to diminish the plausibility of these hypotheses. These analyses were further hampered by the lack of a consistent prawn biomass estimate other than catch or CPUE. Further, regional variations in effort were seen to affect the predictive capacity of environmental variables. The environmental change hypotheses were therefore given a low likelihood ranking for explaining the observed banana prawn catch decline.

Other anthropogenic-induced changes

The notion that recruitment has collapsed due to a pollutant (H3) and that pumping of groundwater has lowered the water table and reduced run-off (H7) were dismissed because there is no evidence for a decline of the estuarine populations of banana prawns (anecdotal information from cast net fishers), and because there have been no reports of mortality or declines in estuarine fishing – indicating that other estuarine species have not been affected). Furthermore, a fishery-independent empirical field study undertaken during this project indicated stable populations of estuarine fish populations over time.

6.5.3 Decision Support Framework

A decision support framework (Figure 6-40) was developed during and after the third project workshop to: (1) provide empirical data that would further narrow down the alternative explanations for the recently observed declines in banana prawn catches; and (2) ensure the best management decisions in the context of the results of the present study and in future situations where data are limited. As part of the framework three surveys were proposed: (1) an experimental fishing survey – opening the fishery prior to the first season (in the Weipa area only); (2) a pre-season juvenile prawn survey in the nursery ground; and (3) a January recruitment survey (recruitment of adults into the fishery; already underway).

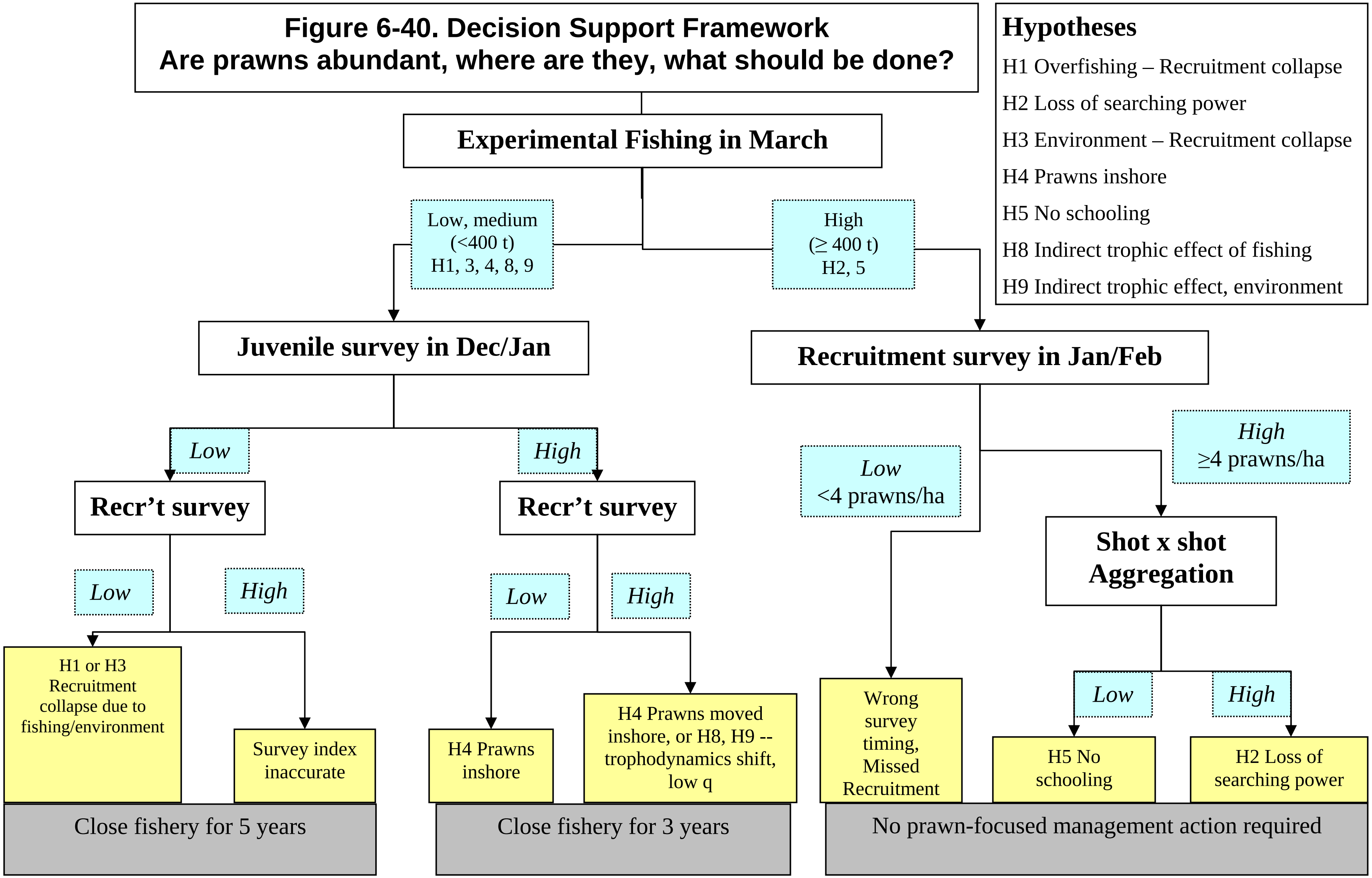

Figure 6-40. Decision Support Framework
Are prawns abundant, where are they, what should be done?

This framework and these surveys were designed to help resolve alternative hypotheses and allow management decisions for the Weipa banana prawn fishery (e.g. should the fishery be closed and for how long). For example, strong management action such as a complete 5-year closure would be required when prawns are deemed to be scarce in most of their habitats (using this framework), regardless of the causes of the low abundance. A critical aspect of this framework is that the participating fishing industry would commit to the management outcomes of the framework *a priori*. Another critical aspect of this framework would be the explicit recognition of risks associated with this management experiment. Finally, the various alternative hypotheses can be re-tested or verified by subjecting the new information from these surveys to the statistical and dynamical analyses developed during the current project.

7. CONCLUSIONS

We learned a great deal about the biology, ecology and fishery dynamics of the banana prawn during this 18-month desktop study, but we have been unable to determine unequivocally the causes of the decline in the banana prawn catch in the Weipa area since 1999/2000. We have, however, ranked the likelihood of the alternative explanations (Table 6-22) in light of the results of the various analyses undertaken here. During the project, we expanded the number of hypotheses in the original proposal from three to nine and then reduced them again to the two or three most plausible. *Efforts to use historical studies, current logbook data and contemporary modelling and analytical techniques have been hampered by the lack of an unequivocal and consistent measure of banana prawn biomass. This is the most conspicuous hole in the available information about banana prawns in this region from an analytical perspective.* As catch has fluctuated so has effort, largely due to changes in fishery management measures (i.e. shortening seasons and reduced fleets). Thus, the impact of these effort changes on prawn biomass estimates could not be clearly discerned such that catch indices are not reliable indicators of biomass. In light of these fundamental analytical problems, a Decision Support Framework was developed including three types of surveys to help differentiate between the potential causes of the decline, and in particular to help discern the two highest ranked explanations – recruitment overfishing and inadequate effort to find the stocks. The more problematic and difficult potential cause lies in the complex interactions between the prawns, their predators and their prey and factors that affect coastal productivity. For example, trophodynamic analyses bolster the plausibility that contemporary prawn trawling may adversely impact prawns indirectly by modifying predator abundances (as well as directly), but that prawn trawling at appropriate levels and with intentional bycatch selectivity has the potential to enhance prawn stocks. This area of research will require more sophisticated models parameterised with more and better information on prawn-predator-prey-productivity interactions. Improvement of such models will rely on an investment in strategically designed empirical field research programmes. Exploratory research has already begun with both small-scale laboratory and field work during this project and more is hoped for. Proposals for more intensive coastal and estuarine productivity have been written; a Gulf-wide Ecopath model will be developed as part of a study of the illegal fishing of sharks; and these projects will be integrated by a NPF Management Strategy Evaluation framework that is under development.

8. BENEFITS

The project outcomes will likely be:

- Increased understanding of the factors affecting recruitment and survival of banana prawns and hence reduced uncertainty in assessment and enhanced economic efficiency of the fishery;

- Management process for the NPF that incorporates consideration of the ecosystem;

- Potential for amelioration of detrimental impacts on the fishery or environment;

- Extension of the approach to other regions of the NPF and other prawn species;

- Incorporation of the results by industry in the development of an Environmental Management System for the NPF;

- Use of results by the NPF in application for Marine Stewardship Council accreditation and in the next Strategic Assessment by Department of Environment and Heritage; and

9. FURTHER DEVELOPMENT

The research described in this report (FRDC Project No. 2004/024) has already informed several additional and related research programmes relating to Australia's northern marine and fisheries resources. Several of these projects are listed here:

- AFMA project 2006/825 - The effect of IUU fishing on the ecosystem in the Gulf of Carpentaria: management options and downstream effects of other fisheries.
    - The trophodynamic model constructed for the Albatross Bay Area prawn questions is being adapted and expanded to the Gulf of Carpentaria to estimate broad ecological and economic impacts of IUU fishing and management options. Results of the Weipa project provide a foundation for this ongoing project.

- TRACK/CERF/FRDC proposal – Environmental drivers of coastal and marine productivity and the importance of rivers in northern Australia.
    - Much was learned from the Weipa project to embark on this broadly collaborative project to learn about the role of Australia's northern rivers in coastal and marine productivity so that impacts of future changes in those river systems can be planned for.

The current project also opened a very real debate in NORMAC about what to do if prawn fishing fails in a particular region. This debate is on-going, and the decision support system that this project developed can continue to evolve as well.

The ongoing prawn stock assessment work by Dr. Norm Hall and Dr. Cathy Dichmont (e.g. Dichmont *et al*. 2006) was complemented well by the current project in various synergistic ways including cross verification; each came up with similar (and also their own) set of recommendations after taking different, though sometimes similar, approaches.