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Assessing data poor resources: developing a management strategy for byproduct species in the Northern Prawn Fishery

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1. NON-TECHNICAL SUMMARY

2006/008 Assessing data poor resources: developing a management strategy for byproduct species in the Northern Prawn Fishery

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OBJECTIVES:

1. To identify, collate and analyse all available data on the distribution, biology, population dynamics and catches of byproduct species (or at least species groups) in the NPF in order to identify knowledge gaps and provide critical life-history parameters for modelling byproduct populations.

2. To investigate the feasibility of dividing the byproduct groups recorded in NPF commercial logbooks into individual component species on the basis of available research data.

3. To develop models of impacts on byproduct species with the purpose of (a) assessing the sensitivity of results to uncertainty in the biological parameters with a view to determining minimum data requirements and (b) assessing the relative effect on population size of each byproduct species (or group) under alternative prawn management scenarios.

OUTCOMES

- The species composition of the byproduct of the Northern Prawn Fishery has been identified and trends in the catch examined.
- Life-history characteristics of bug, squid, cuttlefish and species caught as byproduct by the NPF have been documented from the Gulf of Carpentaria.
- Statistical models have been developed to predict the proportions of squid, cuttlefish and bug species from aggregated data reported in logbooks.
- Estimates of harvest reference catch limits for each byproduct group have been made with a new method.
- The estimates of harvest reference catch limits range between:
  Squid: 267 – 345 t

  Cuttlefish: 258 – 306 t

  Bugs: 1716 – 2058 t

  Scallops: 159 – 213 t
- Simple models of the bug catch in the NPF have been developed and alternative management scenarios evaluated. For each scenario, models optimise benefits to the fishery and the bug population while taking compliance costs into account. They incorporate environmental and economic factors that influence catch.
- The current minimum legal size (MLS) fishery regulation restricting the retention of bugs < 75 mm carapace width was best for the bug population, but not the fishery under all scenarios except when catch increased substantially. If a large increase in catch occurs, the best management regulation was to increase the minimum legal size to 80 mm. When compliance costs are ignored, the best MLS falls to between 65 and 70 mm CW.
- A simple model predicted that total catch and overall value were maximised when the MLS was set at 65 mm. This is consistent with the large maximum sustainable catch limits found with the new method.
- The Australian Fisheries Management Authority manager, the Northern Prawn Fishery Management Advisory Committee and the NPF Resource Assessment Group have been advised on the most appropriate management strategy for each byproduct group and the report updated following feedback.

OBJECTIVE 1: BIOLOGY, POPULATION DYNAMICS AND CATCH OF BYPRODUCT SPECIES

Byproduct in the Northern Prawn Fishery (NPF) has been recorded in up to 30 categories in commercial fisher logbooks. Among these, four categories comprise over 90% of the catch. These groups, squid, cuttlefish, bugs and scallops are made up of multiple species – six squid, five cuttlefish, two bug and two scallop species. The life-history characteristics of these species were examined from samples collected by the AFMA-funded NPF prawn monitoring surveys that began in 2002.

Size at maturity, spatial and temporal patterns in breeding and number of eggs laid were examined for all species. The smaller mud bug *Thenus parindicus* matured at a similar size to the current MLS for bugs (75 mm carapace width (CW) or 52 mm carapace length (CL)). The larger reef bug, *T. australiensis* matured at 85 mm CW (59 mm CL) and were immature at the MLS. However, reef bugs only make up a small proportion of the bug catch in the NPF (< 10%) and so there was no detectable impact on the population.

Spatial, temporal and environmental variables were important factors in the distribution and abundance for squid, cuttlefish, bug and scallop species in the Gulf of Carpentaria. The squid and bug groups showed a decline in their catch rates from the fishery-independent NPF prawn monitoring surveys between 2002 and 2008. There was also relatively high inter-annual and seasonal variability in their abundances. Squid landings from the NPF commercial fishery were highly variable between years. Squid aggregations were targeted in some years resulting in annual catches of more than two to four times the long-term mean. Commercial catches of bugs showed a steady decline from 1998 to 2007. No clear temporal patterns in abundances were evident for the cuttlefish and scallop groups in the Gulf of Carpentaria. However, monthly commercial landings of cuttlefish increased in spring (October – November) each year.

Squid were more abundant in the shallower waters while cuttlefish and scallops had higher catches in deeper waters. The two bug species showed the clearest trends in abundance with species being separated on depth, region and substrate type. Highest catches of *T. parindicus* were in the 15 – 35 m depth zone, around Mornington and Karumba and on grounds with substrates comprising 20 to 60% mud. In contrast, *T. australiensis* showed a distinct preference for deeper offshore waters (> 35 – 40 m) around Vanderlins and Weipa and on grounds with a high percentage of sand.

Most squid, cuttlefish and bugs spawned on the prawn fishing grounds in the Gulf of Carpentaria. Squid, cuttlefish and bugs spawned continuously throughout the year, with a greater proportion of each population involved during the dry season (May – November). Juvenile scallops and bugs were only caught during the pre-season surveys (January – February) and were probably the progeny from spawning that occurred during the previous dry season.

OBJECTIVE 2: PREDICTING THE SPECIES COMPOSITION OF LOGBOOK BYPRODUCT RECORDS

The species composition of subsamples of the byproduct catch from the NPF prawn monitoring surveys were used to develop statistical models to predict the species composition of logbook byproduct records. Two types of models were developed – a two-species model for bugs, and separate multi-species models for squid and cuttlefish. A range of temporal, spatial and environmental predictors were used in the analyses. The models explained > 60% of the variation in the proportion of each species within a byproduct group. For bugs, over 90% of the commercial catch is mud bugs *T. parindicus*. The most important squid species were *Uroteuthis* sp 3 and *Uroteuthis* sp 4. Large hauls of squid (> 400 $kg.d^{-1}$) were made by some vessels several times each year and these were predicted to be *Uroteuthis* sp 4. An AFMA scientific observer collected samples of squid from one such aggregation in May 2007. The whole sample (n = 119) were *Uroteuthis* sp 4 in either breeding or post-breeding condition. The sample species composition confirms the predictions made by the statistical model and suggests that the data may be useful for stock assessment.

OBJECTIVE 3: EVALUATION OF MANAGEMENT SCENARIOS FOR BYPRODUCT SPECIES

Evaluating management strategies for byproduct species in fisheries will always be hampered by a lack of data and poor data quality. We have addressed this issue in two ways – by estimating a biologically-sustainable total annual catch for each of the four main byproduct groups and by undertaking a management scenario evaluation of the current bug regulations. Both methods required developing new approaches to the problem and each approach will potentially have broad applications to other fisheries and issues. They each rely on fishery-independent estimates of abundance obtained from the NPF prawn monitoring surveys. These surveys will continue for at least the next two years and will allow the optimal catches of each byproduct species s to continue to be updated with additional data.

We calculated the biologically-sustainable total annual catch from the biomass estimates of the NPF prawn monitoring surveys and life-history characteristics of each group. These indices show that the recent annual catches of each byproduct group are a small proportion of the estimated biologically-sustainable total annual catch for those groups. Bugs had the highest estimate of between 1716 – 2058 t, much higher than the recent catches of 15 – 25 t. The estimated ABCs of squid and cuttlefish were similar (306 ± 39 t and 282 ± 24 t respectively). The sustainable allowable catch of squid was similar to the recent commercial catch (~200 t) and below the current AFMA reference catch trigger of 500 t. However, historical catches of squid from areas within the NPF but outside the current commercial prawn fishing grounds suggest that our calculated biomass for squid may be an underestimate. If squid catches increase by more than 50% in the NPF and exceed the ABC, further studies may be required to improve our estimate of the true biomass of squid in the Gulf of Carpentaria. Until that occurs, the squid catches should continue to be monitored. The estimate of sustainable total annual catch of scallops of 159 – 213 t is the lowest of the four groups analysed. However, the recent commercial catch of scallops has been < 2 t and so well below the estimate.

Bugs are the only byproduct group in the NPF with management regulations restricting their catch. We undertook a management scenario evaluation of the current MLS restriction on bugs under a range of fishing effort scenarios. We developed a model of the bug fishery and the environmental, economic and management factors influencing catch. The cost of fisher compliance was included in the model in two ways: through the estimation of a sustainable catch trigger and explicitly recognising the costs of compliance. We assessed the benefits to the fisher and the resource of changing the MLS from 75 mm CW or removing the restriction altogether. Four scenarios were compared – (1) status quo (95% compliance, 5% decline in biomass and passive management (existing regulations)), (2) decline in bug biomass of 20%, 20% increase in fishing effort with 50% compliance under passive management, (3) 50% reduction in bug biomass, 50% increase in effort, no compliance and passive management or (4) status quo, but with active management (change current regulation) and ignore additional compliance costs. The optimal solution under scenarios 1 and 2 was to retain the current MLS regulation banning the retention of bugs < 75 mm CW. Under the most extreme fishery scenario 3, it was better to increase the MLS to 80 mm CW. Under scenario 4, when compliance costs were ignored and the MLS is able to be changed, then a MLS of 65 – 70 mm CW is optimal. By recognising compliance as a cost, the model penalised the catch optimisation and thus provided a more conservative outcome.

If compliance was not included, as in scenario 4, the model predicted that a reduction in the MLS would be associated with a substantial increase in the probability of causing a large decline in the biomass of bugs. This increased risk is consistent with the situation in the NPF in the late 1990s. At that time, a decline in the catch rate for bugs led to the introduction of the current MLS regulations to further protect the adult population. Studies of other bug species elsewhere have also found that they are more susceptible to over-fishing than other invertebrates of similar size or age. These studies provide further circumstantial support of the results from the model under recent fishing effort scenarios.

Within the management scenario modelling, analyses showed that the total catch of bugs was maximised when the MLS was reduced to 65 mm CW. This size was below the MSL optimal solution from the most realistic scenarios in the model (75 mm), but consistent with the high sustainable total catch estimate for bugs. The scenario modelling optimises the MLS solution by maximising a function that trades off fisher profit, bug sustainability and compliance costs. It will always be conservative compared with approaches that ignore these hidden costs. Further fine-tuning of the management scenario model is advisable before it could be used operationally to assess alternative management options for bugs.

KEYWORDS: squid, cuttlefish, bugs, scallops, acceptable biological catch, management scenario modelling, Bayesian Belief Network

2. ACKNOWLEDGEMENTS

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3. BACKGROUND

In the Northern Prawn Fishery (NPF), commercially-valuable species of marine organisms that are caught during trawling can be retained. The Australian Fisheries Management Authority defines *byproduct* as "the part of the catch that is caught incidentally (a non-target species) and is retained for commercial value or consumption on board the vessel" (AFMA 2009). In the NPF, byproduct species include squid, bugs, scallops, some fish and scampi (Ciccosillo 2008). AFMA have implemented a range of restrictions on some byproduct groups in the NPF with the intention of allowing the stocks to rebuild and also be available to other fisheries.

Australia introduced a Harvest Strategy Policy (HSP) for all Commonwealth fisheries that aims to cease overfishing and rebuild overfished stocks. The HSP is underpinned by a target and limit reference point biomass (B_{TARG} and B_{LIM}). All fisheries had to implement harvest strategies consistent with the HSP by 1st January 2008. The harvest strategy for the NPF was submitted to the AFMA Board in late 2007 and contains catch limits for squids, several fish species groups, mud crabs and tropical rock lobsters. There was a restriction on minimum legal size (MLS) of bugs (*Thenus* spp) and no berried female bugs can be retained (refer http://www.afma.gov.au/fisheries/northern_trawl/northern_prawn/mgt/opinfo/docs/2008/section_02.pdf)

In the NPF, as in most fisheries, limited data are available on the catches and biology of byproduct species. This is a situation that creates challenges for fishery managers. Since the introduction of the Environmental Protection and Biodiversity Conservation Act and the Strategic Assessment process for fisheries, information on byproduct has become critical for the fishery to demonstrate its sustainability. Recommendations from the Strategic Assessment of the NPF in 2005 were that the fishery needed to develop harvest strategies for all byproduct species with suitable biological reference points and management responses.

Byproduct in the NPF includes four major groups: squid, cuttlefish, bugs and scallops, comprising at least eight species. Research into these groups in the NPF has been limited and data on individual species distribution and abundance are rare. Models that utilize minimal data to help assess the relative benefits of alternative management strategies provide a first step towards assessing fishery sustainability. This project proposed to analyze the data collected by the annual NPF prawn monitoring project for basic biology and dynamics and to model the impact of different prawn management options on the byproduct populations. Existing models and others currently being developed will be modified rather than be developed from first principles. This technique should be transferable to other data poor bycatch species and other data poor fisheries.

4. NEED

World-wide declines in prawn prices and rising fuel costs have led to a shift in fisheries practices in the Northern Prawn Fishery (NPF). One such change is an increase in targeting of valuable byproduct groups such as bugs and squid. Little research has been done on byproduct in the NPF or in other tropical prawn trawl fisheries. The 2002 catch of byproduct in the NPF was almost 250 t (AFMA), comprised of four main species groups, squid, cuttlefish, bugs and scallops, of at least eight species. However, the catch of squid alone has been 400 t in some years. The impact of trawling on these groups has never been assessed. This situation is common among many Australian fisheries. Despite the value of byproduct being substantial, the fisheries managers lack sufficient data to undertake specific assessments or even to evaluate options for their management. Thus, there is a need to develop methods to help identify management options for groups that are data poor like byproduct species in the NPF. New approaches developed in this fishery will be applicable to other Australian trawl fisheries, especially the Torres Strait Trawl, Queensland East Coast Trawl and Western Australian prawn trawl fisheries. Operational advice from this project will contribute to at least two possible management strategies: the first would be to control fishing on byproduct through species-specific stock assessments. The second would be to control effort on byproduct through spatial and temporal closures by identifying the key areas and seasons when these byproduct groups are most vulnerable. The most efficient approach to assess the relative merit of alternative management options is to adapt existing trawl impact assessment scenario models to account for non-target catch in their strategy evaluations.

5. OBJECTIVES

1. ***To identify, collate and analyse all available data on the distribution, biology, population dynamics and catches of byproduct species (or at least species groups) in the NPF in order to identify knowledge gaps and provide critical life-history parameters for modelling byproduct populations.***

2. ***To investigate the feasibility of dividing the byproduct groups recorded in logbooks into individual component species on the basis of available research data.***

3. ***To develop models of impacts on byproduct species with the purpose of (a) assessing the sensitivity of results to uncertainty in the biological parameters with a view to determining minimum data requirements and (b) assessing the relative effect on population size of each byproduct species (or group) under alternative prawn management scenarios.***

6. DESCRIPTION OF BYPRODUCT IN THE NORTHERN PRAWN FISHERY

6.1 Abstract

In the NPF, about 30 different categories of byproduct have been recorded in logbooks since 1998. The total annual byproduct catch has varied between 6 and 400 t since that time. Squid (Loliginidae) are the most important component of the catch and represent between 50 and 80% of the byproduct recorded. Other commercially-valuable byproduct groups include bugs (*Thenus*), cuttlefish (Sepiidae), scallops and mixed fish. Total byproduct catch has been declining as the trawl effort in the NPF has been reduced. However, trends in recorded landings of each group are not a reliable index of byproduct abundance. The retention of byproduct and subsequent recording in logbooks is related to a complex combination of fishery operational costs, prawn and byproduct prices, prawn and byproduct catch rates and vessel crew behaviour.

Anecdotal evidence from fishers suggests that the introduction of the minimum legal size for bugs in 2001 has led to a decline in overall landings as only a small proportion of the catch can be retained. This appears to have led to an increase in relative catch of squid. Squid are lower priced, but are more abundant than bugs and higher catches are more readily made.

6.2 Data

The logbook records of byproduct in the NPF were obtained in an electronic format from AFMA. AFMA categorised the reported species into about 30 different categories based on commonly used names. We have grouped these further, into 14 categories that summarise the most frequently reported byproduct groups.

6.3 Species composition

The total landings of byproduct in the NPF have been declining since logbook records became compulsory (Figure 6.1). The 1998 landing of 470 t was the highest recorded with the lowest in 2006 (10 t). The total landings increased in 2007 to about 200 t. The majority of the byproduct reported was squid (Figure 6.2). Not only have the total landings declined, but the species composition reported in logbooks has become dominated by squid, with bugs becoming less important (Figure 6.3). Annual landings of squid ranged from about 400 t in 2001 to only 5 t in 2006. The other byproduct group that was important in the late 1990s were bugs (Figure 6.3). The landings of bugs have declined from 140 t in 1998 to less than 3 t in 2006. A similar reduction in landings was seen for the mud scallop *Amusium pleuronectes* (Figure 6.3 c) with none being recorded in 2006. In 2007, the NPF recorded about 0.2 t of mud scallops. This is down from the highest reported catch of 30 t in 2000.

Other groups of byproduct also show a trend with the lowest reported landing occurring in 2006 (Figure 6.1). In some years, up to 20 t of mixed fish were landed. This comprised a wide range of species, including high-value *Lutjanus* species, grunter *Pomadasys*, *Plectorhinchus* and several trevallies (Carangidae). Reef fish remained a small component of the reported byproduct catches since records began in 1998. The landings of some of the other byproduct groups such as fish and cuttlefish have remained at a similar proportion of the overall byproduct landings (Figure 6.2), but the quantities have also declined. The annual cuttlefish (*Sepia*) landings have varied between 3 – 10 t (Figure 6.4 c).

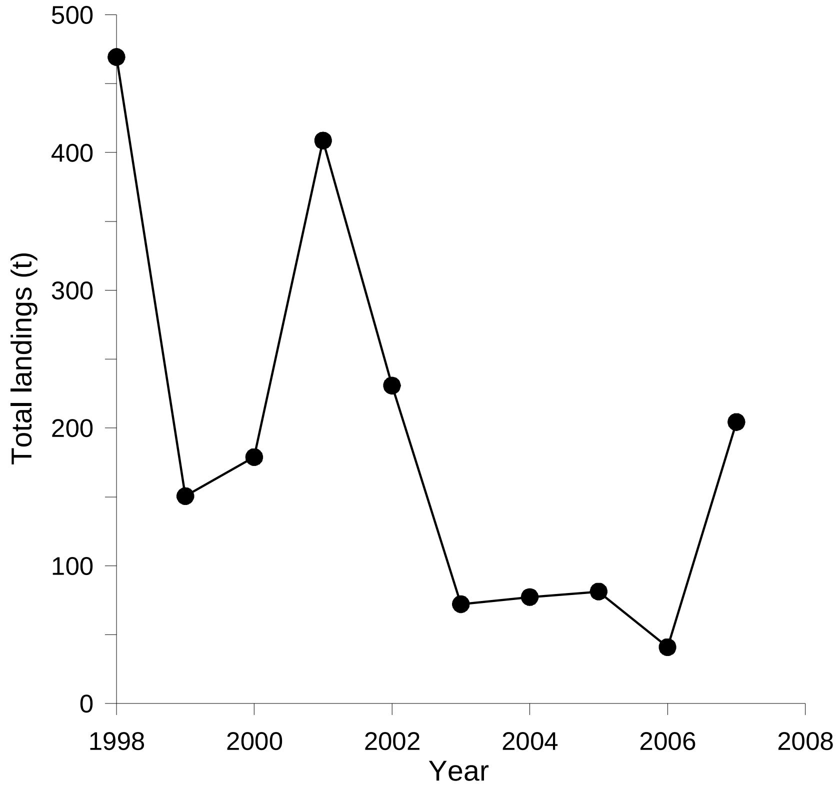


Figure 6.1. The total reported landings of byproduct in the Northern Prawn Fishery since logbook records became compulsory in 1998.

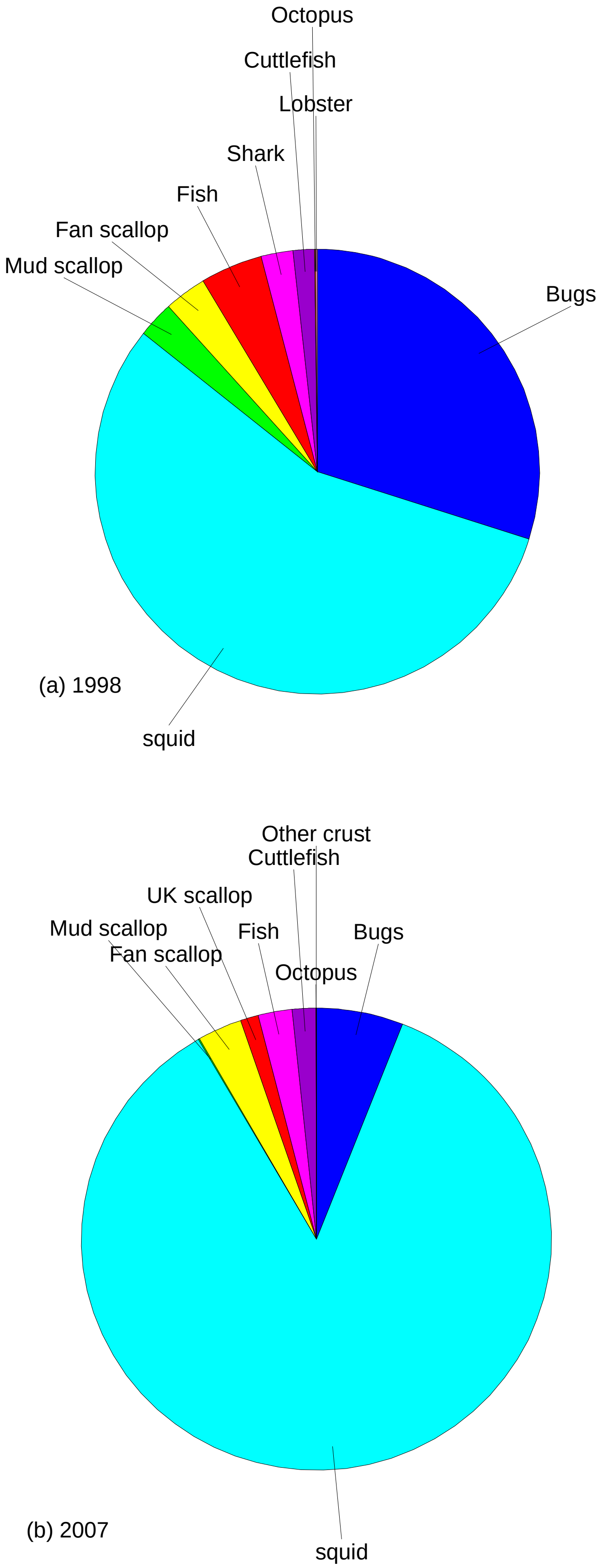


Figure 6.2. Species composition of the byproduct recorded in the NPF logbooks in (a) 1998 and (b) 2007

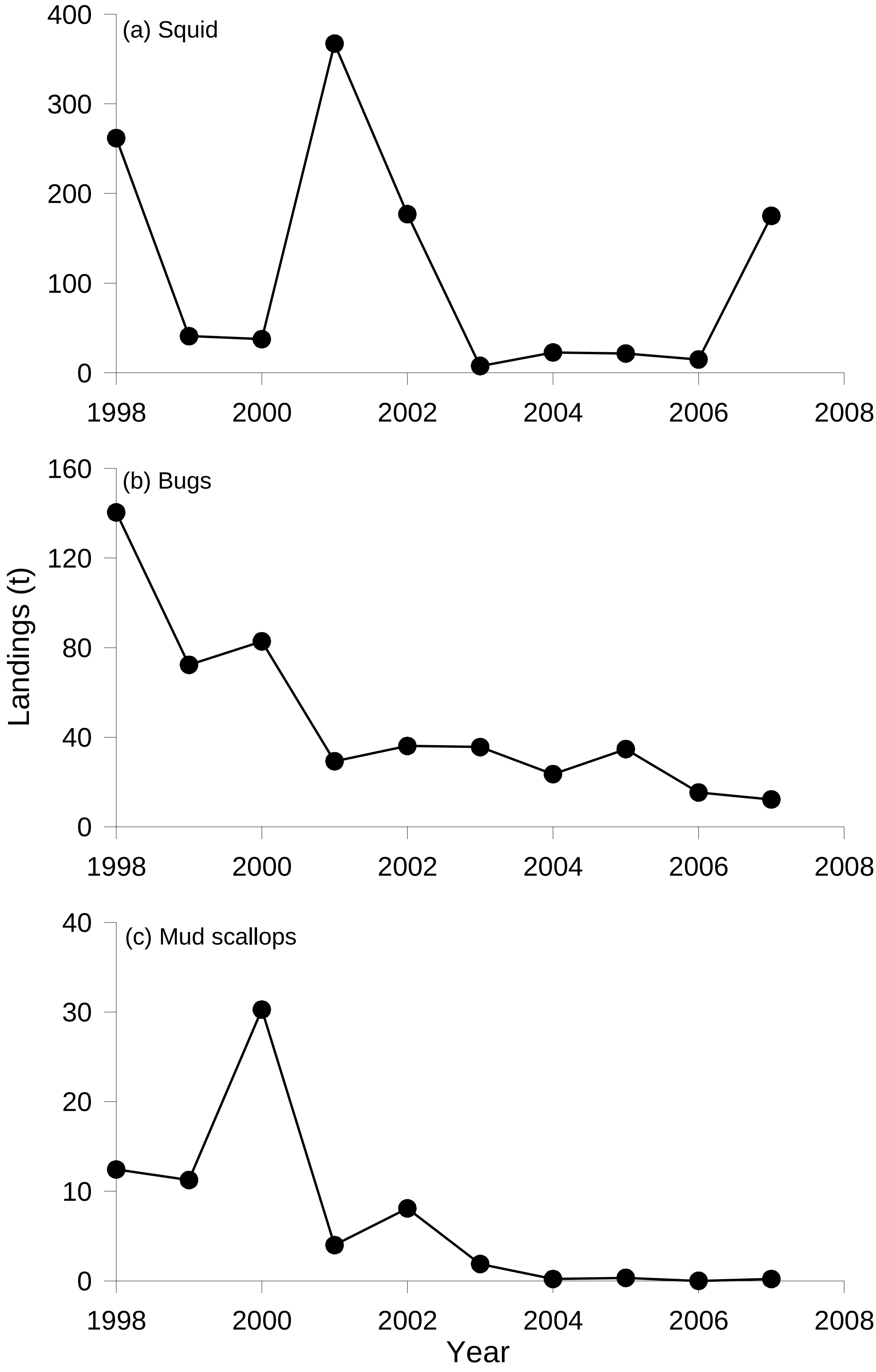


Figure 6.3. Trends in the reported landings of squid, bugs and mud scallops in the NPF since 1998.

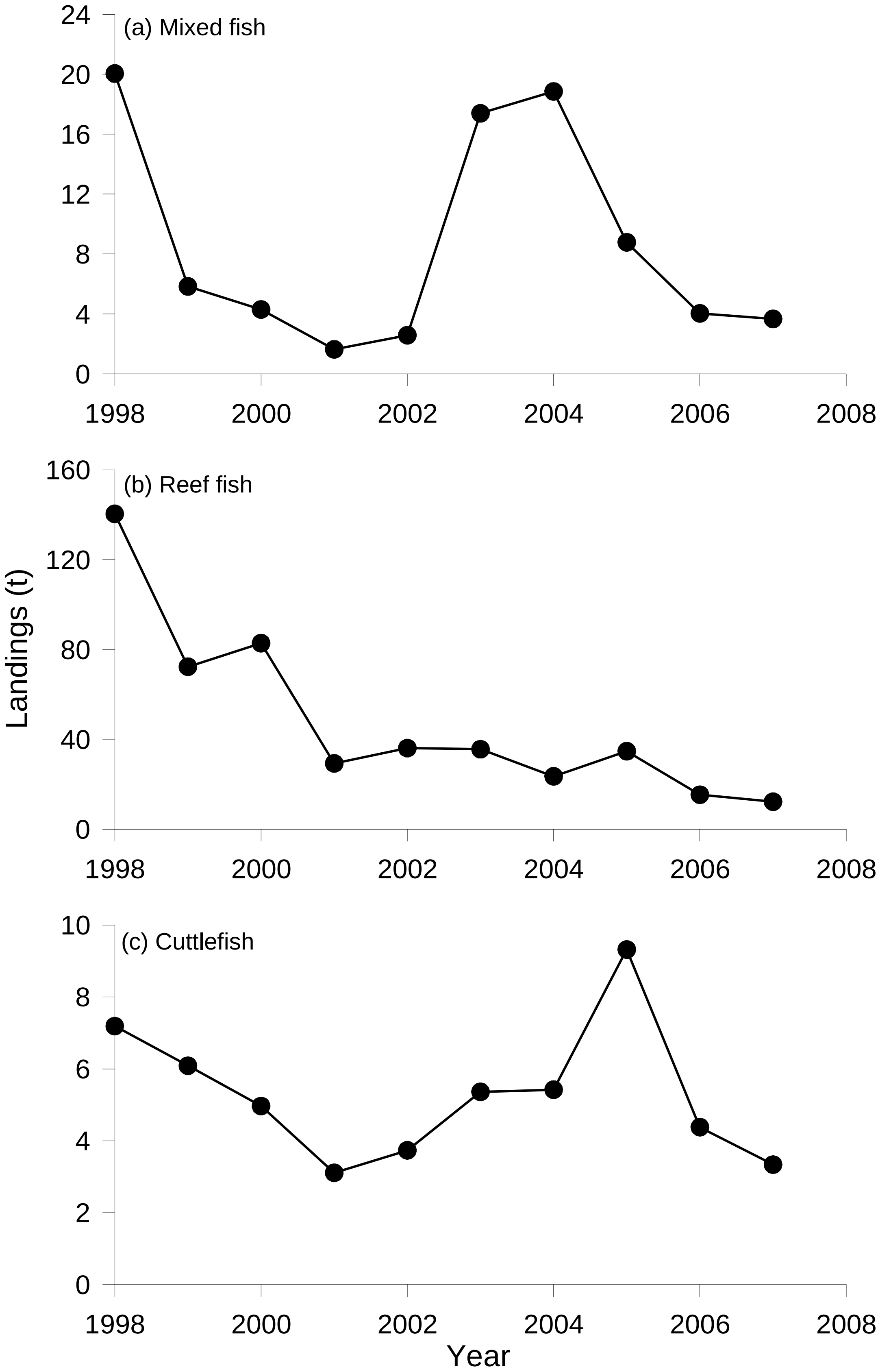


Figure 6.4. Trends in annual landings of fish byproduct (Mixed fish and Reef fish) and Cuttlefish (*Sepia* species) in the NPF since 1998.

6.4 Discussion

The species composition of the byproduct catches recorded in the logbooks of the NPF has changed over time. Squid (*Uroteuthis* species) were the most important byproduct group by weight. The second most important group was bugs, followed by mixed fish, scallops and cuttlefish. All were relatively important components of the landings in different years. There appears to be a strong negative relationship between squid and bug catches (Figure 6.5). The reasons for this relationship are unclear. Squid was the most important byproduct group recorded and there were no significant relationships between squid catches and the other byproduct groups, or with prawn catches. The quantities of bugs retained may be dependent on the catches of squid. If very large catches of squid are made, then fewer bugs may be retained. This may be due to the fishing grounds for these groups being quite separate or the trawl methods being different. We will examine factors influencing the distribution and abundance of byproduct species in Chapter 8.

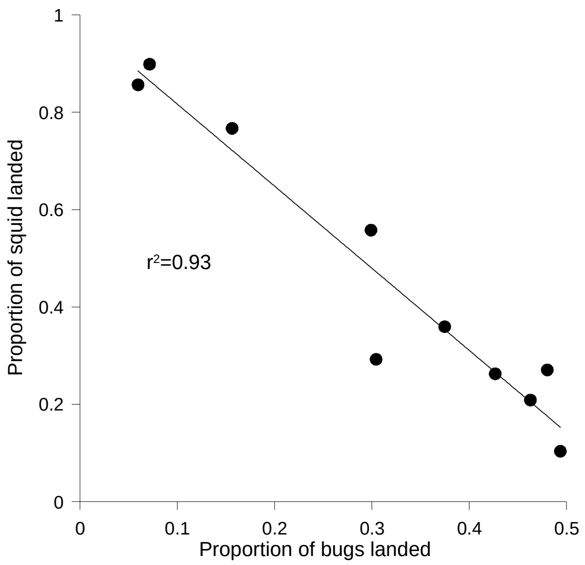


Figure 6.5. The relationship between the reported total annual logbook catches of squid and bugs in the NPF.

There have been major changes in the value of the prawn catch and fleet size in the Northern Prawn Fishery over the last 10 yrs (refer http://www.afma.gov.au/fisheries/northern_trawl/northern_prawn/at_a_glance.htm). These changes have resulted from industry restructuring as a consequence of overfishing on tiger prawns and the recent economic downturn in the value of the catch at a time of increasing fuel prices. This 10-yr period has also coincided with a reduction in the quantities of the main byproduct groups. The dramatic reduction in the value of prawn production in 2002 – 2003 also coincided with a reduction of over 60% in the quantity of byproduct recorded (Figure 6.1). This reduction in byproduct recorded appears to be almost entirely due to a reduction in the quantity of squid landed (Figure 6.3). As the fishery does not normally target squid, it is difficult to assess whether this change in the landings of squid are related to their abundance. Historical records suggest that catches of over 4200 $t.yr^{-1}$ have been taken in the Arafura Sea and Gulf of Carpentaria in the past (Edwards 1983; Dunning and Willan 2004). The life history of the loliginid squids (*Uroteuthis* species) is one of rapid growth, early maturity and short life-span (< 1 yr) and spawning multiple batches of eggs (Jackson 2004). Thus, these species appear to be adapted to high natural mortality and environmental uncertainty. It would seem unlikely that the decline in the reported catch of squid is related to fishing mortality. Large catches of squid are possible at spawning aggregations and these appear to be somewhat predictable (see Chapter 7, Figure 7.4). This may have led to local depletions, but the fact that aggregations have been targeted in the same region in successive years suggests that their populations are resilient to the removal of large proportions of these aggregations. Possibly the relative pricing and abundance of squid and bugs may be the main factor influencing fishers to differentially keep more or less of these groups. Another factor influencing these patterns was the introduction of a MLS for bugs in 2001. This has meant that only a small proportion of bugs caught can be retained (< 10%: M. O'Brien pers. comm.). Indeed, the bug catch since 2001 has been relatively stable and thus supported this contention.

7. LIFE HISTORY OF BYPRODUCT SPECIES IN RELATION TO MANAGEMENT OF THE NORTHERN PRAWN FISHERY

7.1 Abstract

Life-history traits relevant to possible future management options were examined for eight abundant invertebrate species caught as byproduct in the NPF. Understanding these species-specific life-history characteristics will assist in the management and sustainability of these species. Bugs, *Thenus parindicus* and *T. australiensis*, differed in their size at maturity and fecundity. *Thenus parindicus* matured at a smaller size and was less fecund than *T. australiensis*. Both species had a similar seasonal spawning pattern, with most recruitment early in the year (January – March). Our estimates of size at which 50% of females are mature (CL_{50}) suggest that current MLS for *Thenus* are probably adequate for *T. parindicus*, but allows retention of immature *T. australiensis*. However, *T. australiensis* only contribute a small proportion of the *Thenus* catch and are likely to be somewhat protected by their preferred habitat not overlapping greatly with the NPF. If *Thenus* stocks were considered to be in decline or at risk, then increasing the minimum legal size to 80 mm CW should be considered. This would potentially increase egg production and reduce the likelihood of recruitment overfishing, particularly for *T. australiensis.* Squid and cuttlefish species also showed variation in fecundity, size at maturity and reproductive seasonality. We suggest that squid and cuttlefish stocks are most likely underexploited based on historical catches. At current fishing levels, we also suggest that squid appear to be resilient to the opportunistic targeting of spawning aggregations in similar NPF regions over successive years. Despite this, we recommend that spawning aggregations (squid) or high catch rates of cuttlefish (> 50 $kg.d^{-1}$) be monitored. Samples should be taken from these aggregations in order to determine species-specific biological information that will provide baseline data for future management options. One of the potential management options could be restrictions on fishing of spawning aggregations. However, with predictions of rising water temperatures in northern Australia over the next few decades, squid and cuttlefish populations may increase. If these predictions eventuate, a targeted fishery for squid and cuttlefish could be undertaken. Should this occur, more rigorous assessments of their populations will need to be considered.

7.2 Introduction

The level of sustainable harvest of animal populations is related to their ability to reproduce and replenish their populations. Thus, understanding aspects of their life history are critical to setting realistic harvest limits. Size at sexual maturity, fecundity, reproductive seasonality, spawning sites, and growth rates are some of the most important life-history parameters needed for stock assessment and setting sustainable exploitation levels (Chubb 1994). For the bugs *Thenus* spp, there have been few detailed studies of their life history. Courtney (2002) and Jones (2006) have summarised the most detailed studies from north eastern Australia which provided information on growth, longevity, maturation, fecundity and seasonal productivity. Growth rates of both species are similar up to 70 mm CL (~ 2 yrs old). After that, *Thenus* *australiensis* grow larger and live longer (at least 6 – 8 yrs) than *T. parindicus* (4 – 6 yrs) (Courtney 2002).

The taxonomy and life history of the squid and cuttlefish species in northern Australia are poorly known (Dunning and Brandt 1985; Moltschaniwskyj and Doherty 1994; Dunning et al. 1998). Preliminary genetic studies in the early 1990s have shown the Australian taxa to be different from similar species in southeast Asia (Yeatman 1993). The two most abundant squid species, *Uroteuthis* sp 3 and *Uroteuthis* sp 4 occur across northern Australia (Yeatman 1993). They occur in a wide variety of habitats from coastal intertidal areas, offshore to at least 170 m (Moltschaniwskyj and Doherty 1994; 1995). These two squid species have rapid population turnover, as they are short-lived (< 1 yr) early maturing species, and produce many relatively large eggs in a protective capsule (Jackson and Domeier 2003; Jackson 2004). Their population dynamics appear to be driven mostly by flexible reproductive and somatic growth rates that respond to environmental variability such as temperature and food availability (Boyle and Boletzky 1996; Jackson and Moltschaniwskyj 2001).

The largest species of cuttlefish in northern Australia, *Sepia pharaonis* is widespread from eastern Africa, southern China, southeast Asia to northern Australia (Reid 1998; Anderson et al. 2007). It is an important component of the cuttlefish catches throughout its distribution, with landings of almost 100,000 t in Thailand and the Philippines in 1995 (Dunning 1998). In southeast Asia, *S. pharaonis* occur mostly in waters between 10 and 40 m deep. Females mature at 142 mm mantle length (ML) and spawning occurs throughout the year, with peaks in January – February and July – September (Reid 1998). Recently, Anderson et al. (2007) found that *Sepia pharaonis* actually comprises five species of cuttlefish, each apparently differing in their life history (Norman 2000). Of the five species Anderson et al. (2007) identified, one was restricted to northern Australia.

Tropical cuttlefish live up to two years (Bouhlel and Musaibli 1985; Meriem et al. 2001) and adults of many species are thought to spawn only once and then die (Norman and Reid 2000). However, other studies suggest that some cuttlefish species such as *Sepia pharaonis* (Gabr et al. 1998) and *S. officinalis* (Boletzky 1987) are capable of multiple spawnings within their short breeding season.

This chapter describe studies that were undertaken to: i) identify size at maturity, fecundity and examine spatial and temporal variations in reproductive condition for species in the three most economically-important byproduct groups caught in the NPF; ii) consider new species-specific biological information in relation to current management measures and fishing activity, in order to aid sustainability assessments; and iii) propose new alternate management measures if required.

7.3 Methods and material

7.3.1 Field sampling

Between August 2002 and February 2008 byproduct samples (bugs, cuttlefish, squid and scallops) were collected from prawn trawlers during NPF prawn monitoring surveys. Preliminary studies of samples of scallops found that it would be difficult to identify the reproductive cycle of scallops in frozen samples. Thus, no life-history studies were undertaken on scallops. These NPF prawn monitoring surveys were undertaken twice a year, the first in January – February where approximately 200 sites were sampled. The second survey was made in July – August when samples from approximately 300 sites were taken (Figure 7.1). The sampling sites were allocated among six geographic regions based on commercial fishing effort: Weipa; Karumba; Mornington; Vanderlins, south Groote and north Groote. Within regions, the locations of trawls were stratified by depth. All trawls were made at night when prawns are most active. Each trawl was made for 30 minutes at 3.2 knots. For consistency, all vessels used twin rig 12 fathom 'Florida Flyer' nets with 50 mm diamond mesh and a codend of 50 mm mesh that were 120 meshes long and 150 meshes round. A single straight bar top opening Turtle Excluder Device (TED) was used in each net. After each trawl, the bugs were identified to species and total weights and numbers were separately recorded for each net. Up to 100 individuals of each species of bug were measured (carapace length in mm: CL) per trawl, and sex and their egg-bearing condition recorded. During each survey, up to 10 berried females per region were retained for further reproductive analysis. All squid and cuttlefish were counted and weighed on board, frozen and returned to CSIRO Marine and Atmospheric Research laboratory for further analysis.

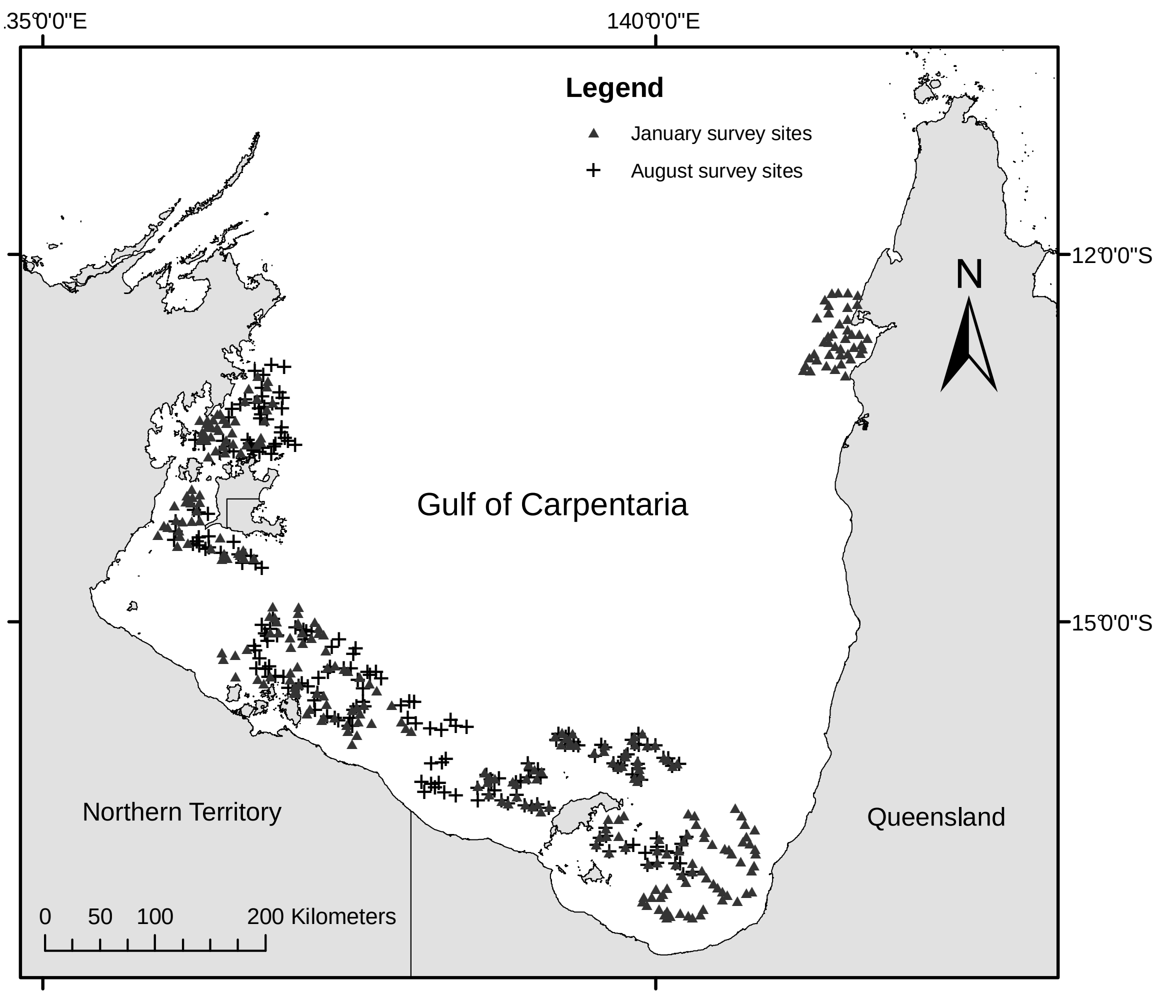


Figure 7.1. Map of the Gulf of Carpentaria showing the location of the NPF prawn monitoring survey sites sampled for byproduct life-history studies between 2002 and 2008.

7.3.2 Bug life history

In the laboratory, egg-bearing bugs were identified to species, weighed, measured (carapace length in mm), and the eggs removed and weighed (± 0.001 g). Identification of species was based on the taxonomic descriptions of Burton and Davie (2007). To measure fecundity, eggs from a subsample of about 0.2 g were counted. The count of eggs from the subsample was then raised proportionally to the total egg weight in order to determine the total number of eggs produced.

The mean length at sexual maturity (CL_{50}) of female bugs was defined from the mean size of berried females in the population. It was estimated by fitting a logistic function of the form:

$$y = \frac{1}{1 + \exp\left(-k\left(CL - CL_{50}\right)\right)} \qquad (7.1)$$

where y is the proportion of berried females in each size class (CL), k, the parameter determining the slope of the maturity curve and CL_{50} is the estimated mean CL when 50% of the carapace length class were berried.

7.3.3 Squid and cuttlefish life history

The volume of squid and cuttlefish caught during each survey was too large to enable complete processing of all individuals. Instead, we subsampled the catches, stratified by region, season and year. For the trawl catches examined, we identified and dissected all squid and cuttlefish caught. Identification of species was based on taxonomic descriptions provided by Yeatman and Benzie (1993; 1994). Specimens were measured (mantle length in mm: ML), weighed (± 0.001 g), sexed and gonads removed and weighed. Gonadosomatic index (GSI) was calculated using the following formula:

GSI (%) = (gonad weight/(body weight – gonad weight)) x 100 (7.2)

To measure fecundity of animals with enlarged eggs, a subsample of ovary was taken, weighed and the number and size of eggs was measured. The count of eggs for the subsample was then raised proportionally to the total gonad weight.

Squid spawning aggregations

Anecdotal evidence from fishers suggested that most squid reported in the logbooks were taken when spawning aggregations were found. To verify the logbook records and assess the species composition and reproductive status of squids caught at large aggregations, we examined a 20 kg subsample taken by an AFMA scientific observer on board a commercial trawler that found a large squid aggregation in May 2007. The subsample was sent to CSIRO and the sample was processed in a similar manner to other scientific samples. The total commercial catch of squid from this aggregation was estimated to be at least 200 t (Dee White unpubl. data). Daily logbook records of the vessels fishing this aggregation showed each vessel caught > 400 kg of squid.d^{-1}. We examined the commercial logbook records (available from 1998 –2007) to assess the spatial and temporal variation in catches of > 400 kg of squid.d^{-1} in order to assess the predictability of these spawning aggregations.

7.3.4 Spatial and temporal variation in spawning

To calculate the percentage of mature females in spawning condition we needed to define several criteria. First, it was necessary to identify the mature female population for each byproduct species. Secondly, to determine which individuals of these were in spawning condition. To set the first criteria, we found the minimum size of cephalopods with enlarged gonad development based on their GSI. For bugs, we estimated the mean size at maturity (CL_{50}) from berried females (see above). We estimated the proportion of mature females in the population at each region (Karumba; Mornington; Vanderlins; north Groote; south Groote; Weipa) and season (Wet (January – March); Dry (June – October)) based on the following criteria: *Sepia elliptica* and *S. papuensis* – females ≥ 40 mm ML, *S. pharaonis* and *S. smithi* ≥ 60 mm ML, *Uroteuthis* sp 3 ≥ 80 mm ML, *Uroteuthis* sp 4 ≥ 90 mm ML, *T. parindicus* ≥ 52 mm CL and *T. australiensis* ≥ 59 mm CL. To determine the percentage of mature females in spawning condition, we used the following criteria: cuttlefish spawning individuals were those that had enlarged oocytes (GSIs ≥ 2.5%), for squid with enlarged oocytes (GSIs ≥ 5%) and for bugs, if they were egg-bearing.

7.4 Results

7.4.1 Overall catch summary

A total of 191,411 byproduct specimens (bugs, squid and cuttlefish) were collected (Table 7.1). Of these, 13,731 were examined for species composition, GSI, sex ratio, length-weight relationships and fecundity. Bugs were the most abundant species examined as they were readily identified and sexed in the field. Cuttlefish were the most abundantly caught byproduct group, but the need to examine them internally for species identification and reproductive condition limited the number of specimens identified and processed (Table 7.1).

7.4.2 Size at maturity

The carapace length of mature female *T. parindicus* ranged from 30.3 to 81.5 mm and from 52.7 to 89.5 mm for *T. australiensis*. The estimated mean carapace length of females at sexual maturity (CL_{50}) was 52.0 ± 0.5 mm for *T. parindicus* and 58.9 ± 0.5 mm for *T. australiensis* (Figure 7.2). The mean size at maturity of each species was described by the equations:

T. parindicus females: $$y = \frac{1}{1+e^{(-0.27\pm0.02(CL-52\pm0.5))}}$$ r^2=0.99

T. australiensis females: $$y = \frac{1}{1+e^{(-0.53\pm0.04(CL-58.9\pm0.5))}}$$ r^2=0.98

Table 7.1. Summary of total number of byproduct specimens collected in the Gulf of Carpentaria and processed for life-history studies from August 2002 to February 2008. (* species could not be identified at sea).

Byproduct Group	Common Name	Species	Collected at sea	Laboratory processed
Bugs	Mud Bug	*Thenus parindicus*	127308	240
	Reef Bug	*Thenus australiensis*	3127	8
Squid*	*U. etheridgei* complex	*Uroteuthis* sp 3		2433
	U. chinensis complex	*Uroteuthis* sp 4		816
	Squid	Unidentified	14873	–
Cuttlefish*	Ovalbone Cuttlefish	*Sepia elliptica*		6981
	Papuan Cuttlefish	*Sepia papuensis*		571
	Pharaonis Cuttlefish	*Sepia pharaonis*		1129
	Smiths Cuttlefish	*Sepia smithi*		1553
	Cuttlefish	Unidentified	46103	–

Among the two species of squid, *Uroteuthis* sp 3 females matured at a slightly smaller size than *Uroteuthis* sp 4 (Figure 7.3). *Uroteuthis* sp 3 as small as 80 mm ML had enlarged gonads and a GSI > 5%. *Uroteuthis* sp 4 matured at about 90 mm ML and a similar size to the largest cuttlefish, *Sepia pharaonis*. GSI values of mature and spawning animals for each cuttlefish species were lower (< 8%) compared with the two *Uroteuthis* squid species (up to 20%) (Figure 7.3).

7.4.3 Spawning

The seasonal pattern of spawning by bugs was similar for the two species, although with a shift in the timing (Figure 7.4). Both species reached a maximum percentage of berried females in the late dry season (August – October), when almost 50% of the mature populations were berried. In *T. parindicus*, the spawning season appears to be protracted with some berried females in most months (Figure 7.4). Whereas, in *T. australiensis*, there were few females caught later in the wet season (March) and none were berried.

The spawning season for the squid and cuttlefish species also appears to be extended for several species (Figure 7.5). Mean GSIs were higher later in the dry season (August – October) for both *Uroteuthis* species and *Sepia smithi* and *S. papuensis*. The seasonal pattern of reproduction was less clear in the other two species of cuttlefish (*S. elliptica* and *S. pharaonis*), with a similar mean GSI throughout the year (Figure 7.5).

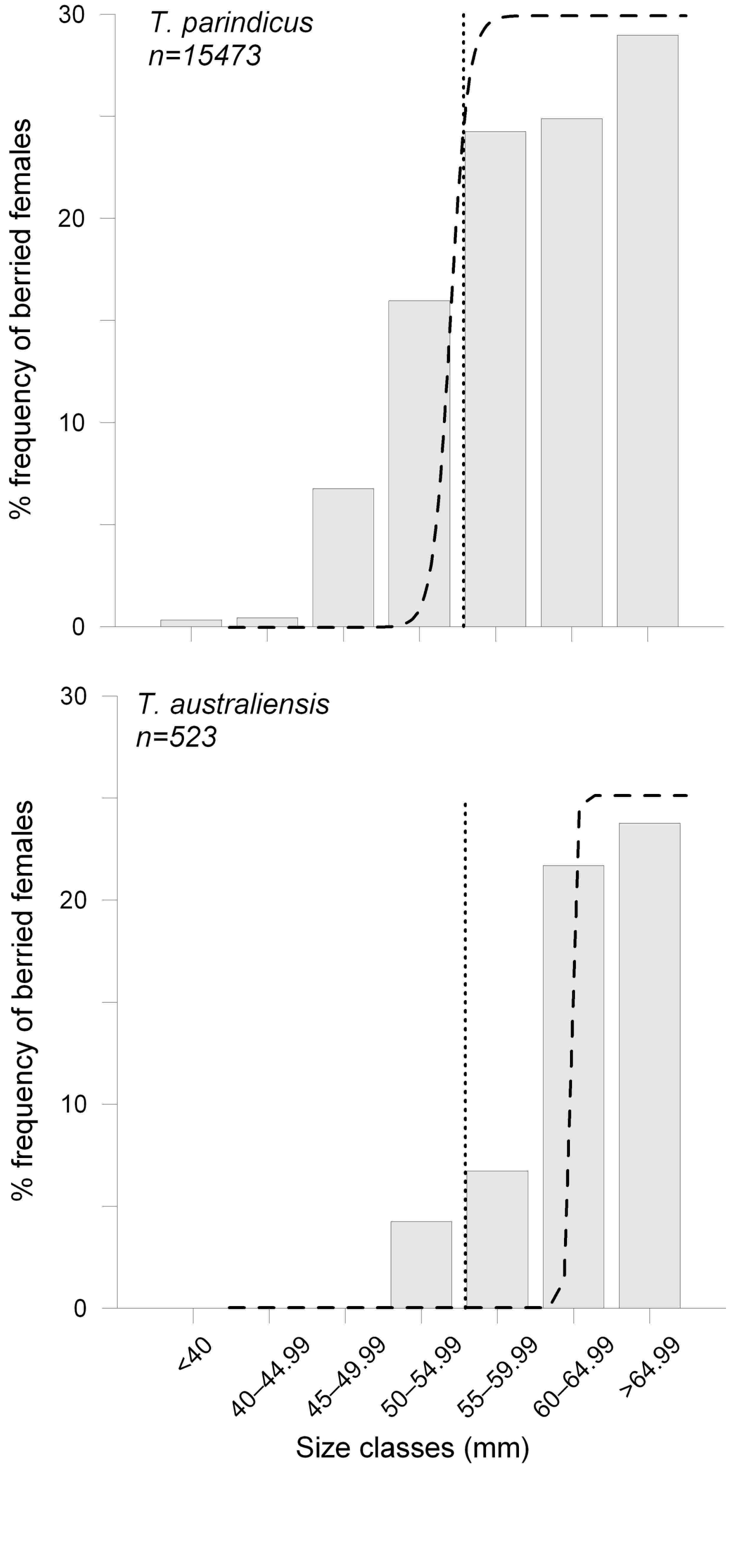


Figure 7.2. The percentage of berried female *Thenus* bugs for each size class from samples collected between 2002 and 2008. The vertical dotted line is the minimum legal size that is allowed to be retained in the NPF. The dashed curve shows the mean logistical regression best fit.

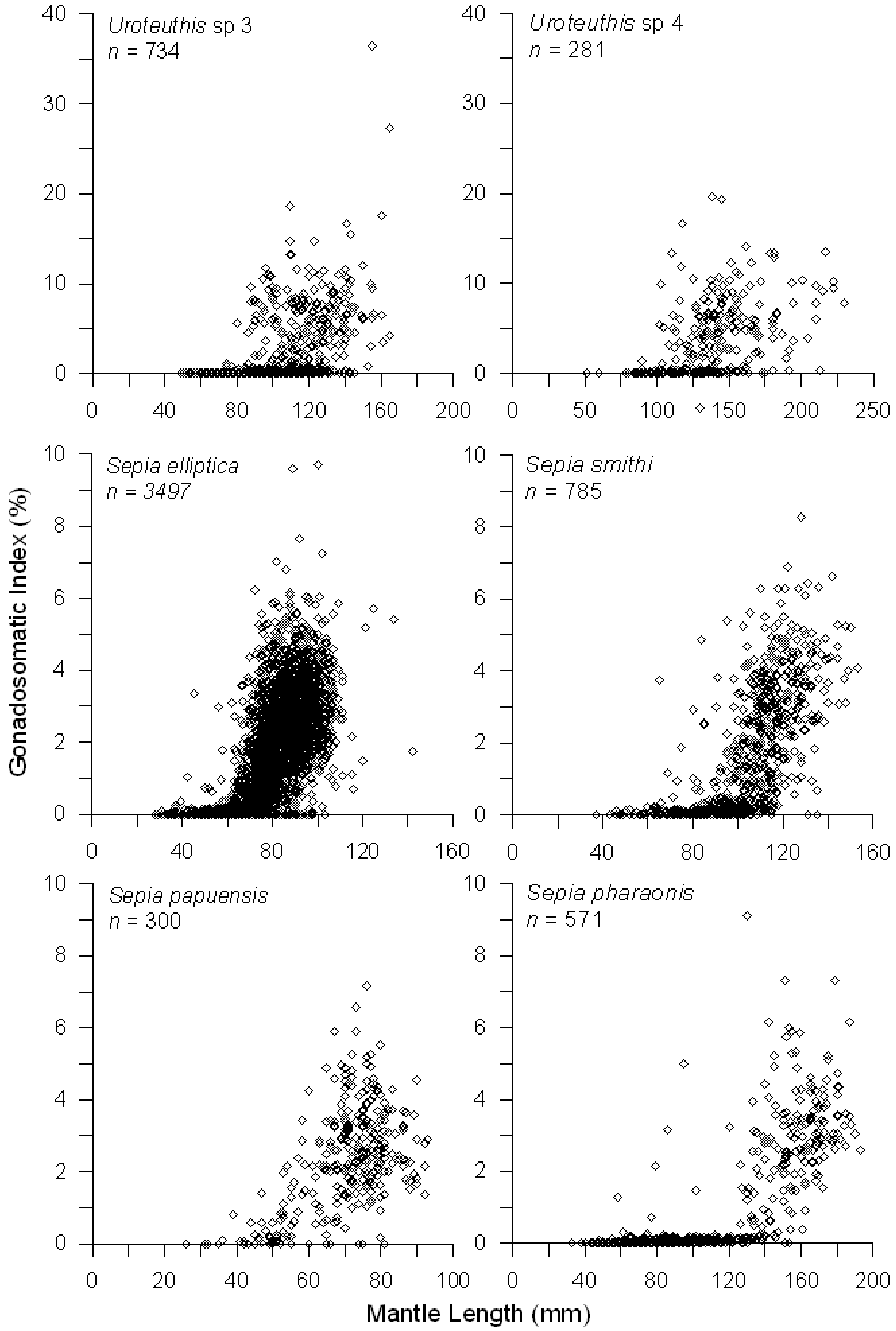


Figure 7.3. The gonadosomatic Index (%) for females of two species of squid and four species of cuttlefish caught in the Gulf of Carpentaria from August 2002 to July 2008.

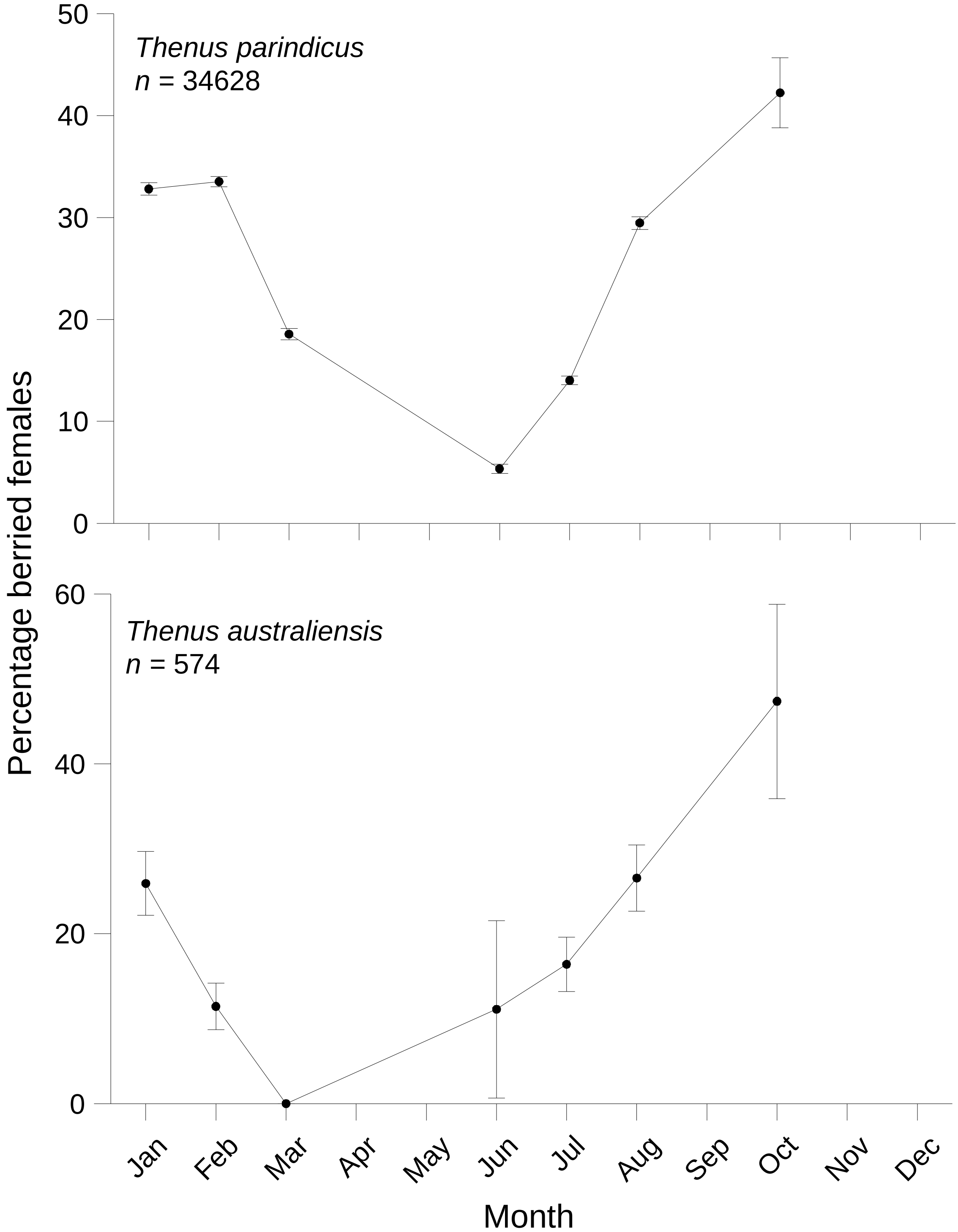


Figure 7.4. The mean percentage ± 95% confidence limit of berried females of two species of bugs caught in the Gulf of Carpentaria from August 2002 to July 2008.

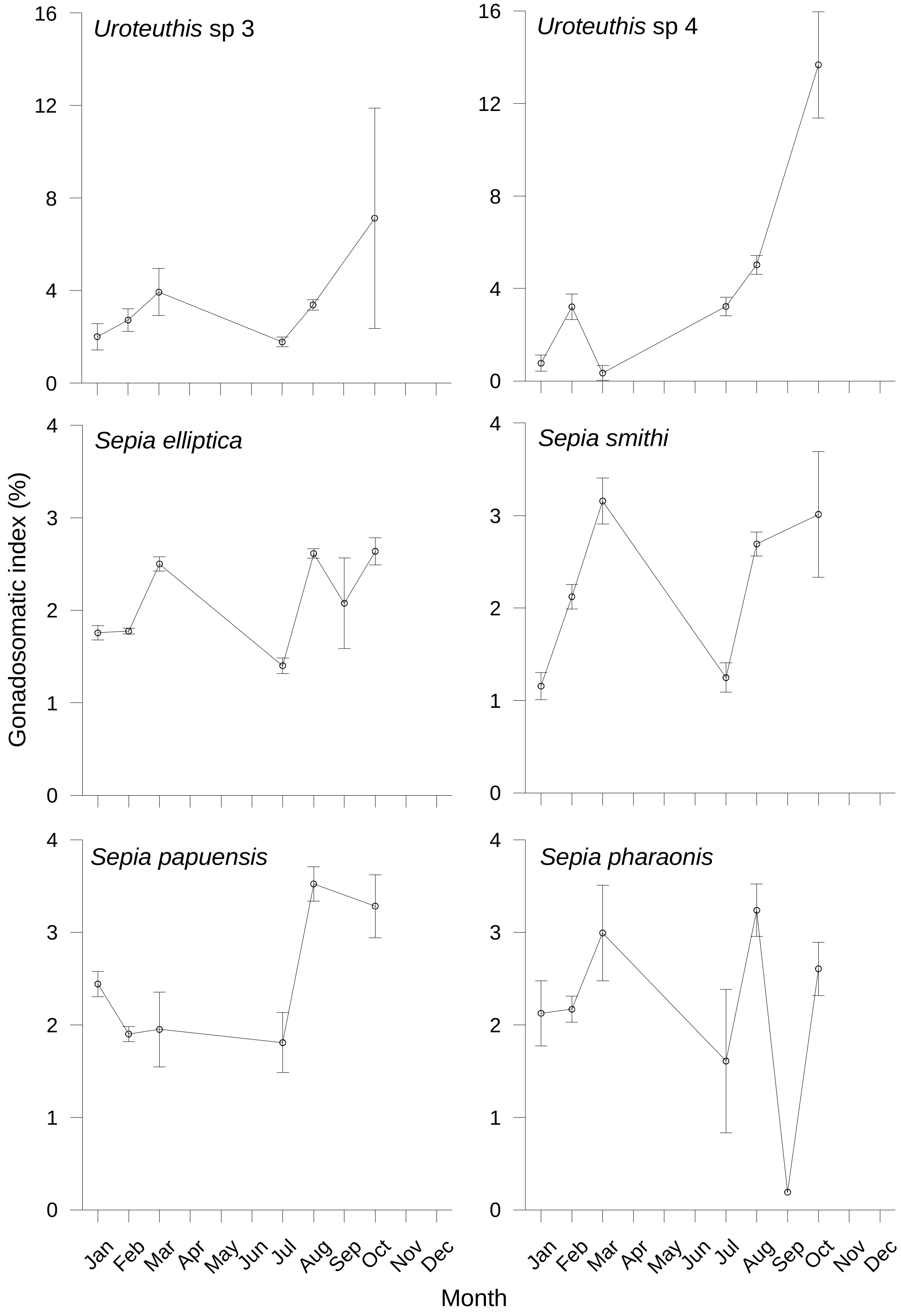


Figure 7.5. The mean monthly gonadosomatic index (%) of females of two species of squid and four species of cuttlefish caught in the Gulf of Carpentaria from August 2002 to July 2008.

7.4.4 Squid spawning aggregation

The squid spawning aggregation subsampled in May 2007 was located west of Mornington Island in the Gulf of Carpentaria (Figure 7.6). In total, 119 adult squid weighing 7.3 kg were processed. All squid examined were identified as *Uroteuthis* sp 4, comprising 57 males and 62 females (M/F ratio of 0.92). The female squid varied widely in their GSI (Table 7.2), with some specimens clearly spent and suffering some mantle muscle breakdown. The size composition was strongly skewed to males among the larger specimens. However, a cohort of smaller males was also present in the aggregation (Figure 7.7). Several other large catches of squid recorded in the logbooks also occurred in May and in the vicinity of Mornington Island (Figure 7.6). Large catches later in the year (September – October) were made further west, around Groote Eylandt. These aggregations appear to be relatively predictable as large catches were made in the same areas in May 2001 and 2002. The species involved in these aggregations may have been either of the two *Uroteuthis* species, as both showed an increase in mean GSI at this time (Figure 7.5).

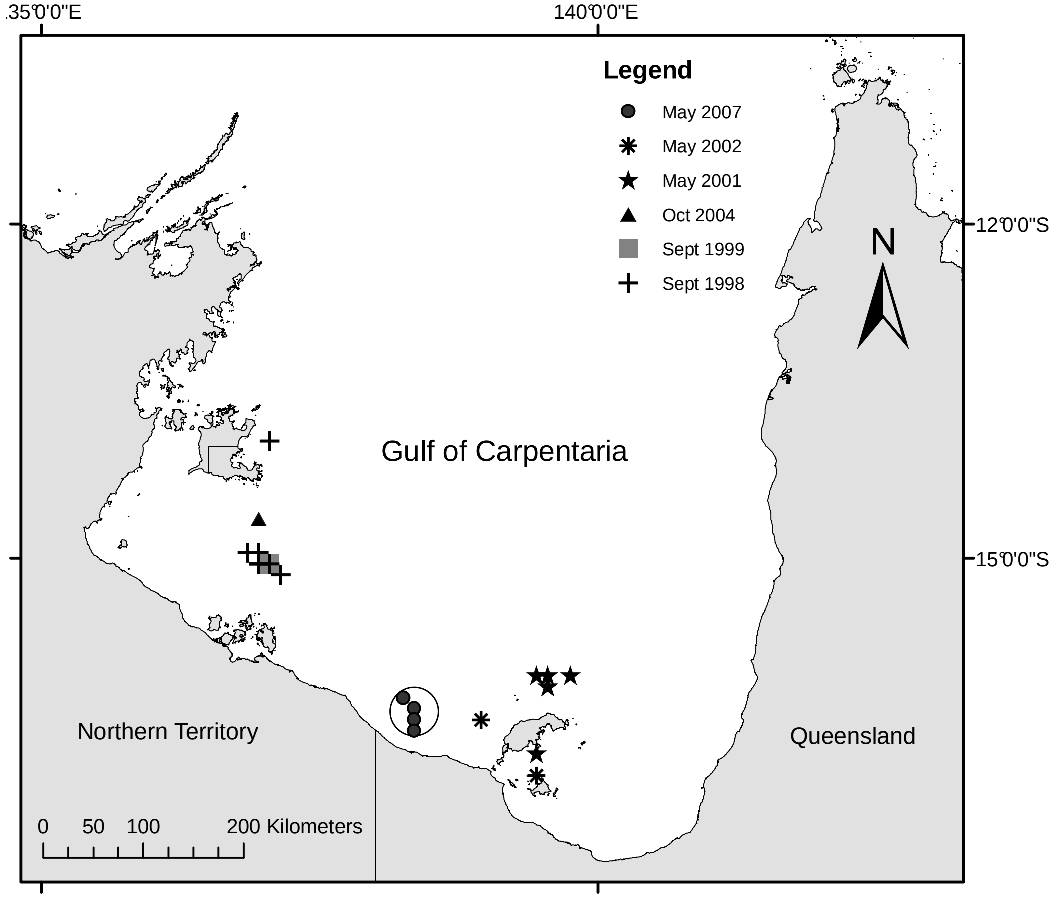


Figure 7.6. Map of the Gulf of Carpentaria showing the location (circled) of the *Uroteuthis* sp 4 spawning aggregation examined. Other probable squid aggregations (catches > 400 kg.vessel.d^{-1}) in September or October in other years are also shown.

Table 7.2. Biological data collected from the *Uroteuthis* sp 4 spawning aggregation around Mornington Island on 23rd May 2007 (ML = mantle length (mm), BW = body weight (g)).

Sex	*n*	ML range (mm)	Mean ML ± SE	BW range (g)	Mean BW ± SE	GSI range (%)	Mean GSI ± SE
Male	57	117 – 280	198 ± 5.9	27.5 – 142.2	74 ± 3.8	0.21 – 2.4	0.9 ± 0.06
Female	62	118 – 175	139 ± 1.7	28.8 – 87.2	48 ± 1.8	0.85 – 14.4	5.4 ± 0.4

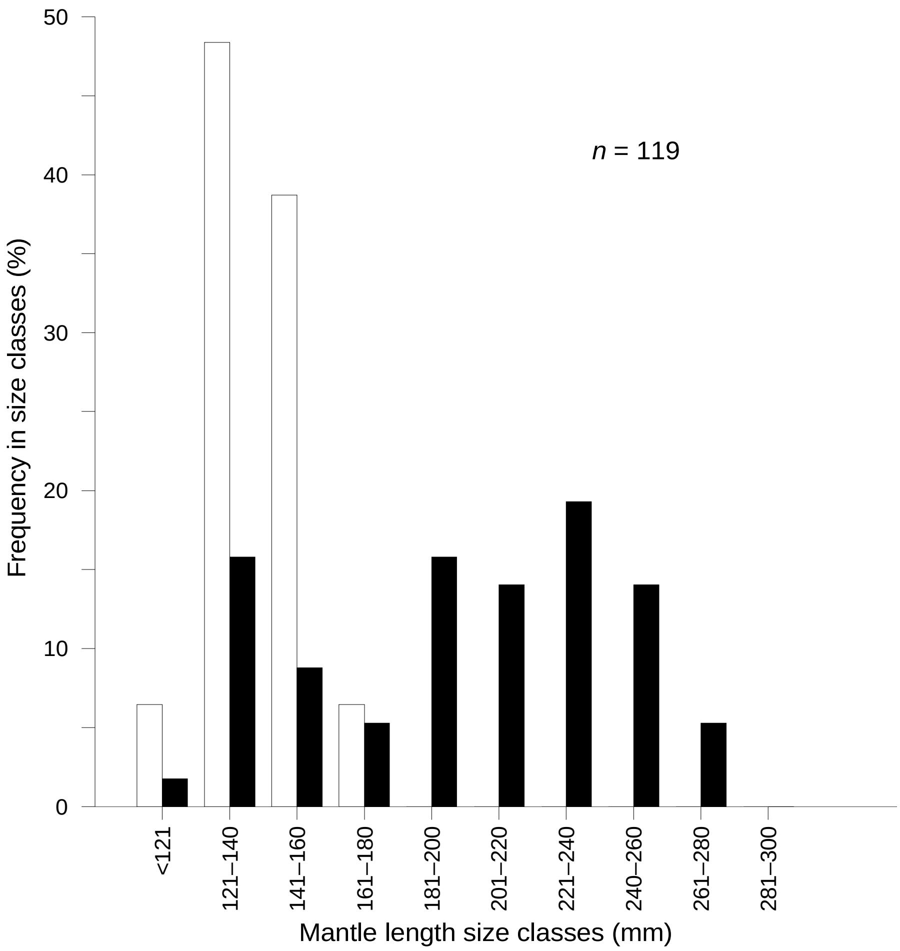


Figure 7.7. Percentage length-frequency distributions of *Uroteuthis* sp 4 caught from a single spawning aggregation (23 May 2007) west of Mornington Island (see Figure 7.6). White bars represent females; black bars represent males.

7.4.5 Fecundity

Of the cephalopods examined, cuttlefish were considerably less fecund than squid (Table 7.3). Among the cuttlefish the two smaller species, *Sepia elliptica* and *S. papuensis*, had similar mean fecundities. Their mean fecundities were approximately 60% of the fecundity of the two larger species, *S. pharaonis* and *S. smithi*, which also produced a similar number of eggs. Of the squid, *Uroteuthis* sp 4 was approximately 1.5 times more fecund than *Uroteuthis* sp 3, although relative fecundities were similar. The two bugs also showed a similar pattern with *Thenus australiensis*; producing approximately 1.5 times more eggs than the smaller *T. parindicus* (Table 7.3).

Table 7.3. Mean size and fecundity and relative fecundity (eggs.g^{-1}) ± SE of cuttlefish, squid and bug species in the Gulf of Carpentaria from August 2002 to February 2008.

Group	Species	Size range (mm)	Size (mm) ± SE	Mean fecundity ± SE	Relative fecundity ± SE	*n*
Cuttlefish	*Sepia elliptica*	67 – 121	89 ± 1	180 ± 10	58 ± 3	89
	Sepia papuensis	66 – 89	76 ± 2	172 ± 18	122 ± 17	15
	Sepia pharaonis	86 – 190	155 ± 3	343 ± 40	34 ± 3	35
	Sepia smithi	100 – 140	118 ± 2	274 ± 30	42 ± 3	39
Squid	*Uroteuthis* sp 3	59 – 143	102 ± 13	3341 ± 1001	698 ± 140	6
	Uroteuthis sp 4	125 – 222	170 ± 11	4779 ± 677	641 ± 34	17
Bugs	*Thenus parindicus*	40 – 70	55 ± 0.5	11350 ± 328	1426 ± 20	240
	Thenus australiensis	61 – 75	70 ± 2	16829 ± 2481	1494 ± 114	8

7.4.6 Commercial logbook effort

The commercial catch of bugs is spread throughout the entire Gulf of Carpentaria fished area (Figure 7.8). The mean retained catch rate in most regions was < 25 kg.d^{-1}, but there were localised areas where > 100 kg.d^{-1} have been landed. These were mostly in the south eastern Gulf around Karumba. Here, the catch comprised almost exclusively *T. parindicus*. Berried female bugs were caught in all regions. However, the proportion of berried females of each species of *Thenus* varied, mostly between seasons rather than spatially (Figure 7.8).

The spatial distribution of squid catches was more restricted than those of bugs (Figure 7.9). However, the reported catches were much larger than for the bugs, with over 500 kg.d^{-1} recorded from several locations in the Vanderlins and Mornington regions. These catches were mostly *Uroteuthis* sp 3. Spawning occurred throughout the year, with a higher proportion spawning during the dry season in most regions (Figure 7.9).

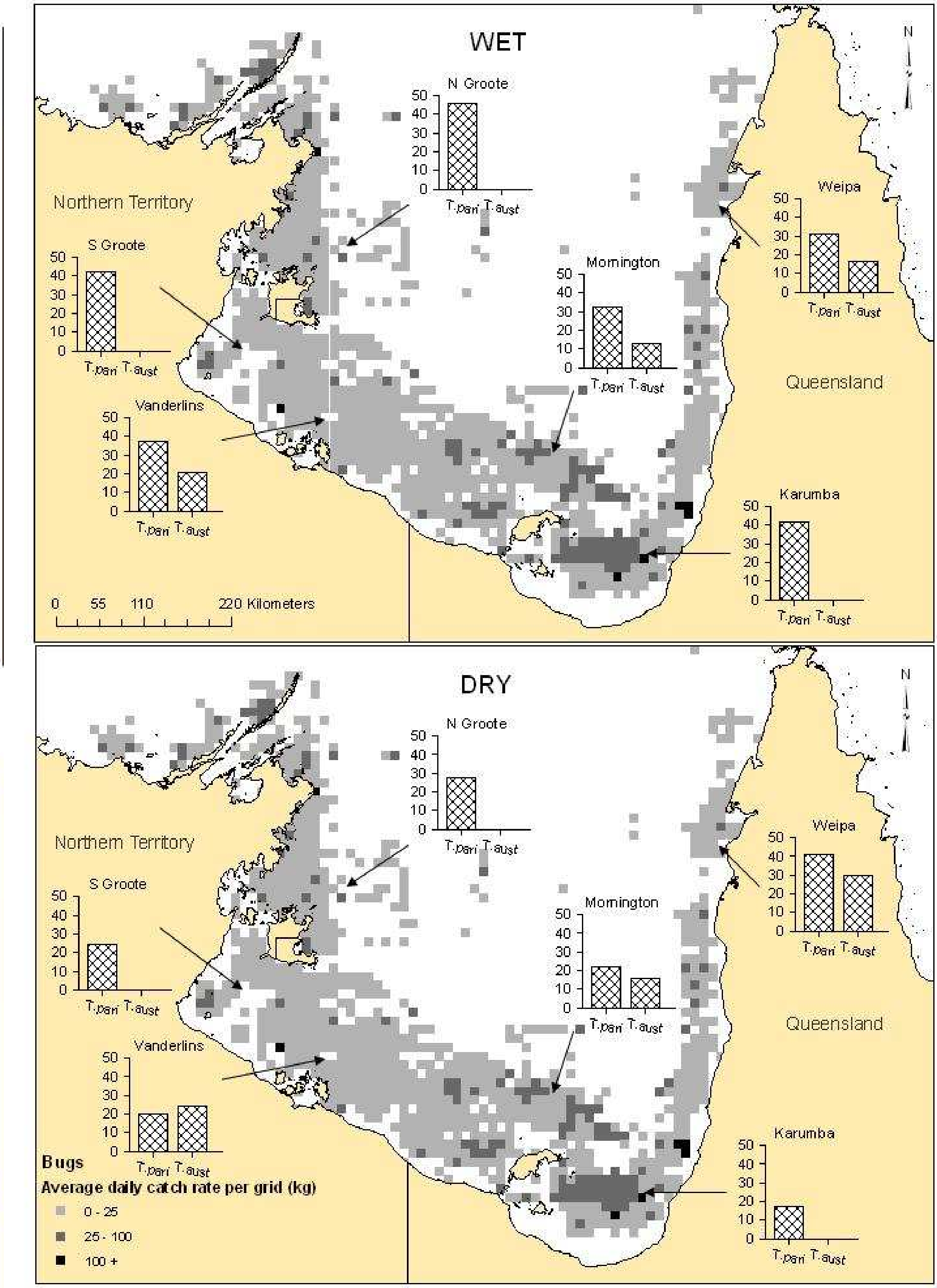


Figure 7.8. Maps of the Gulf of Carpentaria showing mean annual commercial catch rates (grid point) of two species of bugs (*Thenus*) and the mean wet (November, March – May) and dry (June – October) season percentage (histogram) of the adult female population that are berried. (T.pari: *Thenus parindicus*, T.aust: *Thenus australiensis*).

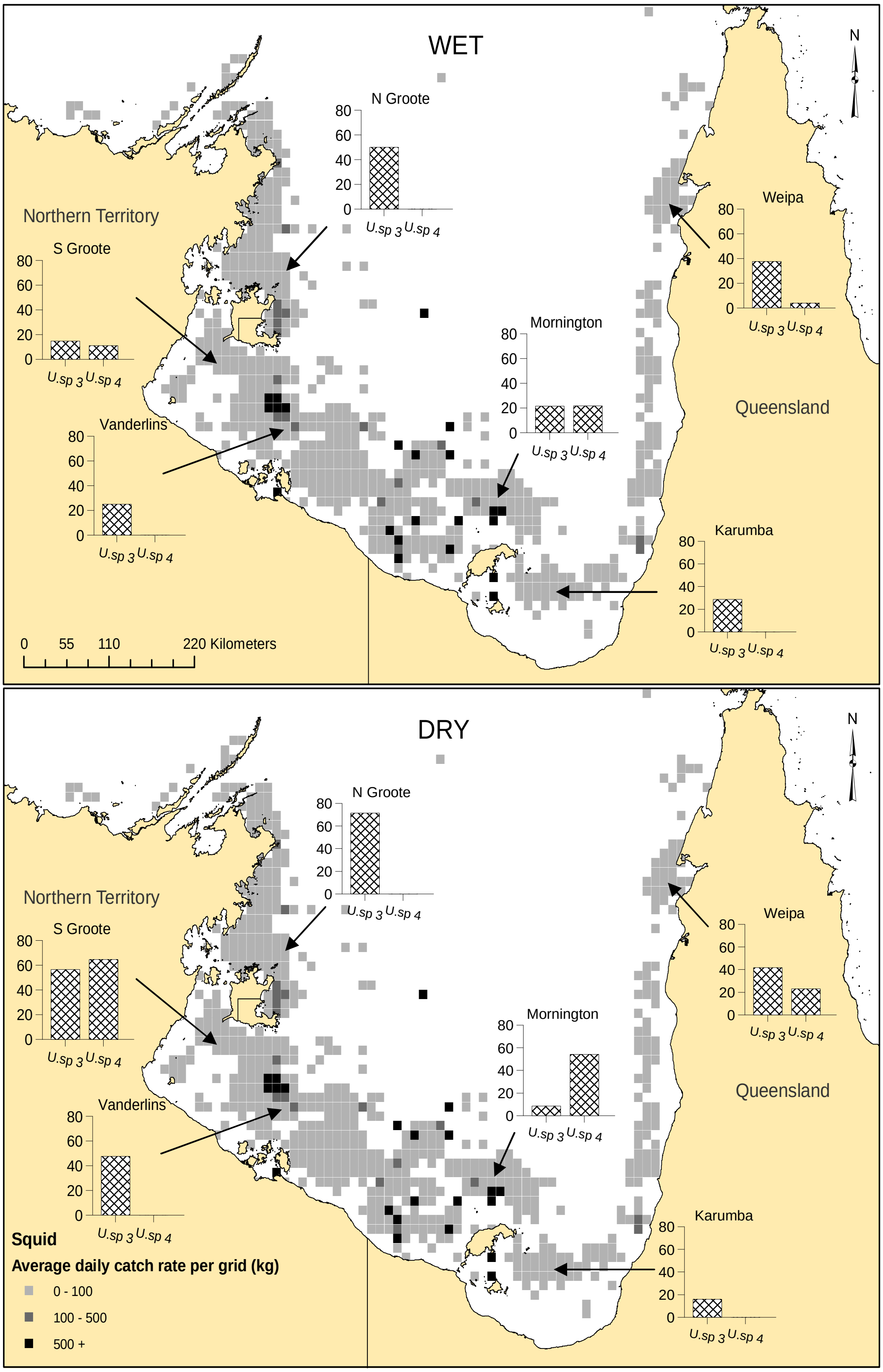


Figure 7.9. Maps of the Gulf of Carpentaria showing the mean annual commercial catch rates (grid point) of two species of *Uroteuthis* squid and the wet (November, March – May) and dry (June – October) season mean percentage (histogram) of the adult female population in spawning condition. (U.sp 3: *Uroteuthis* sp 3, U.sp 4: *Uroteuthis* sp 4).

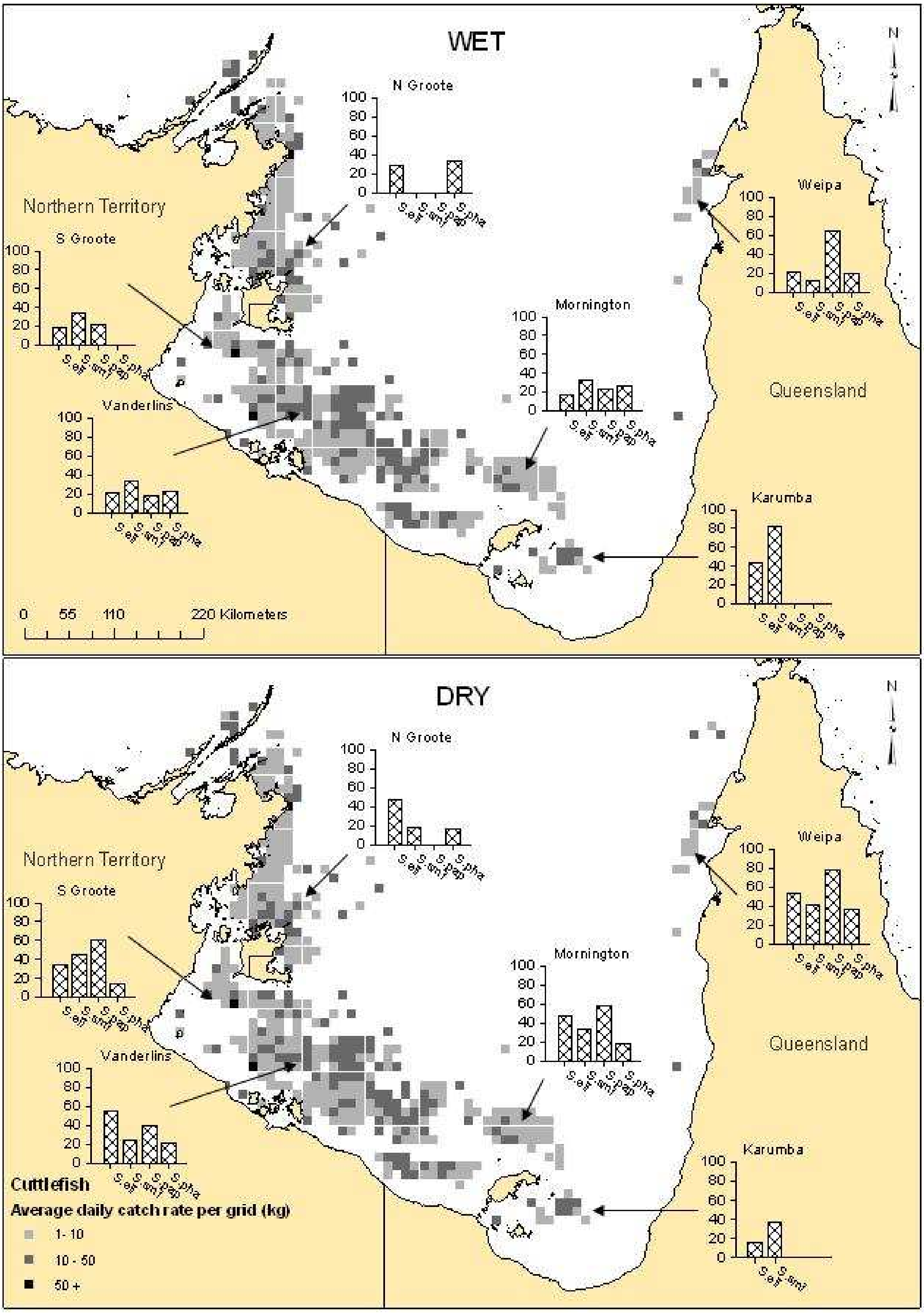


Figure 7.10. Maps of the Gulf of Carpentaria showing the mean annual commercial catch rates (grid point) of four species of *Sepia* cuttlefish and the mean wet (November, March – May) and dry (June – October) season percentage (histogram) of the adult female population in spawning condition. (S.ell: *Sepia elliptica*, S.smi: *Sepia smithi*, S.pap: *Sepia papuensis*, S.pha: *Sepia pharaonis*).

In contrast, the commercial logbook records of cuttlefish were from the southern and western parts of the Gulf of Carpentaria (Figure 7.10). Catch rates of cuttlefish were lower than for the other two groups, with the highest catch rates coming from the Vanderlins region. The spawning pattern varied among species, with the greatest proportion of each species in spawning condition during the dry season (Figure 7.10). Some species such as *S. smithi* and *S. pharaonis* only spawned in the north western Gulf of Carpentaria around Groote during the dry season. The shallow water around Karumba was the only region where *S. papuensis* and *S. pharaonis* did not spawn. The other two species, *S. elliptica* and *S. smithi*, spawned throughout the year in all regions (Figure 7.10).

7.5 Discussion

The life-history patterns of byproduct species caught in the NPF varied widely. We found species-specific differences in size at maturity, fecundity and temporal and spatial reproductive condition and behaviour. The species examined are all *r*-strategists that are characterised by being short lived, small in size, early maturing and produce one or more batches of eggs during an extended spawning season.

7.5.1 Bugs

The overall reproductive patterns appear to be similar for both species of bug (*Thenus parindicus* and *T. australiensis*). We found that *T. parindicus* mature at a smaller size than *T. australiensis* and at a similar size to this species on the Queensland east coast (Jones 2006). The average fecundity of *T. parindicus* in the Gulf of Carpentaria was similar to estimates from north eastern Australia (Jones 2006). However, the fecundity estimates for *T. australiensis* from the Gulf of Carpentaria were considerably lower in our study (~17000 eggs) compared to Jones (2006) (~32000 eggs) and to that of Hossain (1979) (~21000 eggs). Fecundity of bugs increases with size (Jones 2006; Oliveira et al. 2008). The specimens caught in the Gulf of Carpentaria were of a smaller mean size (70 ± 2 mm CL) compared to 78 mm CL (Jones 2006) and thus proportionately less fecund. Another sub-tropical to temperate water scyllarid, *Ibacus peronii*, also shows a similar relationship between size and fecundity (Stewart and Kennelly 1997). It is worth noting that while *T. australiensis* is more fecund per egg clutch, *T. parindicus* may in fact have similar reproductive potential as they mature earlier at a smaller size and have similar relative fecundities.

According to Jones (2006), both species produce at least two egg clutches per year, with peak recruitment immature bugs to the fishing grounds in the wet season (January – March). We also detected a strong recruitment to the fishery during the wet season for both species (Milton et al. 2008). It appears that the majority of spawning activity occurs in the late dry season (August – October) in which the percentage of berried females increased from ~15% in July to over 40% in October. It is unclear whether this spawning pulse extends into November and December as samples were not collected during these months. There was potential for some spawning activity for both species throughout the year. There were small percentages of berried females in their populations at all times. Year-round spawning may be a response to the variability of environmental conditions in northern Australia as rainfall patterns and nutrient inputs are highly seasonal. For example, other studies have found that large fluctuations in environmental conditions such as temperature, salinity, wind and currents have the potential to influence the survival of larvae of other lobster species (Rothlisberg et al. 1994; Marinovic 1996; McWilliam and Phillips 1997; Caputi et al. 2001).

7.5.2 Squid and cuttlefish

Reproduction in loliginid squids and sepiid cuttlefish is complex. They have a wide spectrum of behaviour, a large energy investment over an extended part of the short life cycle (Hanlon 1998). *Uroteuthis* sp 3 and *Uroteuthis* sp 4 are the shortest-lived species (4 – 6 months: Jackson and Choat 1992; Jackson and Yeatman 1996; Sukramongkol et al. 2007) and both mature in about 75 – 100 days (Jackson 1993; Sukramongkol et al. 2007). There were considerable differences in the sizes at maturity for females among the six cephalopod species analysed. For example, *Uroteuthis* sp 3 had developed gonads when they were as small as 40 mm ML. This was a similar size to that of the smaller cuttlefish species, *S. elliptica* and *S. papuensis*. In contrast, *Sepia pharaonis*, *S. smithi* and *Uroteuthis* sp 4 appear to mature at larger sizes, 60 – 90 mm ML. Gabr et al. (1998) found *Sepia pharaonis* in the Suez Canal matured at 90 mm ML. A marked plasticity has been noted in size at maturity for a number of cephalopods (*Loligo opalescens*, Hixon 1983; *Loligo pealei*, Macy 1982; *Photololigo edulis*, Natsukari and Tashiro 1991; *Loligo vulgaris reynaudii*, Augustyn et al. 1992; and *Sepia pharaonis*, Dunning et al. 1994). Factors such as size, age, food availability and environmental conditions such as temperature and day length have been reported as possible explanations for these differences in size at maturity (Natsukari and Tashiro 1991; Jackson 1993; Jackson and Yeatman 1996).

The squid in northern Australia invest more energy into reproduction than cuttlefish. Their gonad represented up to 20% of total body weight in female squid compared to < 8% for all cuttlefish species. The mean fecundity among the cephalopods showed considerable variation. The squid species produced between 3000 – 5000 eggs per spawning, which is similar to that of another tropical squid from the eastern Atlantic Ocean, *Loligo vulgaris* (Coelho et al. 1994). The cuttlefish however, produced considerably fewer and much larger eggs with mean fecundity ranging from 173 to 343. Our estimates for *S. pharaonis* were similar to that of Gabr et al. (1998). This is interesting considering that they are now thought to be a different species (Anderson et al. 2007), geographically separated and thus more likely to vary in their life-histories. The fecundity estimates for the other *Sepia* species are the first to be published. Differences in reproductive capacity between squid and cuttlefish are probably related to the trade-off between fecundity, egg size and longevity (Pecl and Jackson 2008). Cuttlefish also have more elaborate egg protecting behaviour by laying their eggs in or under structures. This approach is likely to provide some level of protection against predators compared to squid that mostly lay egg capsules on the sea bed.

Squid and cuttlefish populations spawn throughout most of the year in northern Australia, with seasonal peaks in productivity. *Uroteuthis* sp 3, *Uroteuthis* sp 4, *Sepia smithi* and *S. papuensis* had an obvious spawning peak in the late dry season (September – October). In contrast, *S. elliptica* and *S. pharaonis*, did not show clear seasonality in spawning. According to Jackson (1993), Moltschaniwskyj (1995) and Sukramongkol et al. (2007), other *Uroteuthis* species spawn in large aggregations throughout the year, with peaks in spring and autumn. We also detected an increase in spawning during spring (September – October). However, we were not able to collect samples during autumn. The opportunistic sampling of a spawning aggregation in May 2007 (autumn) suggests that at least *Uroteuthis* sp 4 does spawn at this time. Another tropical squid, *Photololigo edulis* also spawns in spring and autumn in the southern East China Sea (Wang et al. 2008). The protracted spawning seasons of these species may be a strategy to compensate for variable environmental conditions that can affect hatching (Boyle and Rodhouse 2005). In comparison, Boletzky (1988) found that cuttlefish (*Sepia officinalis*) were capable of intermittent spawning in captivity over a period of seven months. He suggested that protracted spawning is likely to be important under certain environmental conditions to counteract high mortality rates.

7.5.3 Management Issues

Current regulation of catches of both *Thenus* species in the NPF is through a minimum legal size (MLS) and the prohibition of taking berried females. Our estimate of size at maturity for *T. parindicus* of 52 mm CL is below the current MLS of 55 mm CL (75 mm CW). As a result, a proportion of the mature females can spawn before they are vulnerable to fishing. As *T. parindicus* accounts for over 90% of the *Thenus* catch in the NPF (Chapter 8), the current regulation should reduce the risk of recruitment overfishing. In contrast, *T. australiensis* mature at 59 mm CL and larger than the MLS. Thus, the current MLS regulation does not protecting the adult population of this species. However, the habitat preference for *T. australiensis* may provide a level of protection, as they prefer coarser substrates and deeper water (> 40 m) (Jones 2006; Chapter 8). The level of current commercial fishing effort in the NPF is higher in shallower water (< 40 m) and on the softer substrates preferred by the targeted prawn species. However, if the *T. australiensis* population in the NPF was considered to be in decline or at risk, then a possible management option would be to increase the MLS to 80 mm CW for both species. This would increase egg production and reduce the likelihood of recruitment overfishing on *T. australiensis* (Courtney 2002).

Many species of cephalopods, including *Uroteuthis* sp 3 and *Uroteuthis* sp 4, aggregate when spawning (Dunning et al. 1994). This makes them potentially more vulnerable to targeted fishing. The targeting of squid aggregations by demersal trawling has the potential to heavily disrupt spawning, but also damage egg capsules attached to the seabed. Spawning aggregations have been reported for other squid species, such as *Loligo vulgaris reynaudii* in South Africa (Sauer et al. 1992), *L. pealei* off the U.S. east coast (Arnold 1962) and for *L. opalescens* off California (Fields 1965). In contrast, cuttlefish are usually solitary animals except during spawning (Naud et al. 2004). Large cuttlefish spawning aggregations have only been reported for one species in southern Australia, *Sepia apama* (Hall and Hanlon 2002). We found no evidence of large spawning aggregations for any of the cuttlefish species examined. However, several commercial catches > 50 kg day^{-1} have been reported in regions north of the Vanderlins and south Groote. This may indicate some level of aggregation for spawning and should be investigated further to determine the reproductive characteristics of the species being caught.

Historical catches from Taiwanese trawlers in northern Australia indicate that the recent average annual catch of around 116 t of squid and 5 t of cuttlefish in the NPF from 1998 – 2005 is well below harvest capacity. For example, in 1978, Taiwanese trawlers caught 968 t of squid and 106 t of cuttlefish were caught in the Gulf of Carpentaria by Taiwanese trawlers (Liu and Yeh 1982). In the area northeast of Groote alone, a total catch of ~48 t of squid were caught from 55 hauls (Liu and Yeh 1982). Therefore the current annual take of squid before management action is required (500 t) is probably conservative. The fact that squid aggregations in the same regions within the NPF have been targeted over several years without local depletion suggests resilience at the current level of fishing. However, if this trigger point is reached then one management option might be to introduce a spatial or temporal closure of known squid spawning grounds as has been implemented elsewhere (Sauer et al. 1992; Moltschaniwskyj et al. 2002). Therefore the identification of species-specific spawning aggregations should be a priority. AFMA should encourage collection of samples from these aggregations by fishers or scientific observers in order to determine their biological characteristics. This will provide baseline data that can be used to confirm the species composition predictions (Chapter 9) and thus make better informed management decisions in future.

7.5.4 The future?

According to Jackson (2004), tropical squid tolerate and even thrive in very warm conditions. Therefore, they are likely to be favoured by the predicted increase in sea water temperature in northern Australia due to climate change. Global warming is likely to increase growth rates and accelerate their fast life histories. This could result in an increased rate of population turnover and potentially lead to population expansion. Pecl and Jackson (2008) predict that warmer temperatures will also lead to smaller eggs and smaller size at maturity. Thus, the overall effects of warming seas are difficult to predict. Should warmer waters lead to a higher turnover rate squid may have the potential to become more of a targeted species in the future rather than as byproduct. As a result more rigorous techniques to define stock size may need to be considered. These may include traditional stock assessments methods such as those described by Pierce and Guerra (1994), or newer techniques that combine hydroacoustic and minimum demersal survey swept area estimates of spawning biomass (Lipinski and Soule 2007). There has also been some recent success in estimating stock size from environmental conditions, particularly sea surface temperature (Waluda et al. 1999; Agnew et al. 2002). New risk assessment methods (Zhou and Griffiths 2008) that rely on evaluating the proportion of the cephalopod population being trawled by the NPF could also be investigated (see Chapter 10).

8. FACTORS AFFECTING THE DISTRIBUTION AND ABUNDANCE OF BYPRODUCT SPECIES IN THE NORTHERN PRAWN FISHERY

8.1 Abstract

The effect of a number of spatial, temporal and environmental variables on catches (in $g.ha^{-1}$) of squid, cuttlefish, bug and scallop byproduct species were examined with generalised additive models. The variables used were year, month, depth (m), distance from the coastline (RLand), distance along the coastline from a fixed point (RDist) and sediment composition (percentage mud and sand). Catch rates from recent NPF prawn monitoring surveys on the major prawn grounds were also compared to historical CSIRO scientific and observer survey data and commercial logbook catches to identify any trends in CPUE over time.

Mean catch rates of squid from the NPF prawn monitoring surveys declined from around 15 $g.ha^{-1}$ in 2002 to only 5 $g.ha^{-1}$ in 2008 in the Gulf of Carpentaria. Catches of cuttlefish however have remained relatively stable from 2002 to 2008; ranging from 16 to 30 $g.ha^{-1}$. The abundance of bugs also declined from around 175 $g.ha^{-1}$ in 2003 and 2004 to 120 $g.ha^{-1}$ in 2006 and 2007, and increased again in 2008. Scallop catch rates varied between years, showing higher catches in 2002, 2005 and 2007 with considerably lower catches in 2003, 2006 and 2008.

A number of factors affected byproduct catch rates in both the NPF prawn monitoring surveys and the NPF commercial fishery. The abundance of most squid species differed seasonally and inter-annually. There were significantly higher catches from the NPF prawn monitoring surveys in January – February and June – August of 2003 – 2004 and 2007 – 2008. Squid were more abundant in shallow water (10 – 15 m), especially the smaller species (*A. noctiluca*, *Uroteuthis* sp 1 and *Uroteuthis* sp 2). These species were also more abundant on grounds with mud substrates, whereas *Uroteuthis* sp 4 was more abundant in relatively sandy areas. There were no strong regional differences in catch rates in the Gulf of Carpentaria, except that slightly higher commercial catch rates were recorded around Mornington and Karumba regions.

There was no significant seasonal trend in cuttlefish abundances in the Gulf of Carpentaria. The commercial landings were lowest in April, increasing steadily throughout the rest of the year. All five cuttlefish species had high catches in the deeper offshore waters (> 25 m), although two species (*S. elliptica* and *S. smithi*) also had high catch rates in shallow coastal waters (< 10 m). Cuttlefish species were least abundant around the Weipa region. Most cuttlefish species (*S. elliptica*, *S. papuensis*, *S. smithi* and *Metasepia pfefferi*) had slightly higher catch rates when substrates were a mixture of sand and mud rather than predominantly one type or another.

The mud bug, *T. parindicus*, showed a distinct seasonal pattern in commercial landings. Greater quantities of mud bugs were retained earlier in the year compared to later in the year (April – August) and a greater proportion of reef bugs were recorded during September to November compared to earlier in the year. No seasonal pattern was detected in the NPF prawn monitoring surveys for either species. Highest catches of *T. parindicus* occurred in the 15 – 35

m depth zone, around Mornington and Karumba, and on grounds with substrates comprising 20 – 60% mud. In contrast, *T. australiensis* showed a distinct preference for deeper offshore waters (> 35 – 40 m), around Vanderlins and Weipa, and on grounds with a high percentage of sand.

There was no obvious inter-annual or seasonal patterns in scallop abundances in the Gulf of Carpentaria, except catches were slightly higher in the Groote region and in deeper offshore waters (> 50 m). An understanding of the relationships between abundances and spatial, temporal and environmental variables is important for predicting population fluctuations. It will also be a valuable tool for the management of these byproduct stocks by providing standardised indices of their abundances and population distributions outside of the current NPF commercial fishery areas or seasons.

8.2 Introduction

Of the four main byproduct groups, cephalopods are probably the most important marine resource worldwide, with several species the target of commercial fisheries (Pierce et al. 1994; Pierce and Guerra 1994; Perez and Pezzuto 1998; Denis and Robin 2001; Lu 2002; Wang et al. 2003; Reiss et al. 2004; Zuur and Pierce 2004; Bower and Ichii 2005; Glazer and Butterworth 2006; Nottage et al. 2007; Sukramongkol et al. 2007). However, in many of these fisheries there is a common trend of highly fluctuating catches, both seasonally and inter-annually (Pierce et al. 1994; Bellido et al. 2001; Denis and Robin 2001; Schön et al. 2002; Pierce and Boyle 2003; Reiss et al. 2004; Chen et al. 2006; Royer et al. 2006). This pattern coupled with their life-history characteristics: generally short-lived (1 – 2 years) (Pierce and Boyle 2003) with migratory and spawning aggregation behaviour, makes fishery management difficult as their populations are sensitive to environmental fluctuations (Pecl and Jackson 2008). Information on the spatial, temporal and environmental factors determining their distributions and their high annual variability in abundance are valuable data for effectively assessing and managing these stocks.

Several studies have investigated the correlation of spatial, temporal and environmental effects on the distribution and abundance patterns of these marine groups, especially cephalopods (Rainer 1984; Jones 1993; Schön et al. 2002; Wang et al. 2003; Mqoqi et al. 2007; Semmens et al. 2007). In northern Australia, Jones (1993) found that the bug species, *Thenus parindicus* and *T. australiensis* were highly aggregated or patchy in distribution with significant variability in catches. He reported that they differed in habitat characteristics, suggesting their abundance was most influenced by sediment type and water depth. Wang et al. (2003) reported that the cuttlefish, *Sepia officinalis* showed clear annual migration patterns within French Atlantic coastal waters. Local abundances were positively correlated with sea surface temperature and depth. However, very little is known about the effects of these environmental conditions on the distribution and abundance of these byproduct species in the Gulf of Carpentaria.

The aims of this chapter are to assess the effect of environmental parameters on the catch rates of byproduct species by (1) analysing available research and commercial catch data and associated spatial, temporal and environmental data to identify potential factors that influence the distribution and abundance of byproduct groups throughout the NPF; (2) identify temporal trends in CPUE by comparing catch rates from recent NPF prawn monitoring surveys to historical CSIRO scientific and observer surveys and commercial logbook catches.

8.3 Methods and materials

All available catch and effort data on species in each of the four byproduct groups (squid, cuttlefish, bugs and scallops) caught in the Gulf of Carpentaria were used for catch rate analysis. The datasets were sourced from current NPF prawn monitoring surveys (2002 – 2008), historical CSIRO scientific and observer surveys (1990 – 2005) and NPF commercial logbook data (1998 – 2007). Each of the datasets were standardised for gear and effort to catch weight (g) per trawl swept area (ha) and collated into a central database. This data is stored at CSIRO Marine and Atmospheric Research, Cleveland.

For each trawl record, the swept trawl area (ha) was calculated using the following equation:

$$\text{Swept Area (ha)} = (a * L_{hr} * n * \textit{Trawl duration} * \textit{Trawl speed})/10000 \qquad (8.1)$$

where a is the conversion estimator of the linear trawling width of a net (0.66 of headrope length), L_{hr} is the length of one trawl net headrope (in metres), n is the number of nets towed, *Trawl duration* is in hours, *Trawl speed* is in $m.hr^{-1}$.

Only data records with a latitude and longitude within the NPF boundaries were used. The spatial, temporal and environmental variables used for the catch rate analysis were year, month, depth (m), distance from the coastline in units of degrees (RLand), distance along the coastline from a fixed point in units of degrees (RDist) and sediment composition (mud and sand %) (refer to Chapter 9 for more details). This dataset, excluding depth (available for individual trawls), was based on a 6 nautical mile latitude and longitude grid. Therefore, the Gulf of Carpentaria was also divided into 6 nautical mile (nm) grids. Each trawl data record was assigned a latitude and longitude position corresponding to the centre of the six nm grid that it fell within to match with the spatial, temporal and environmental datasets.

For the NPF prawn monitoring surveys led by CSIRO (AFMA Project 2005/1024), the following data were collected from 2002 to 2008: species, numbers and weights of bugs and scallops were recorded. Numbers and weights of all squid and cuttlefish caught were recorded, however only about 20 – 25% of the total catch for these two groups were identified to species (Chapter 7). Using this subset of data, species catch compositions (by weight) were predicted for the remaining NPF prawn monitoring catch data records where individuals were not identified to species (Chapter 9).

CSIRO have undertaken several scientific surveys in different parts of the Gulf of Carpentaria between 1990 and 2005 (Table 8.1). The objectives of these surveys varied between projects, but all involved a stratified random trawl survey design. Byproduct catches from all trawls during these surveys were recorded to species where possible, counted and weighed. No biological data on the byproduct species were collected in association with these surveys, although Dunning et al. (1994) summarised some biological data for the cephalopod catches of the two most comprehensive surveys in 1990 and 1991.

Byproduct catch in the NPF is recorded in commercial logbooks under broad byproduct groups; squid, cuttlefish, bugs and scallops. Therefore, the species catch composition of the bug (all recorded), squid and cuttlefish groups (predicted from subsamples processed) obtained from the NPF prawn monitoring surveys were used to predict the species compositions of each commercial trawl between 1998 and 2007. The NPF prawn monitoring survey species compositions were assigned to each of the commercial logbook data records based on their six nautical mile latitude and longitude grid designation. As scallops retained by NPF vessels are generally only one species, *Amusium pleuronectes*, the commercial logbook catch records for scallops were assigned to this species only. For these commercial logbook predictions, it should be noted that weights recorded in the logbooks only reflect the proportion of the byproduct catch that was retained and not the total catch of byproduct for each vessel.

It was not possible to compare actual catches of each of the byproduct groups caught during the NPF prawn monitoring and CSIRO scientific and observer surveys to the catch rates recorded in the NPF commercial logbooks. The latter represent only the proportion of byproduct catch that was retained and recorded by trawlers (not total catches). However, patterns in catch rates can be compared between the commercial and scientific research trawls. Catch rates ($g.ha^{-1}$) for each byproduct species were analysed with a smoothing spline term for the independent variables; year, RDist, RLand, percent mud, percent sand and depth. Month was treated as a fixed effect for the three datasets. Year was treated as a fixed effect only for the NPF prawn monitoring surveys and CSIRO scientific and observer survey datasets. Each of the three datasets (1) NPF prawn monitoring surveys, (2) CSIRO scientific and observer surveys and (3) NPF commercial logbook data were analysed separately. This was done to independently compare the influence of each variable on the catch rates of each byproduct species. As the catch rates for most species were not normally distributed, CPUE was log transformed. The three datasets were then analysed with a generalised additive model (GAM) in R.

8.4 Results

8.4.1 Species composition of catches

The sources of each NPF byproduct dataset, the time periods of the data collected, the numbers of trawls, trawl hours and numbers of animals of each byproduct group are summarised (Table 8.1). Of the squid samples collected from the NPF prawn monitoring surveys, the dominant species varied depending on the region sampled (Figure 8.1). *Uroteuthis* sp 3 was the most abundant species overall, between 25% at Weipa and 75% at Karumba and Mornington. The largest of the squid species (in length), *Uroteuthis* sp 4, was most common at Weipa and Vanderlins, making up between 47 and 64% of the squid in these two regions. Two of the smaller species, *Aestuariolus noctiluca* and *Uroteuthis* sp 2, were only common around Karumba and Groote, respectively (Figure 8.1).

The most abundant species of cuttlefish caught during the NPF prawn monitoring surveys was *Sepia elliptica*, ranging between 53 and 94% of the cuttlefish catch (Figure 8.2). S*epia smithi* was also abundant, especially around Mornington and Weipa, comprising about 20% of the cuttlefish.

One species each of bug and scallop dominated the catches across the six regions sampled; *Thenus parindicus* and *Amusium pleuronectes*, comprising at least 93% and 85% of the catch of each group respectively (Figure 8.3, Figure 8.4). Around Karumba and Groote, the species composition of the bugs was comprised almost exclusively of *T. parindicus*; (> 99%). The reef bug (*Thenus australiensis*) was more prevalent around Weipa than other regions (15% of the bugs caught).

8.4.2 Overall catches of byproduct groups

Overall catch rates of squid during the NPF prawn monitoring surveys have declined from around 15 to 5 $g.ha^{-1}$ between 2002 and 2008 (Figure 8.5). In previous CSIRO scientific and observer surveys in the Gulf of Carpentaria, the catches of squids have been variable but generally higher than during the NPF prawn monitoring surveys, ranging from 20 to 90 $g.ha^{-1}$ (Figure 8.5). This may be a result of the method of data collection between the two data sources. The CSIRO scientific and observer surveys were undertaken at different times of the years and at a number of different regions across the Gulf of Carpentaria. This pattern differed from that of the prawn monitoring surveys that revisited the same sites each survey.

The catch rates (in weight) of cuttlefish caught during the NPF prawn monitoring surveys was around twice that recorded for the squids and was generally consistent during the period from 2002 to 2008; ranging from 16 to 30 $g.ha^{-1}$ (Figure 8.5). The catches of cuttlefish from CSIRO scientific and observer surveys showed a similar pattern to the catches of squid with generally consistent catches for most years, and several years when higher catches were made; 1995, 1996 and 2005 (Figure 8.5).

Catches of bugs from the NPF prawn monitoring surveys showed a decline in catch from around 175 $g.ha^{-1}$ in 2003 and 2004 to 120 $g.ha^{-1}$ in 2006 and 2007 (Figure 8.6). This was followed by an increase in 2008 to the levels seen in the 2003 survey year. However, catches of bugs during the previous CSIRO scientific and observer surveys was considerably lower, less than 75 $g.ha^{-1}$, in most years from 1993 to 2004. There were two years, 1995 and 2005, when mean catch rates were similar to NPF prawn monitoring survey catches (Figure 8.6). The catches of scallops were also variable across years, showing higher catches in 2002, 2005 and 2007 (Figure 8.6). Scallop catches recorded during previous CSIRO surveys were generally lower than in the NPF prawn monitoring surveys.

The commercial logbook data showed that although the volume of squid caught and retained each year were high (Table 8.1), mean catch rates of retained squid have been relatively stable at < 20 $g.ha^{-1}$ (Figure 8.5). However during 2001, 2002 and 2007, the annual mean catch was more than double (> 40 $g.ha^{-1}$) and as high as 80 $g.ha^{-1}$ (Figure 8.5). This was due to several vessels finding and targeting large spawning aggregations of squids (Chapter 7, Table 8.1). Apart from these large patchy catches of squids, it is estimated that the commercial fleet retains around half of the volume of squids that they catch in the trawls when compared with the catches made during the NPF monitoring surveys in the same regions.

Table 8.1. Summary of the dataset sources, date ranges, number of trawls, trawl hours and numbers of animals of each byproduct group from northern Australia used in the catch rate analysis. No. trawls = number of individual trawls, except for the NPF commercial logbook dataset where it refers to trawl effort in days.

Dataset	Project	Date range	No trawls	Trawl hours	Total catch weight (kg)			
					Squid	Cuttlefish	Bugs	Scallops
NPF prawn monitoring surveys	2002 Pre-season survey	Aug 02	169	84.4	28.6	99.0	296.6	536.7
	2003 Pre-season survey	Jan – Mar 03; Jul – Oct 03	844	419.0	134.6	507.4	2779.0	1648.2
	2004 Pre-season survey	Jan – Mar 04; Jul – Oct 03	815	406.6	204.4	657.1	2624.0	1880.3
	2005 Pre-season survey	Feb 05; Jul 05	516	257.2	70.0	430.0	1446.9	1603.7
	2006 Pre-season survey	Jan – Feb 06; Jun – Jul 06	511	256.4	64.4	365.6	1081.8	954.9
	2007 Pre-season survey	Feb 07; Jun – Jul 07	517	258.3	64.0	562.8	1132.1	1450.1
	2008 Pre-season survey	Jan – Feb 08	301	150.9	20.8	340.2	974.0	657.4
CSIRO scientific and	Tropical fish ecology	Aug – Oct 93; Mar – Nov 94	40	10.6	-	-	1	2
observer surveys	Effects of trawl design	Nov 93; Feb – Nov 95	442	370.6	-	-	463.9	341.0
	TED and BRD design	Sep 96 – Jun 98	225	697.0	-	-	299.0	879.3
	Bycatch sustainability	Feb 97 – Oct 98	1073	571.3	170.3	125.0	423.6	504.8
	TED and BRD design	Aug – Nov 01	502	1728.2	-	-	-	49.1

Dataset	Project	Date range	No trawls	Trawl hours	Total catch weight (kg)			
					Squid	Cuttlefish	Bugs	Scallops
	Bycatch monitoring	Sep 03; Apr 04; Apr 05	117	123.5	-	16.8	30.6	34.3
	Effects of trawling	Feb – Mar 05	162	29.0	13.2	24.9	31.8	20.2
NPF commercial logbook	1998 Logbook data	Apr – Dec 98	23428	260617	260062	6255.0	131923.8	26654.5
	1999 Logbook data	Apr – Nov 99	18334	206667	39590	5342.0	69501.6	13434.0
	2000 Logbook data	Apr – Nov 00	16416	185617	37345	4959.5	82672.2	37257.3
	2001 Logbook data	Jan – Nov 01	16687	171575	367218	3107.0	28151.5	6064.3
	2002 Logbook data	Apr – Nov 02	12997	142680	176926	3733.5	35221.0	10452.0
	2003 Logbook data	Mar – Nov 03	12617	142350	5809	4121.2	32908.9	3610.5
	2004 Logbook data	Apr – Dec 04	11778	126865	20417	3654.0	19801.2	2174.8
	2005 Logbook data	Apr – Nov 05	11422	125580	14745	6252.0	26067.0	3425.0
	2006 Logbook data	Apr – Nov 06	10302	86659	4014	504.0	2350.0	154.0
	2007 Logbook data	Apr – Nov 07	7587	71940	174978	3336.0	12213.6	8969.0

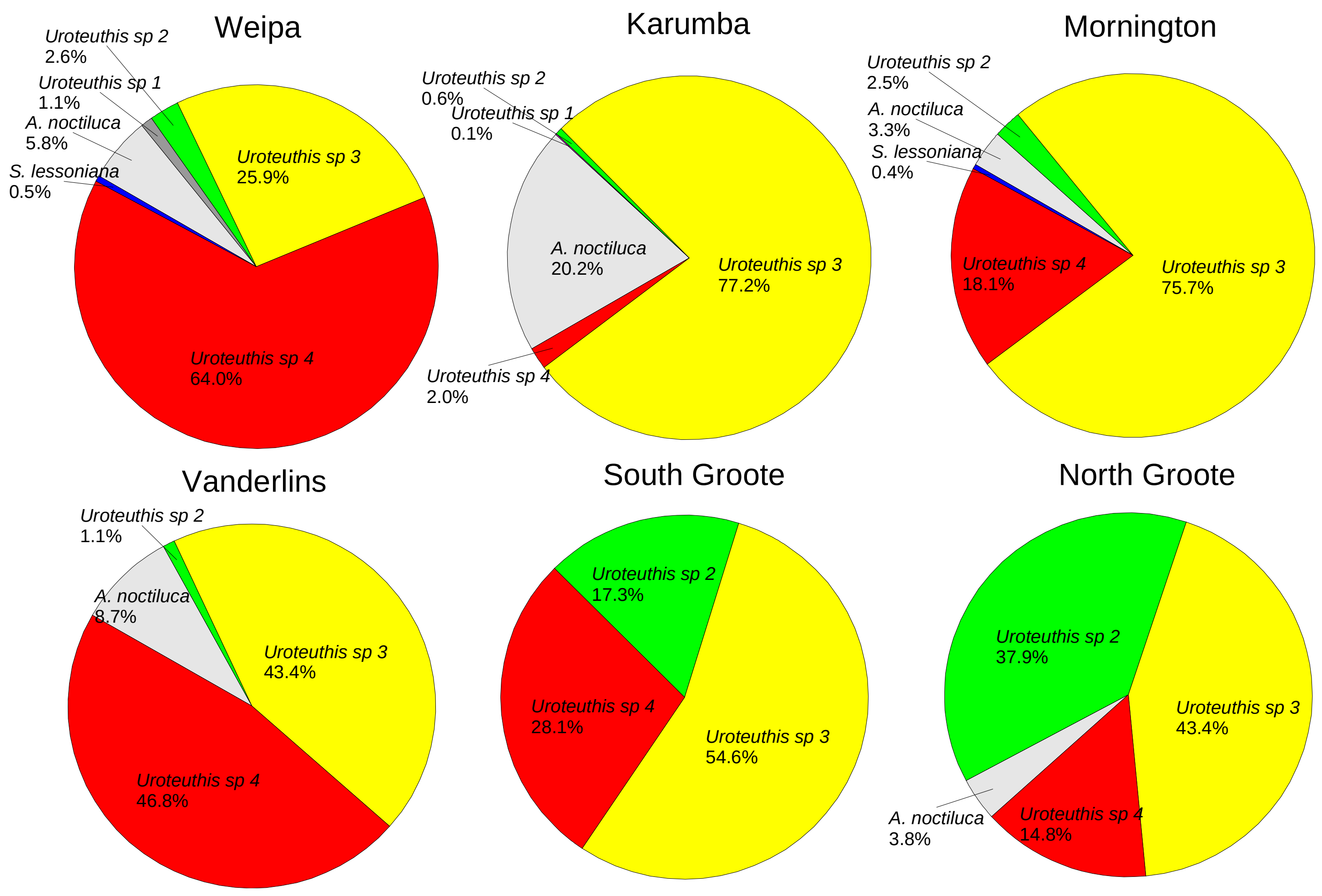


Figure 8.1. Species composition of squid caught in the Gulf of Carpentaria during the NPF prawn monitoring surveys between 2002 and 2008.

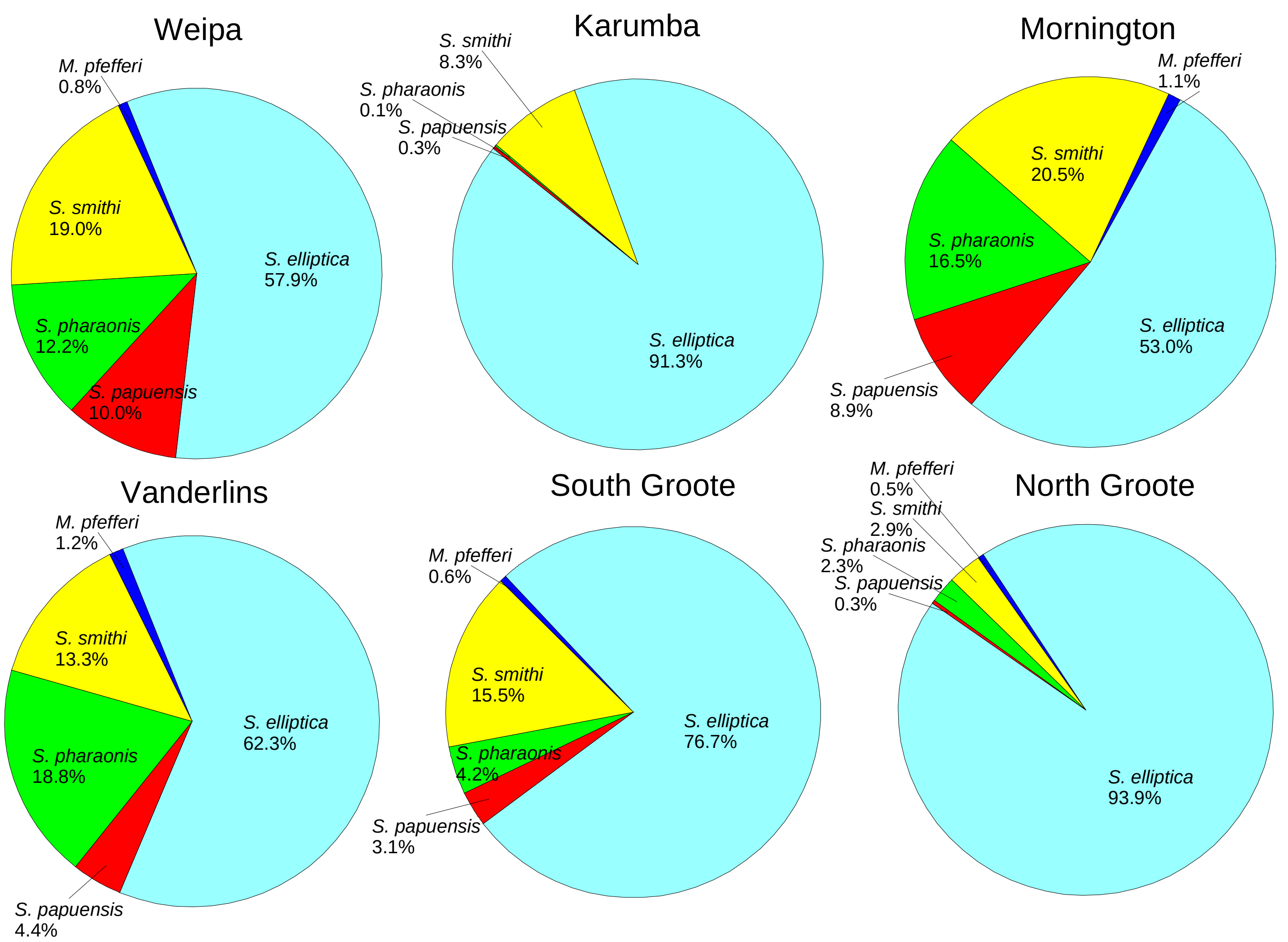


Figure 8.2. Species composition of cuttlefish caught in the Gulf of Carpentaria during the NPF prawn monitoring surveys between 2002 and 2008.

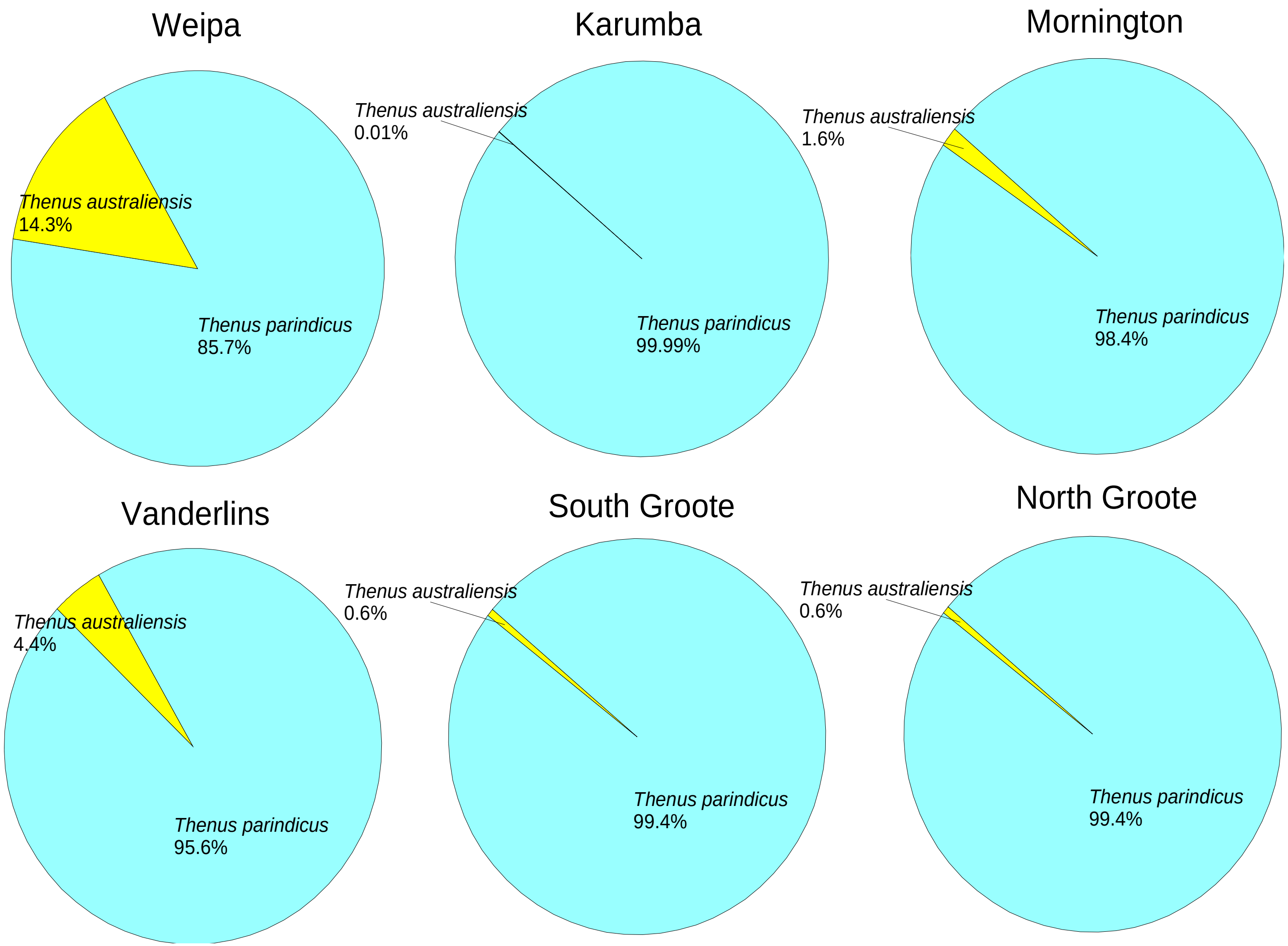


Figure 8.3. Species composition of *Thenus* bugs caught in the Gulf of Carpentaria during the NPF prawn monitoring surveys between 2002 and 2008.

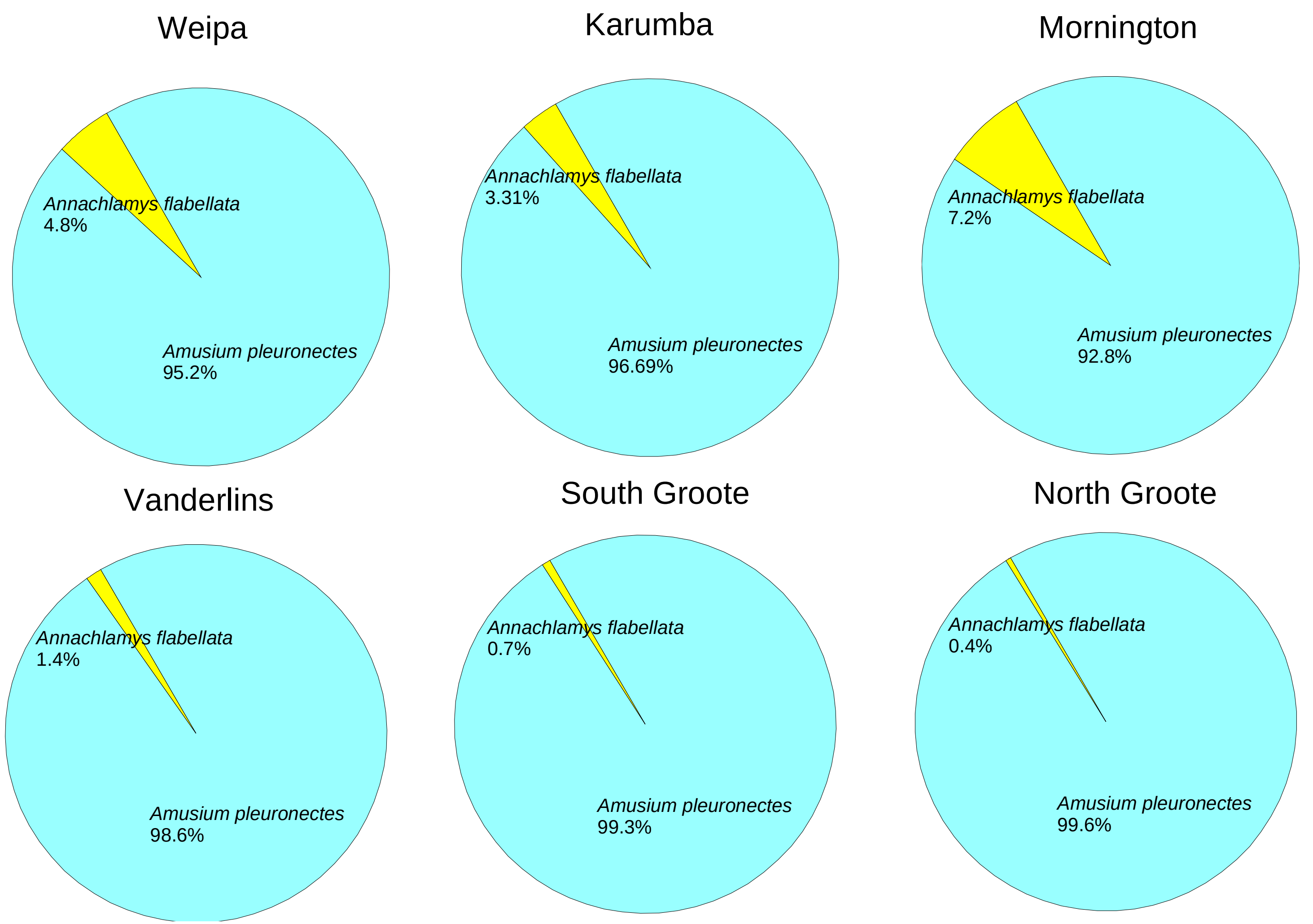


Figure 8.4. Species composition of scallops caught in the Gulf of Carpentaria during the NPF prawn monitoring surveys between 2002 and 2008.

Only the larger-sized cuttlefish were retained, by commercial trawlers, similar to the situation with commercial squid catches. Therefore catch rates from the commercial logbooks were expected to be much lower than from the NPF prawn monitoring surveys (Figure 8.5). The mean retained catch of cuttlefish was less than 1 $g.ha^{-1}$. However, the actual mean catch rates for cuttlefish from NPF commercial trawlers between 1998 and 2007 is likely to be similar to the NPF prawn monitoring survey catches as trawling was done in similar areas and at similar times of the year. From the catches obtained during the NPF prawn monitoring surveys, the commercial fleet appears to retain only about 10% of the weight of cuttlefish caught in trawls (Figure 8.5). The NPF commercial vessels retained only a small proportion of their catch of bugs and scallops (Figure 8.6). The catches of bugs that were retained by the NPF commercial vessels each year has decreased from 1998 to 2007 from about 20 to 10 $g.ha^{-1}$, while the catches of scallops over the same time period have remained relatively stable.

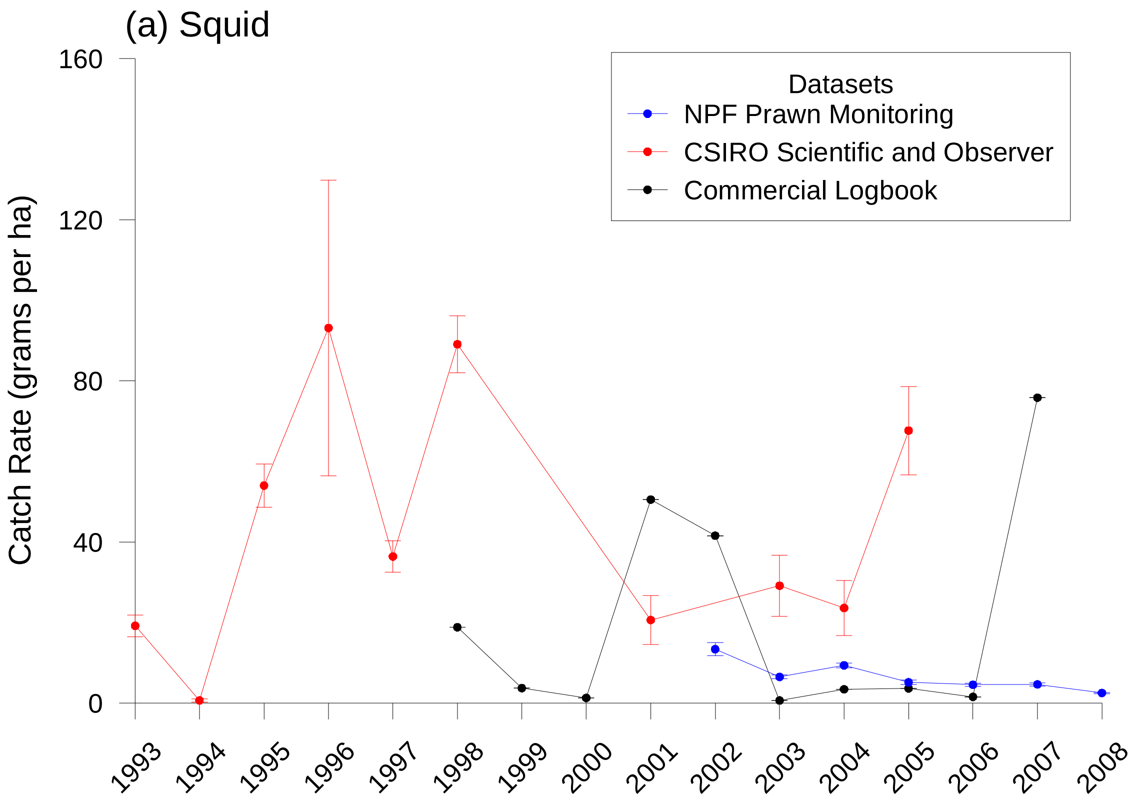
8.4.3 Effects of predictors on byproduct species catches

For each of the three datasets, the effects of the independent variables; RDist, RLand, % mud, % sand and depth (m) and the fixed effects; year and month, on the catch rates (Log CPUE) for each of the byproduct species were estimated with generalised additive models (GAMs).

Squid

Catches of each of the squid species showed distinct annual and seasonal patterns (Figure 8.7 – Figure 8.9). For the NPF prawn monitoring surveys, there were significantly higher catches in the years 2003, 2004 and 2007, 2008; and in the months of February and June to August. There was a similar inter-annual pattern seen in the predicted catches of each squid species from the NPF commercial vessels. Mean catch rates of each squid species retained by commercial vessels had increased slightly in 2002, declined in 2003 and then significantly increased from 2004 to 2007 (Figure 8.10 – Figure 8.12). However, the retained commercial catches of these squid species were much higher in the month of February compared to other months.

The squids were also generally caught at higher rates in the shallower inshore areas of the Gulf. This was especially true for the smaller squid species; *Uroteuthi*s sp 1, *Uroteuthis* sp 2 and *A. noctiluca*, where catches were highest in waters less than 10 m deep and where the substrate was predominately mud. The predicted commercial catches for these three species appeared to be higher in areas where the sediment type was either mostly sand or mostly mud, compared to areas with a mixture of sand and mud substrate (Figure 8.10). For the larger squid species, *Uroteuthis* sp 3 appeared to be more abundant in deeper waters and *Uroteuthis* sp 4 had higher catch rates in areas with sandier substrates (Figure 8.11, Figure 8.12).



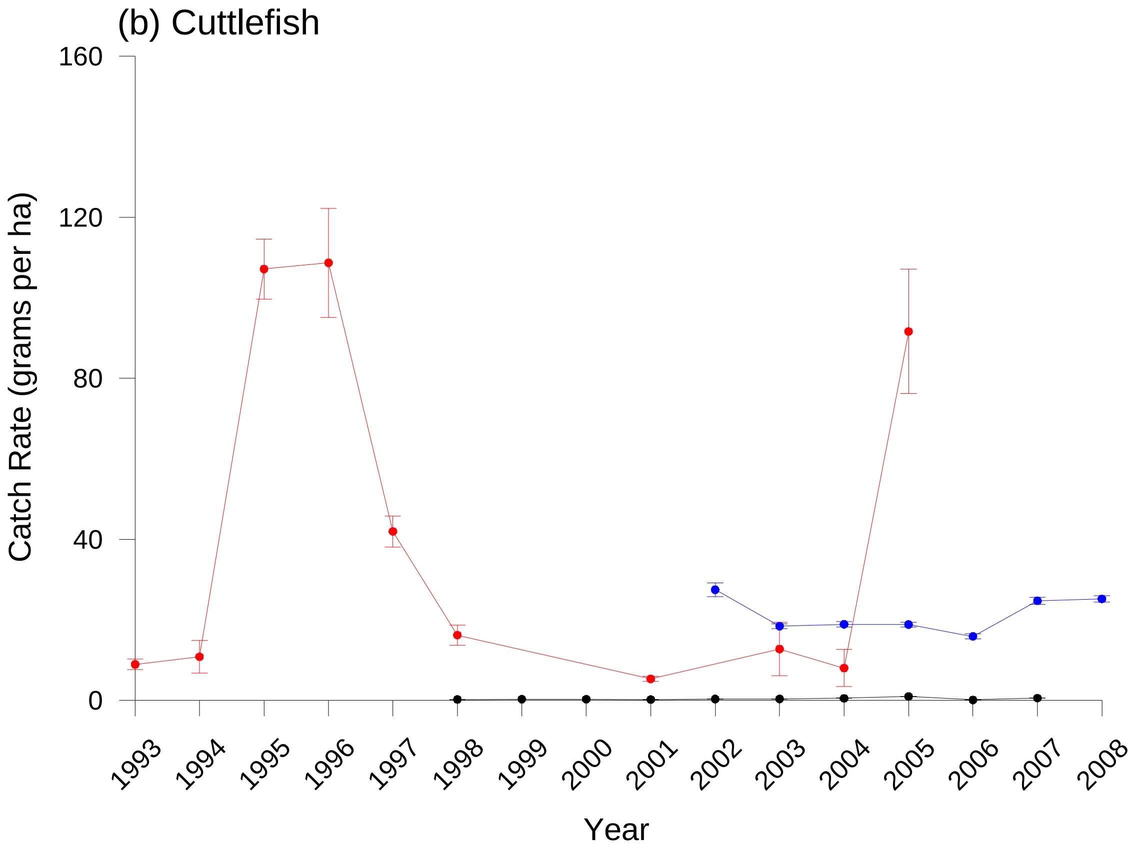


Figure 8.5. Trends in mean catch rates ($g.ha^{-1}$ ± SE) of (a) squid and (b) cuttlefish caught in the Gulf of Carpentaria.

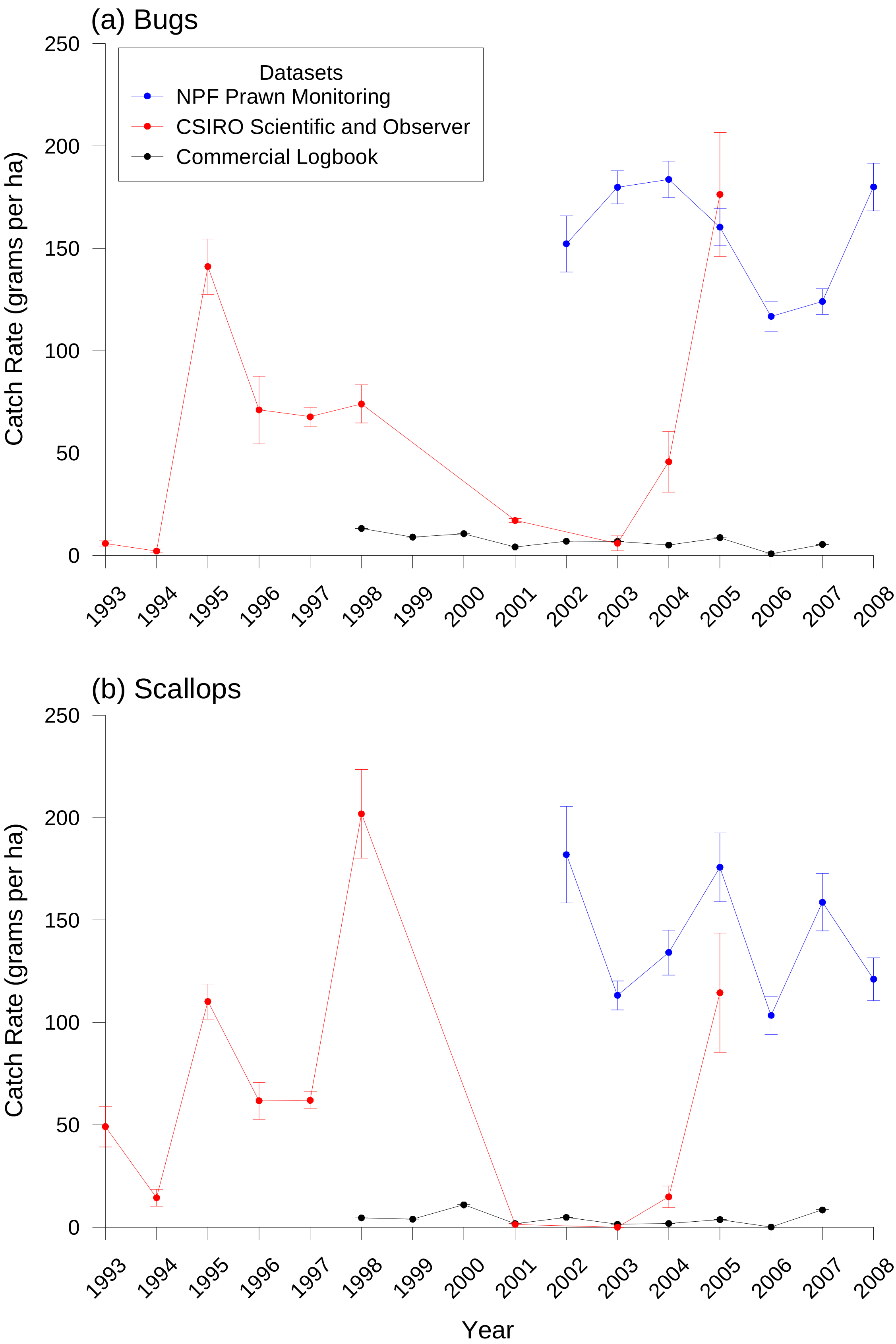


Figure 8.6. Trends in mean catch rates (g.ha^{-1} ± SE) of (a) *Thenus* bugs and (b) scallops caught in the Gulf of Carpentaria.

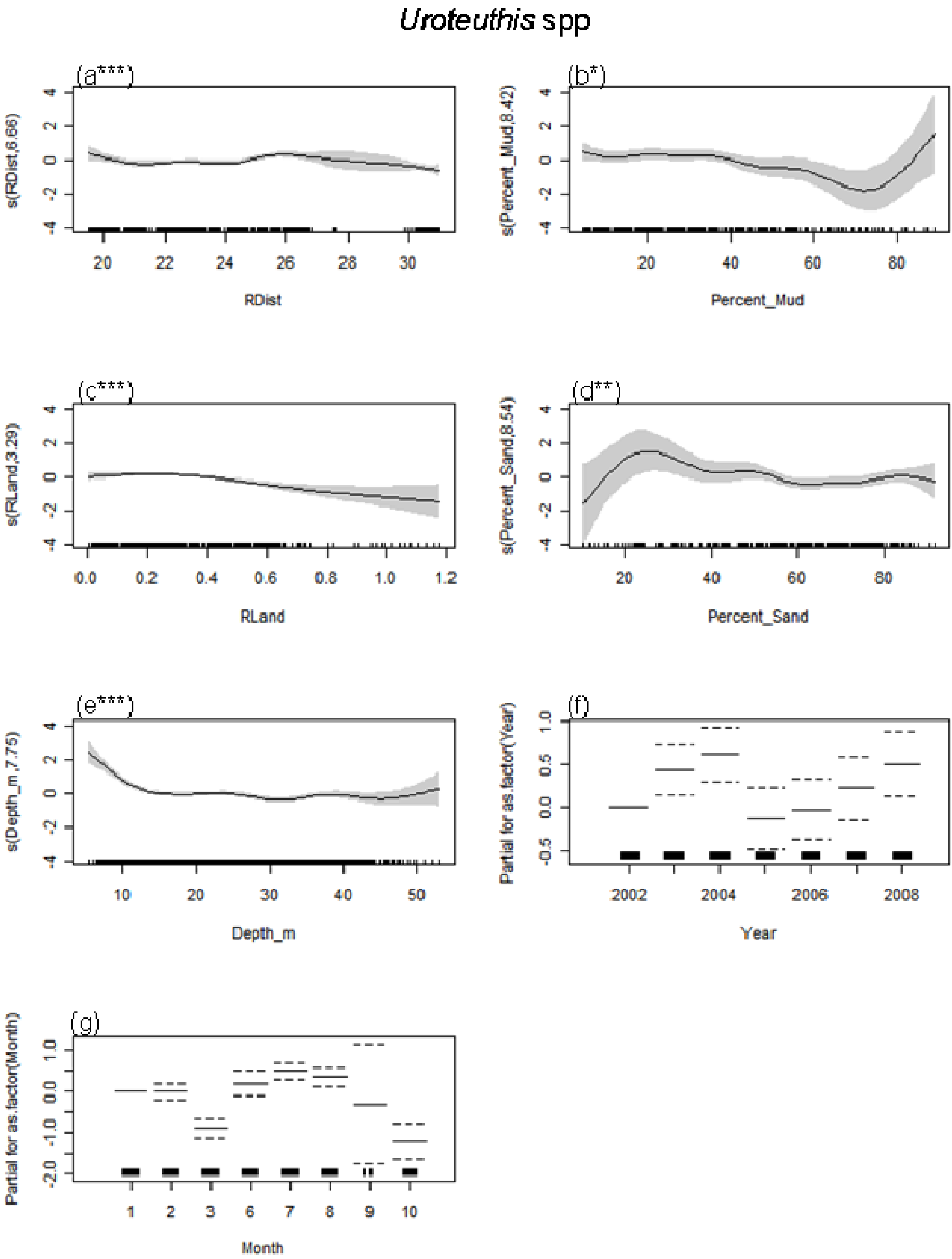


Figure 8.7. Adjusted mean squid *Uroteuthis* spp catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

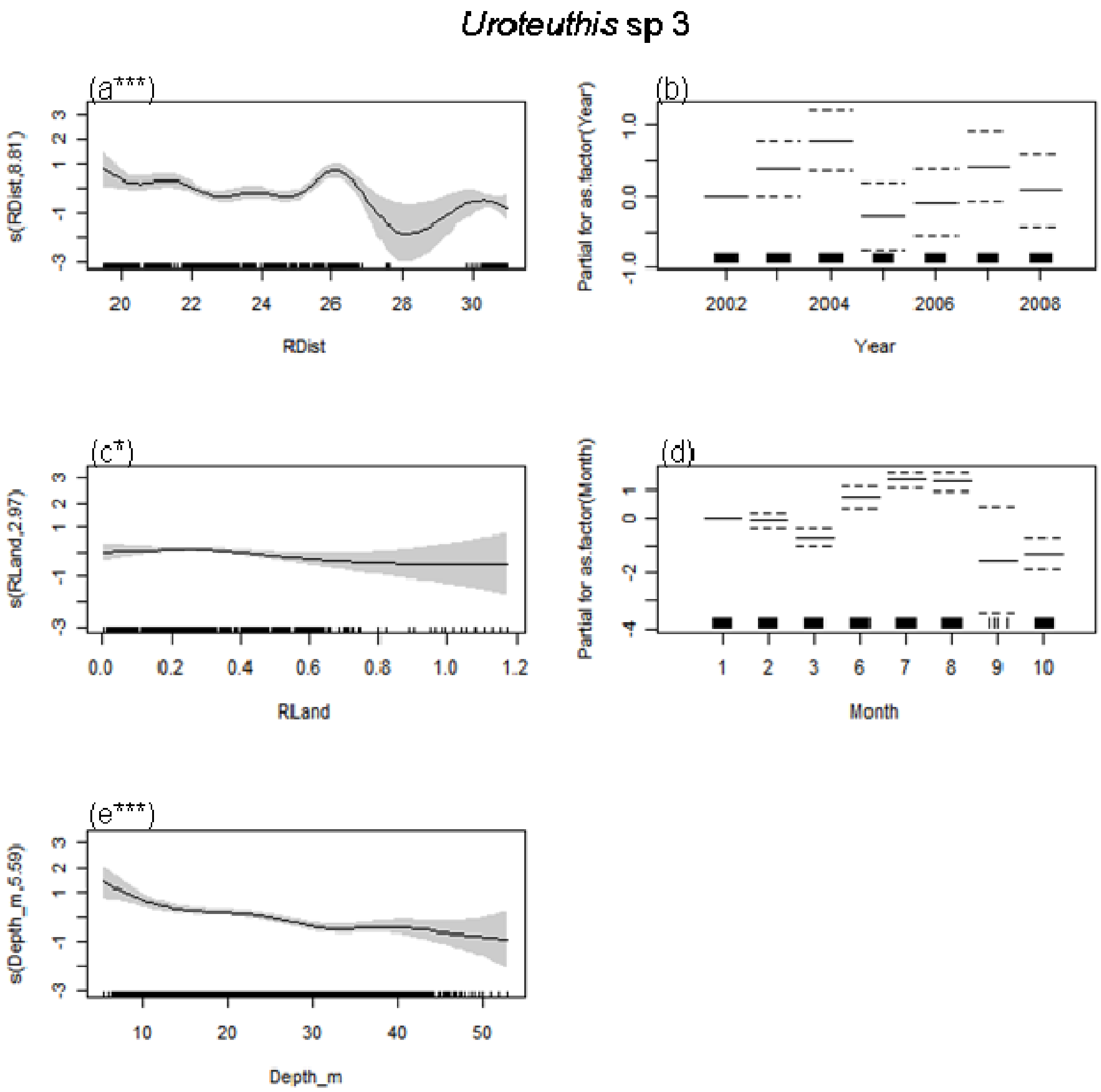


Figure 8.8. Adjusted mean squid *Uroteuthis* sp 3 catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

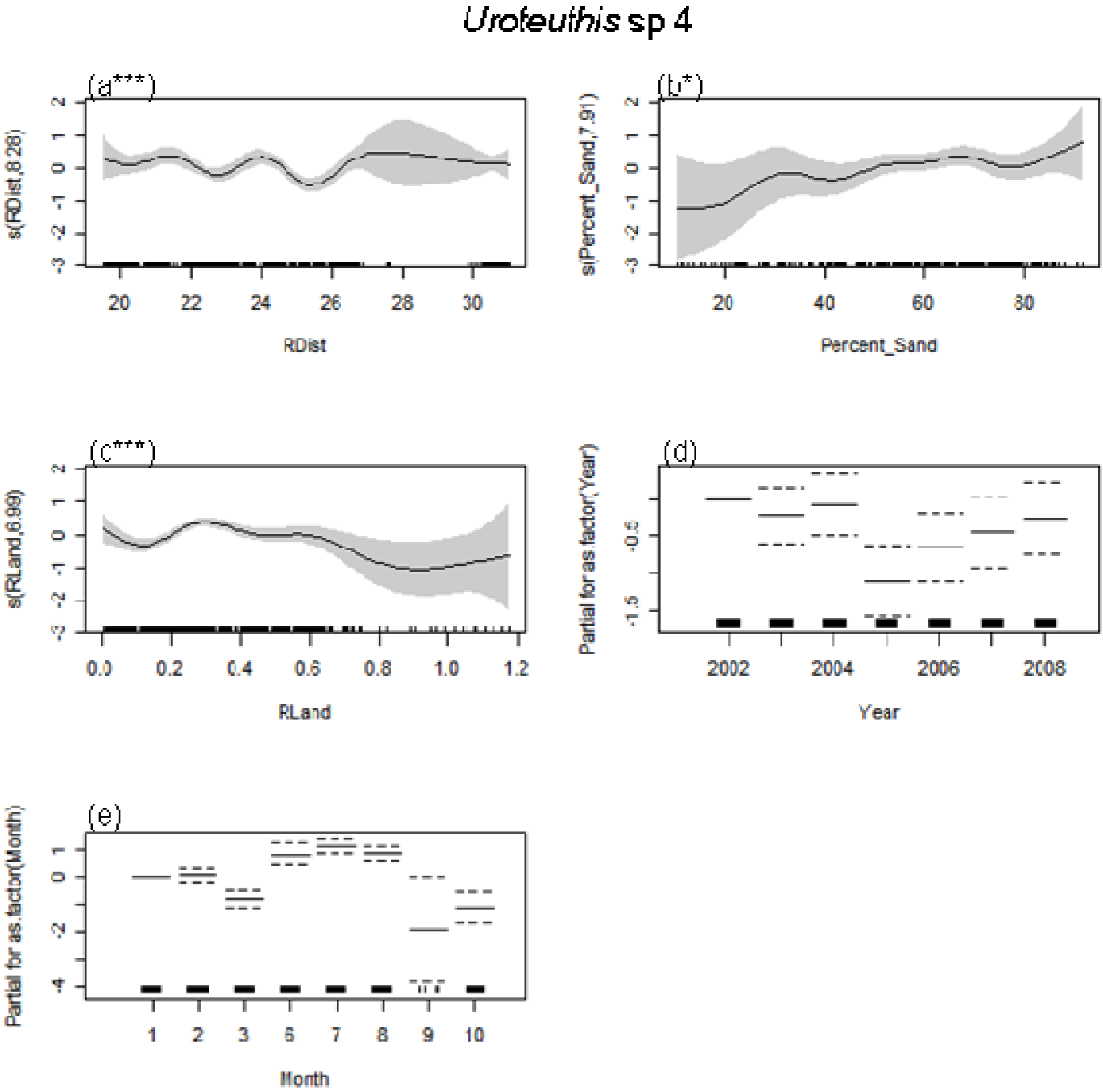


Figure 8.9. Adjusted mean squid *Uroteuthis* sp 4 catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

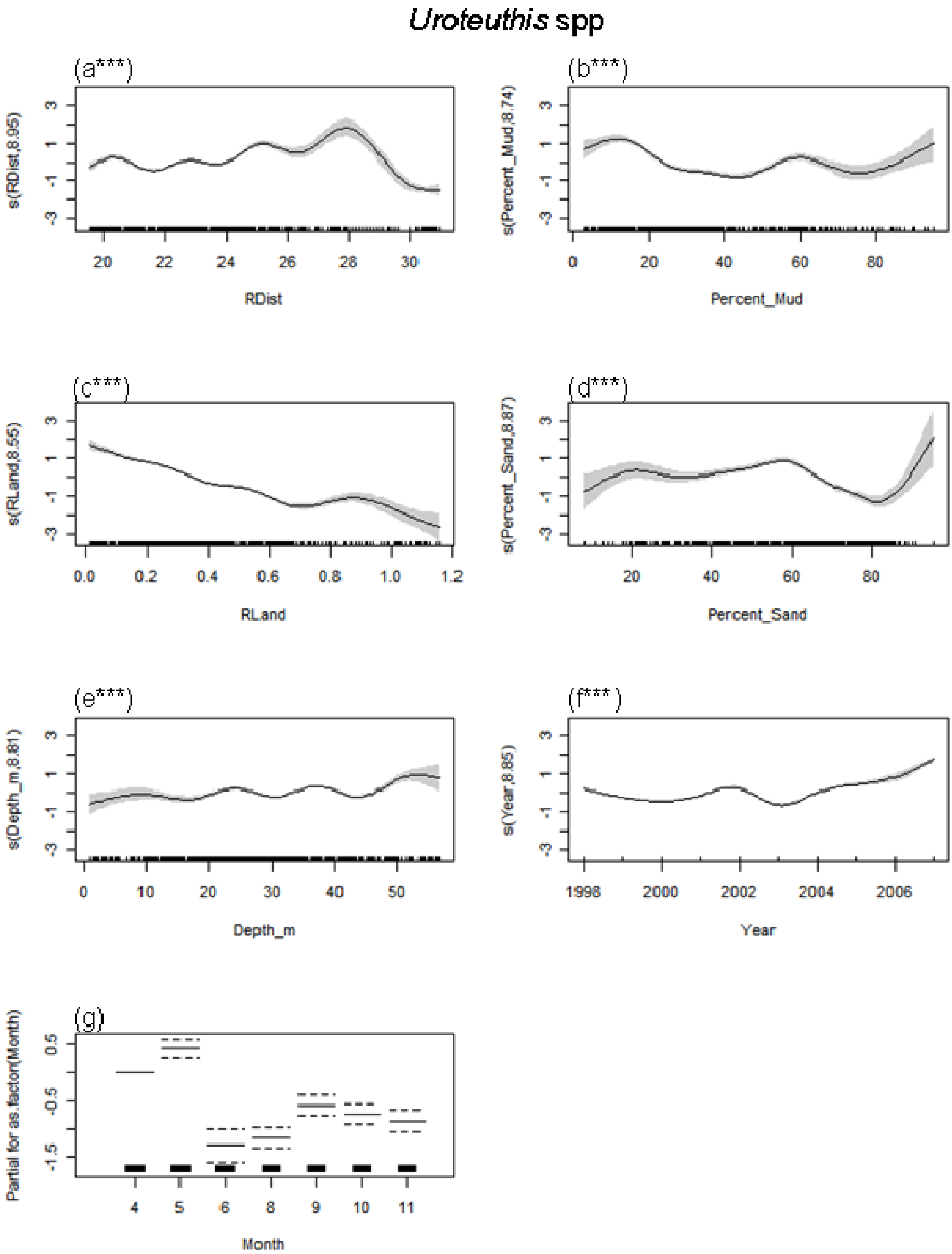


Figure 8.10. Adjusted mean squid *Uroteuthis* spp catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

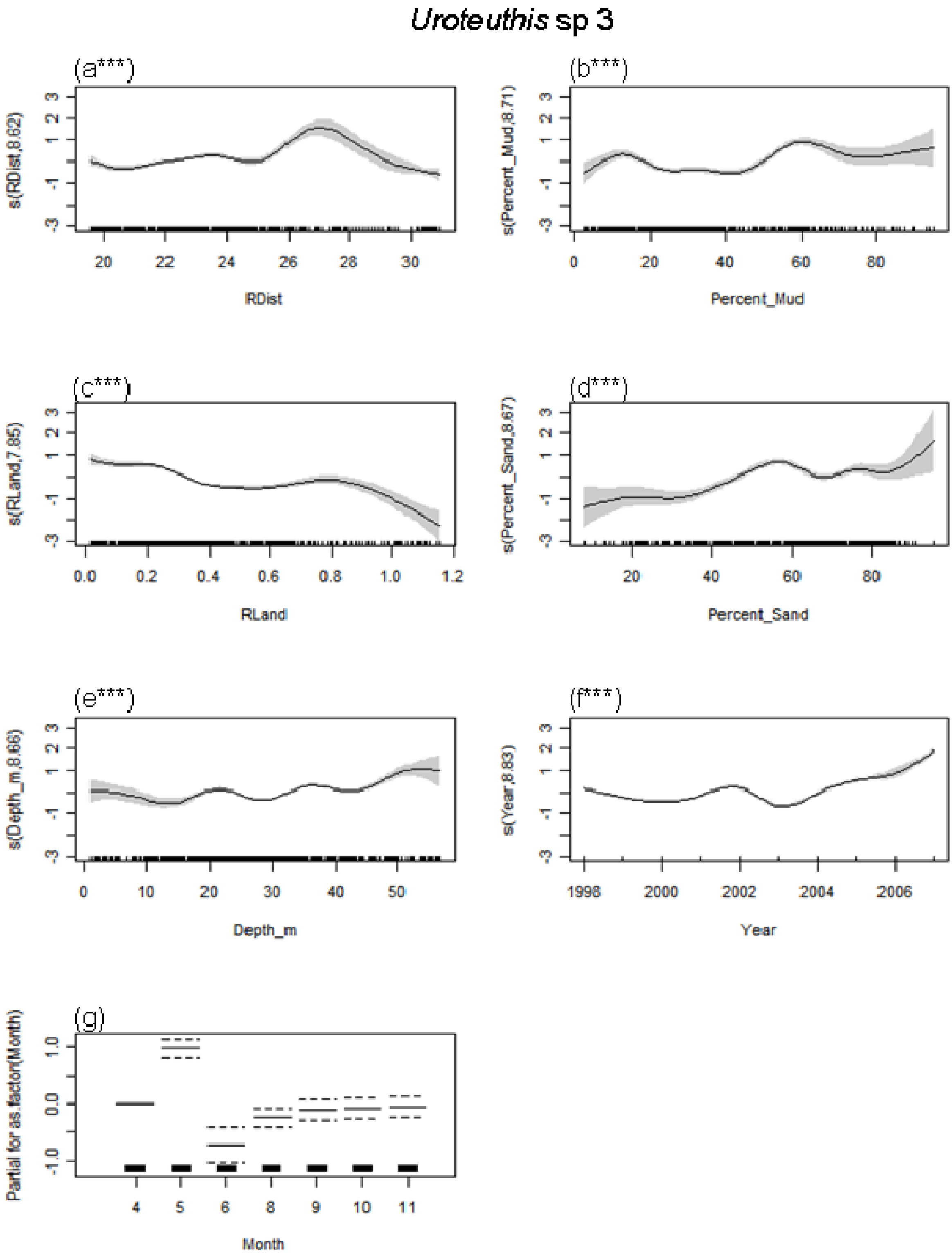


Figure 8.11. Adjusted mean squid *Uroteuthis* sp 3 catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

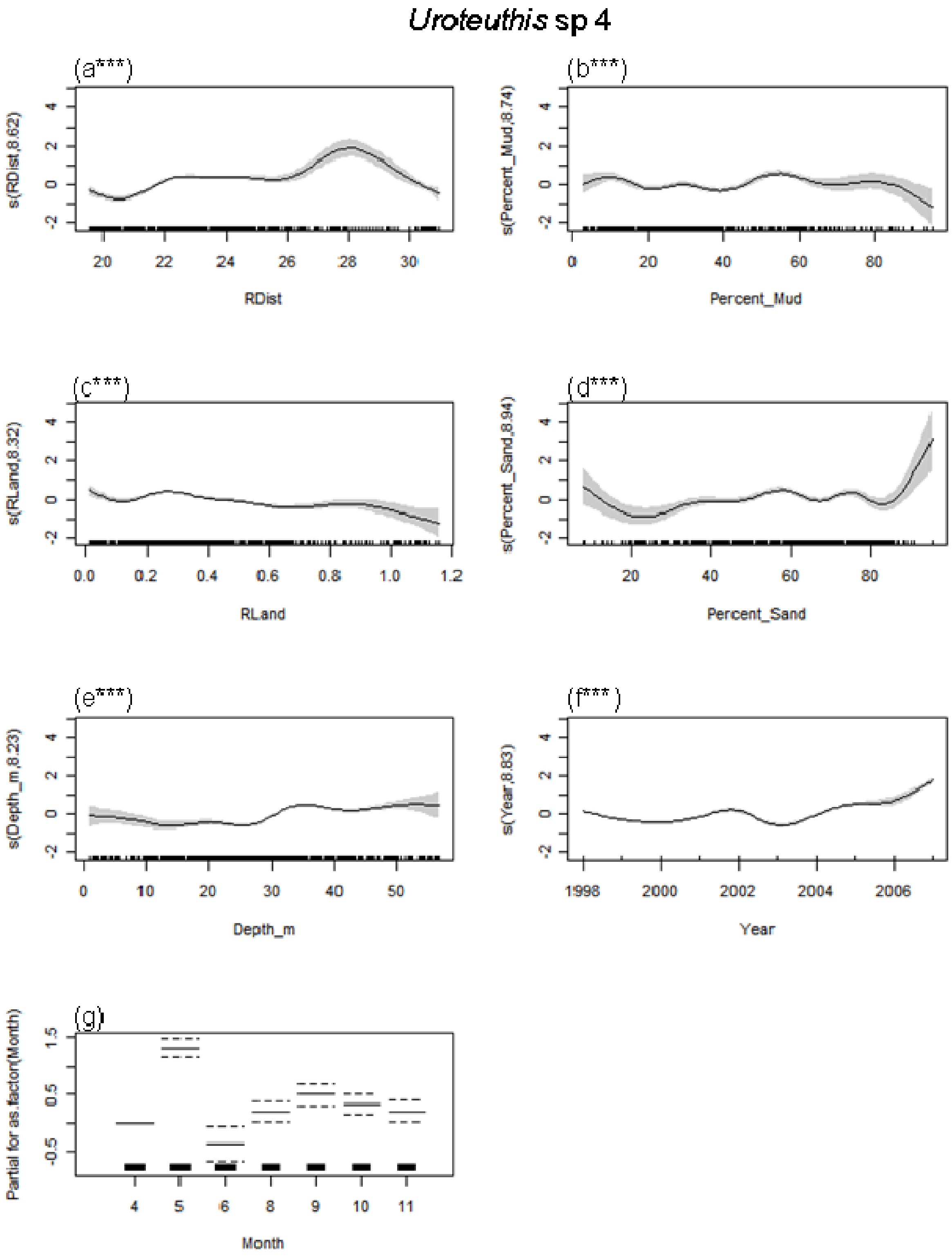


Figure 8.12. Adjusted mean squid *Uroteuthis* sp 4 catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

The analysis of the NPF prawn monitoring surveys found that catch rates of the *Uroteuthis* spp group (*A. noctiluca*, *Uroteuthis* sp 1, *Uroteuthis* sp 2) and *Uroteuthis* sp 4 were similar throughout most of the coastal Gulf region; from Groote Eylandt to Weipa (Figure 8.7, Figure 8.9). The mean catch rate of *Uroteuthis* sp 3 was significantly lower around the north eastern side of the Gulf (Weipa) (Figure 8.8). However, there were no trawls recorded from the south eastern region from the area north of Karumba to south of Weipa (Figure 8.8). From the NPF commercial logbook data, catch rates for each of the squid species were markedly higher around the Mornington to Karumba region compared to other regions within the Gulf (RDist between 26 and 29). Although there was a distinct relationship with higher commercial mean catches in waters closer to the coastline (RLand between 0.0 and 0.6), the predicted catches in the deepest waters trawled were also high but variable (Figure 8.10 – Figure 8.12).

Cuttlefish

Most cuttlefish species caught during the NPF prawn monitoring surveys showed a steady increase in catches from 2002 to 2007 followed by a considerable increase in the 2008 survey. However, *S. smithi* showed a significant decrease in catches in 2008 compared to other years. The most common species, *Sepia elliptica*, had similar catch rates across most years of the surveys. All five species also showed a general trend of similar catches in most months with a significant decline in March. However, the abundance of *S. smithi* was significantly lower in both March and October than other months (Figure 8.13 – Figure 8.17). The annual and monthly catch rates from the CSIRO scientific and observer surveys in the Gulf from 1997 to 2005 have been relatively stable for most species of cuttlefish (Figure 8.18 – Figure 8.21). The predicted annual catch of each species of cuttlefish from the commercial vessels has also been relatively stable from 1998 to 2007 (Figure 8.22 – Figure 8.26). However, there are significant differences in the commercial landing of cuttlefish across months with lowest catches in April, steadily increasing through the year to a high in November.

There was no clear correlation with cuttlefish abundance and environmental effects for most species of cuttlefish caught during the NPF prawn monitoring surveys and CSIRO scientific and observer surveys. Most of the cuttlefish species (*S. elliptica*, *S. papuensis*, *S. smithi* and *Metasepia pfefferi*) generally had slightly higher abundances when substrates were low in sand composition (< 40% sand), but also had lower abundances when mud was high (> 60%) (Figure 8.13, Figure 8.14, Figure 8.16, Figure 8.18, Figure 8.19, Figure 8.21). Greater quantities of most cuttlefish species were retained by the NPF commercial fishery from areas where substrates comprised a mixture of sand and mud rather than predominantly one type or another (Figure 8.22 – Figure 8.26).

Catches of all five species of cuttlefish were significantly lower around Weipa compared to the other five regions sampled during the NPF prawn monitoring surveys (Figure 8.13 – Figure 8.17). Also, *Metasepia pfefferi* did show slightly higher catch rates around the Vanderlins and Mornington than the western side of the Gulf of Carpentaria (Groote Eylandt). From the CSIRO scientific and observer survey data, most cuttlefish species showed no significant difference in catches among any of the regions within the Gulf of Carpentaria. However, mean catch rates for two species, *S. pharaonis* and *S. smithi*, did show slightly higher catches along the eastern side of the Gulf of Carpentaria (Figure 8.20, Figure 8.21). The retained catch of cuttlefish from the NPF commercial fishery was also similar between most regions of the Gulf. Although there appeared to be distinctly higher catches predicted from around the Karumba region (Figure 8.22 – Figure 8.26). This was due to a small number of logbook records where larger volumes of cuttlefish were retained by the commercial vessels in this region compared to elsewhere.

There were depth preferences for most of the cuttlefish species caught during the NPF prawn monitoring surveys and the CSIRO scientific and observer surveys. *Sepia elliptica* and *S. smithi* were both more abundant further offshore, between 25 and 40 m depth (Figure 8.13, Figure 8.16, Figure 8.18). However, they were both also abundant in very shallow coastal waters, less than 10 m deep (Figure 8.13, Figure 8.16). This pattern was also found for *S. elliptica* from NPF commercial logbook records where highest catch rates were from either shallow coastal waters (< 15 m deep) or in the 40 – 50 m depth range (Figure 8.22). However for *S. smithi*, highest catches were predicted within the 10 – 20 m depth range, with catches declining with increasing depth (Figure 8.25). From the NPF prawn monitoring surveys, the other three cuttlefish species (*Sepia papuensis*, *S. pharaonis* and *Metasepia pfefferi*) showed distinct depth preferences where catch rates significantly increased with depth and distance from shore (Figure 8.14, Figure 8.15, Figure 8.17, Figure 8.19, Figure 8.20). The NPF commercial logbook data showed highest catches for these three species were also in the deep offshore waters 20 – 50 m, except for *M. pfefferi* where catch rates increased with depth but declined with distance from shore (Figure 8.26).

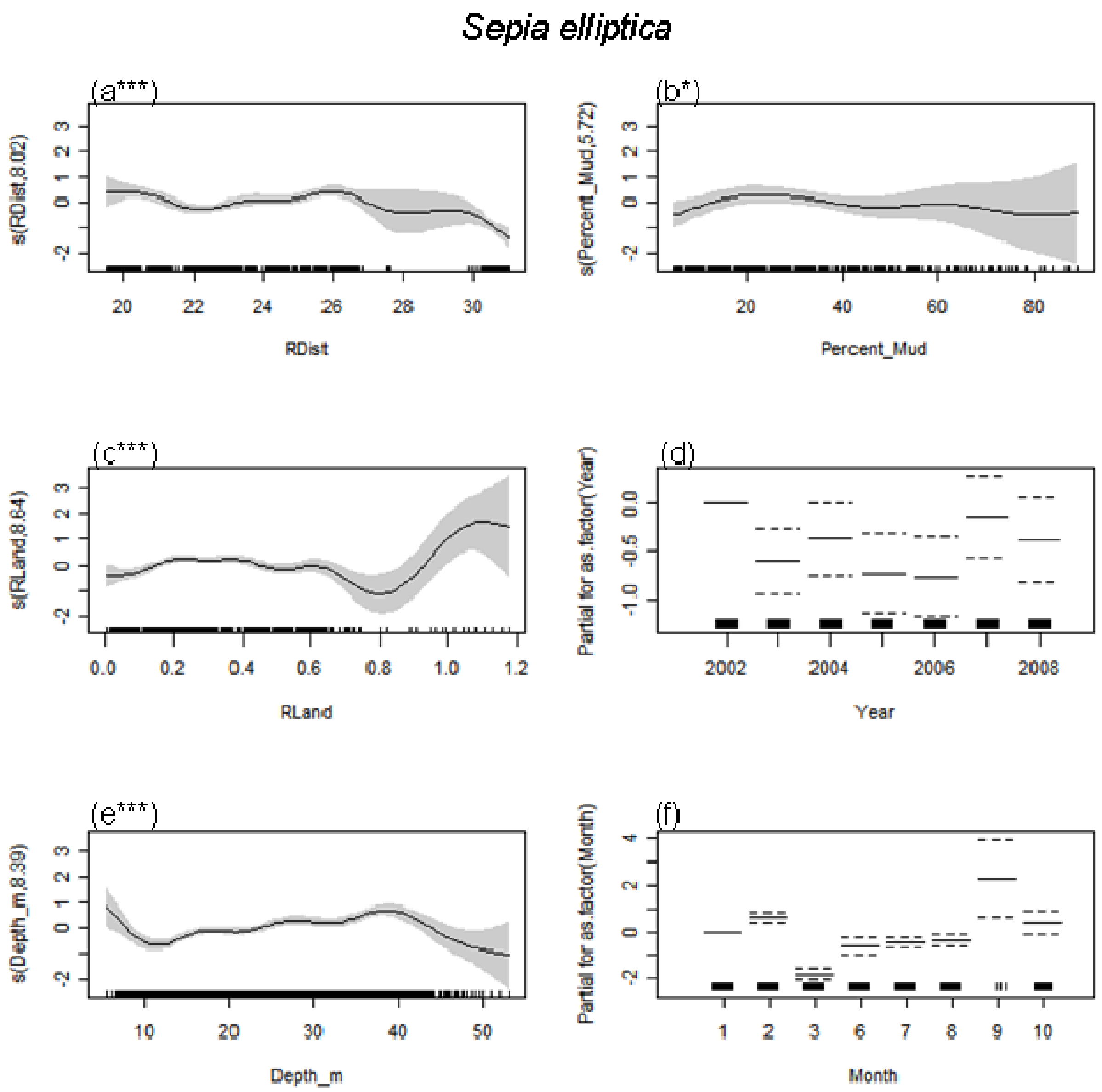


Figure 8.13. Adjusted mean cuttlefish *Sepia elliptica* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence intervals of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

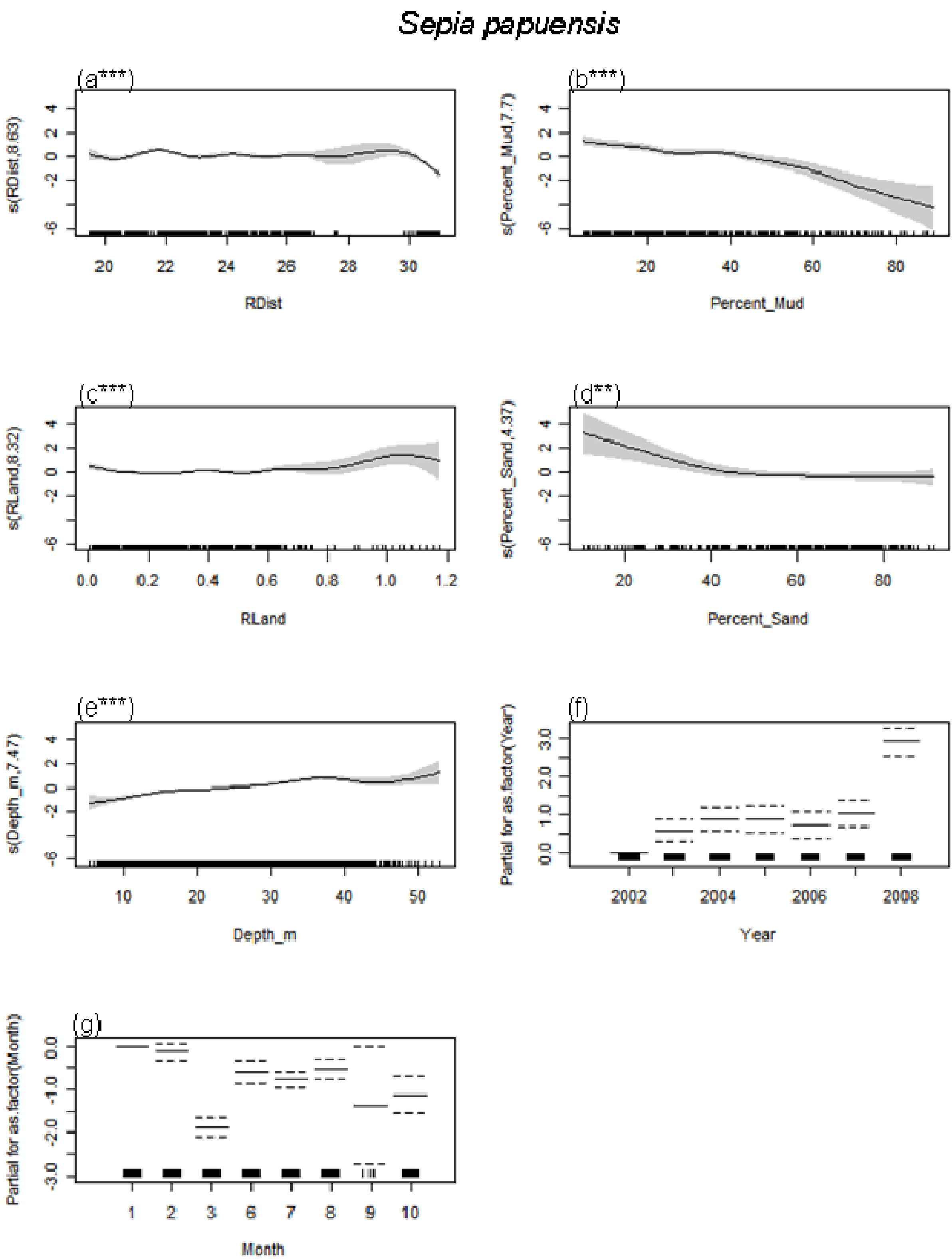


Figure 8.14. Adjusted mean cuttlefish *Sepia papuensis* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence intervals of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

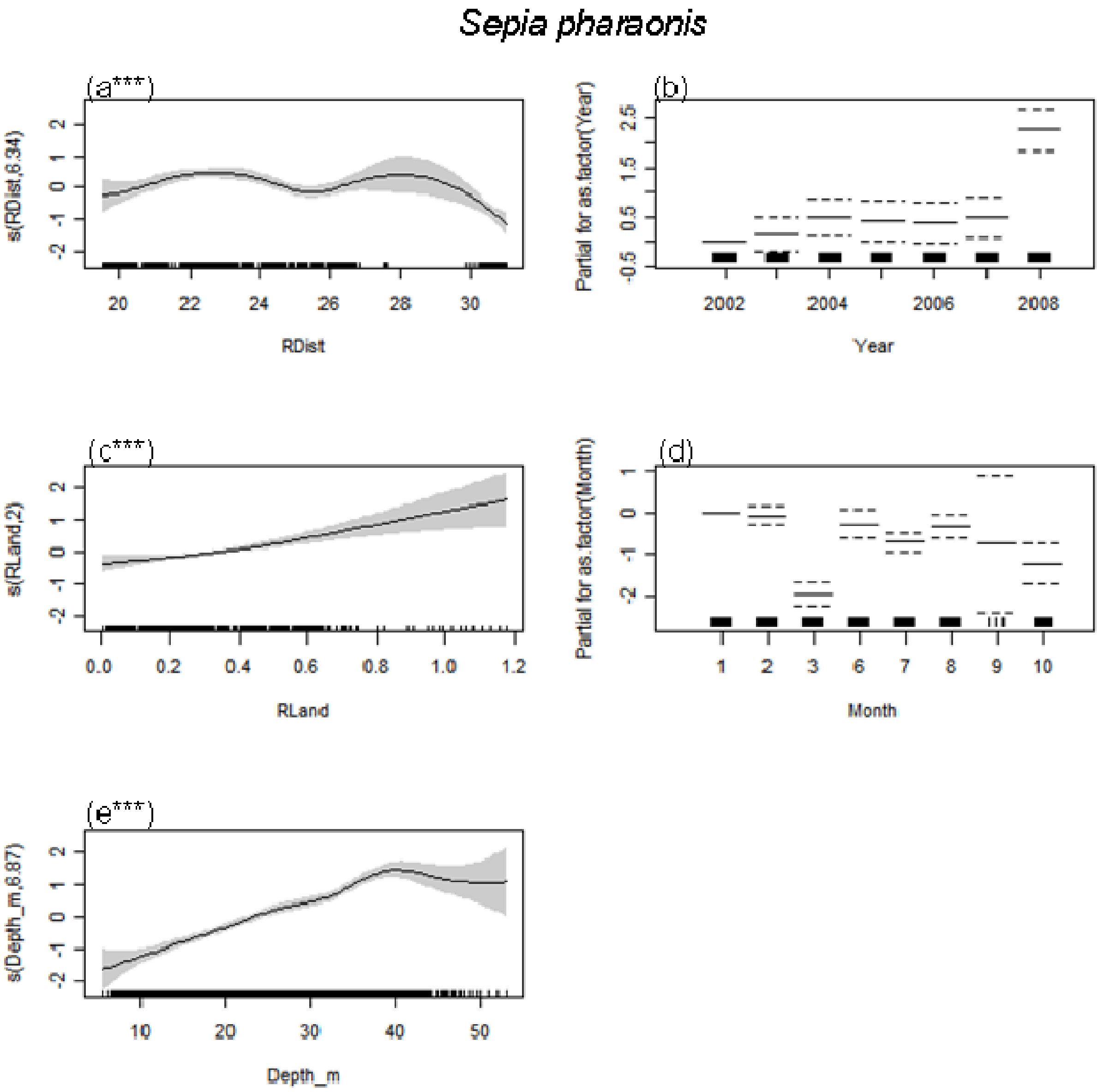


Figure 8.15. Adjusted mean cuttlefish *Sepia pharaonis* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence intervals of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

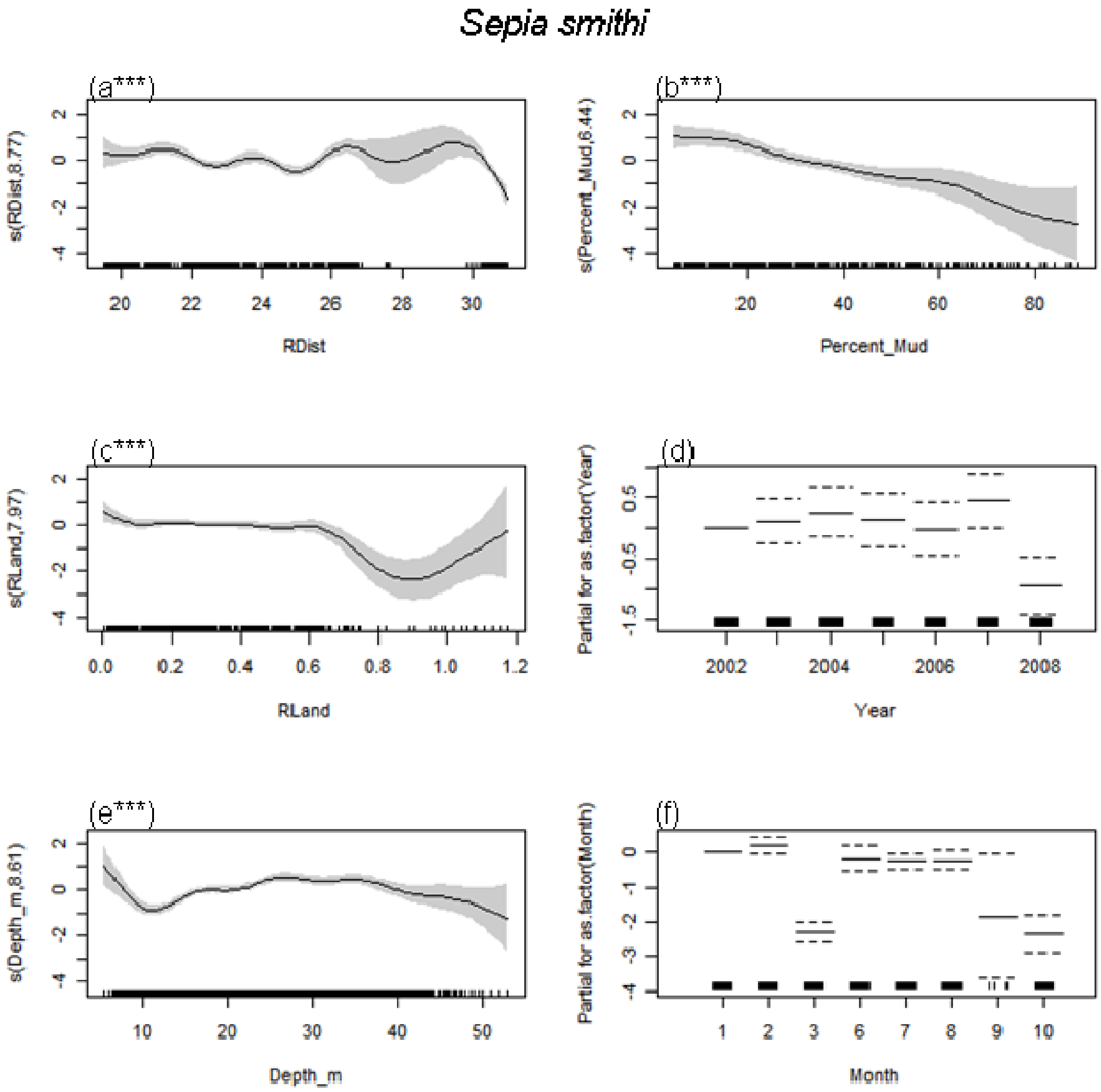


Figure 8.16. Adjusted mean cuttlefish *Sepia smithi* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence intervals of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

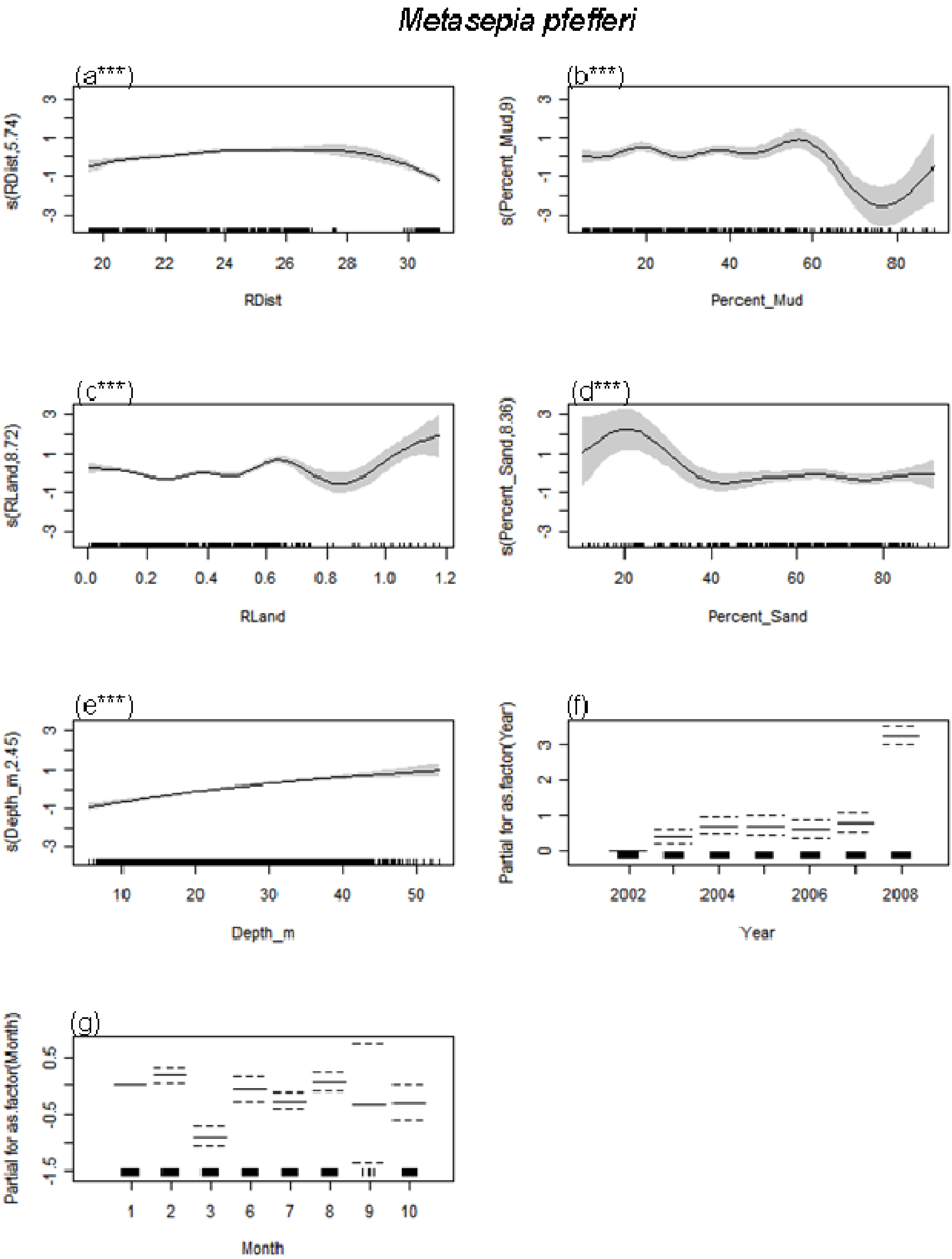


Figure 8.17. Adjusted mean cuttlefish *Metasepia pfefferi* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence intervals of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

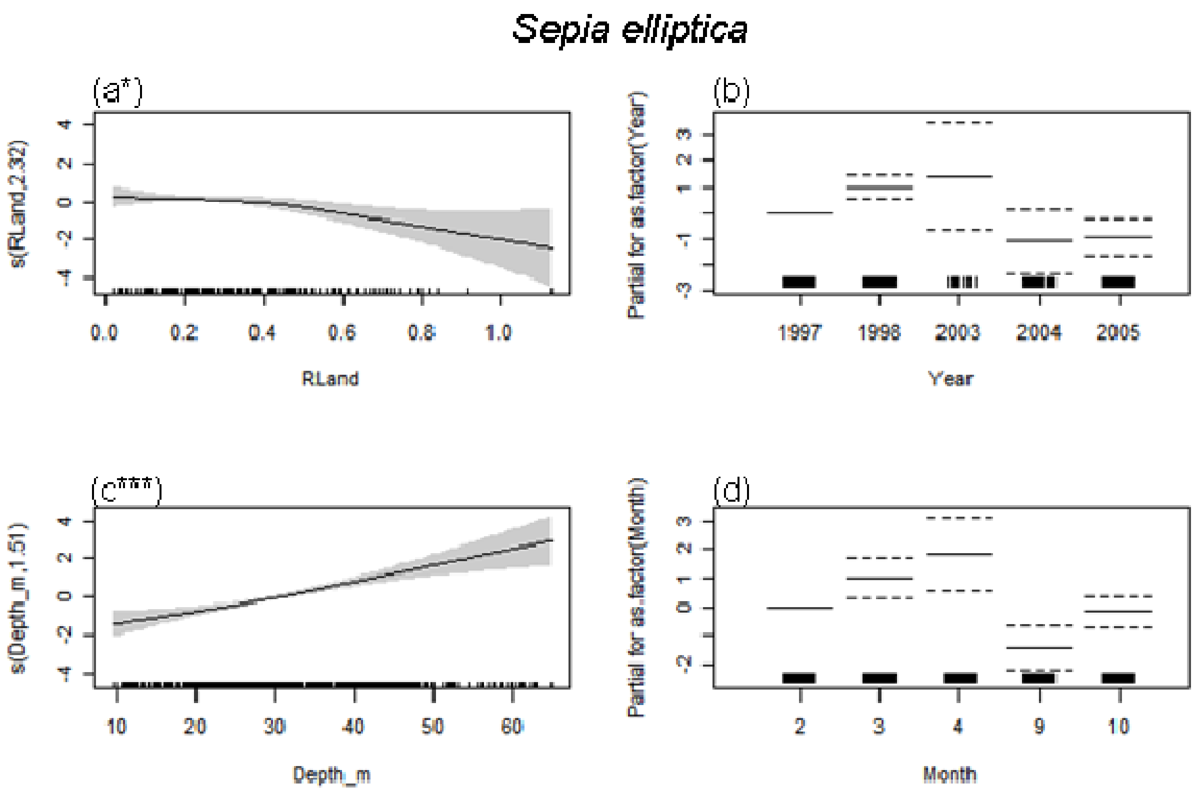


Figure 8.18. Adjusted mean cuttlefish *Sepia elliptica* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria. (Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

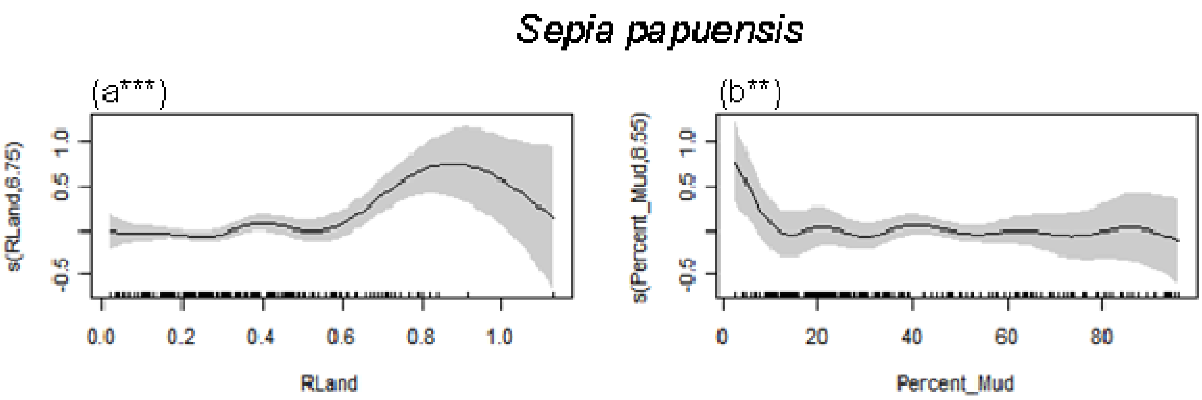


Figure 8.19. Adjusted mean cuttlefish *Sepia papuensis* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria. (Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

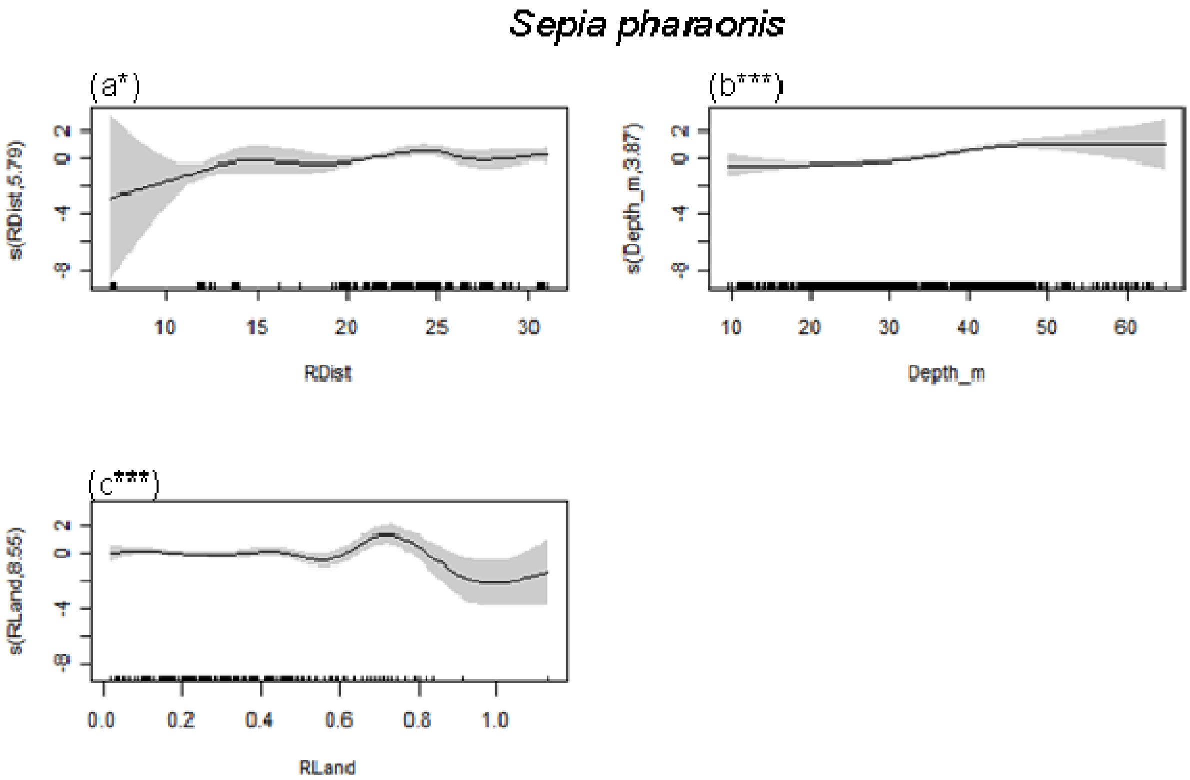


Figure 8.20. Adjusted mean cuttlefish *Sepia pharaonis* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

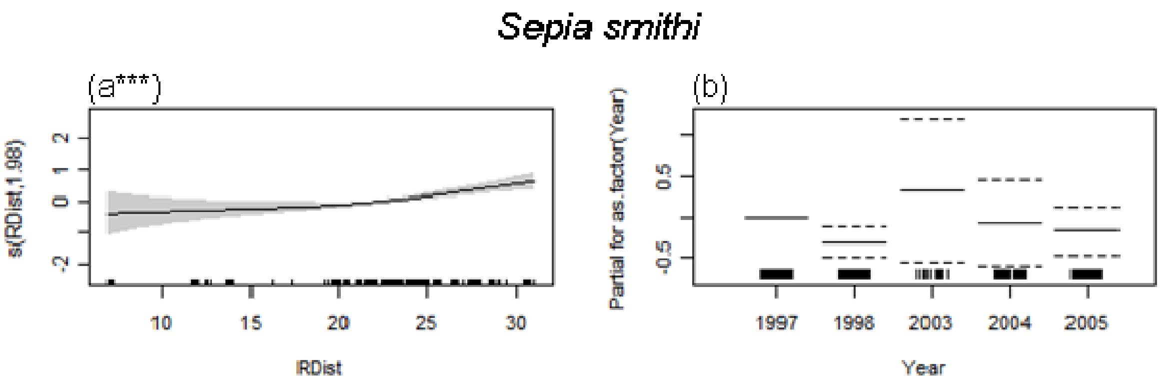


Figure 8.21. Adjusted mean cuttlefish *Sepia smithi* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

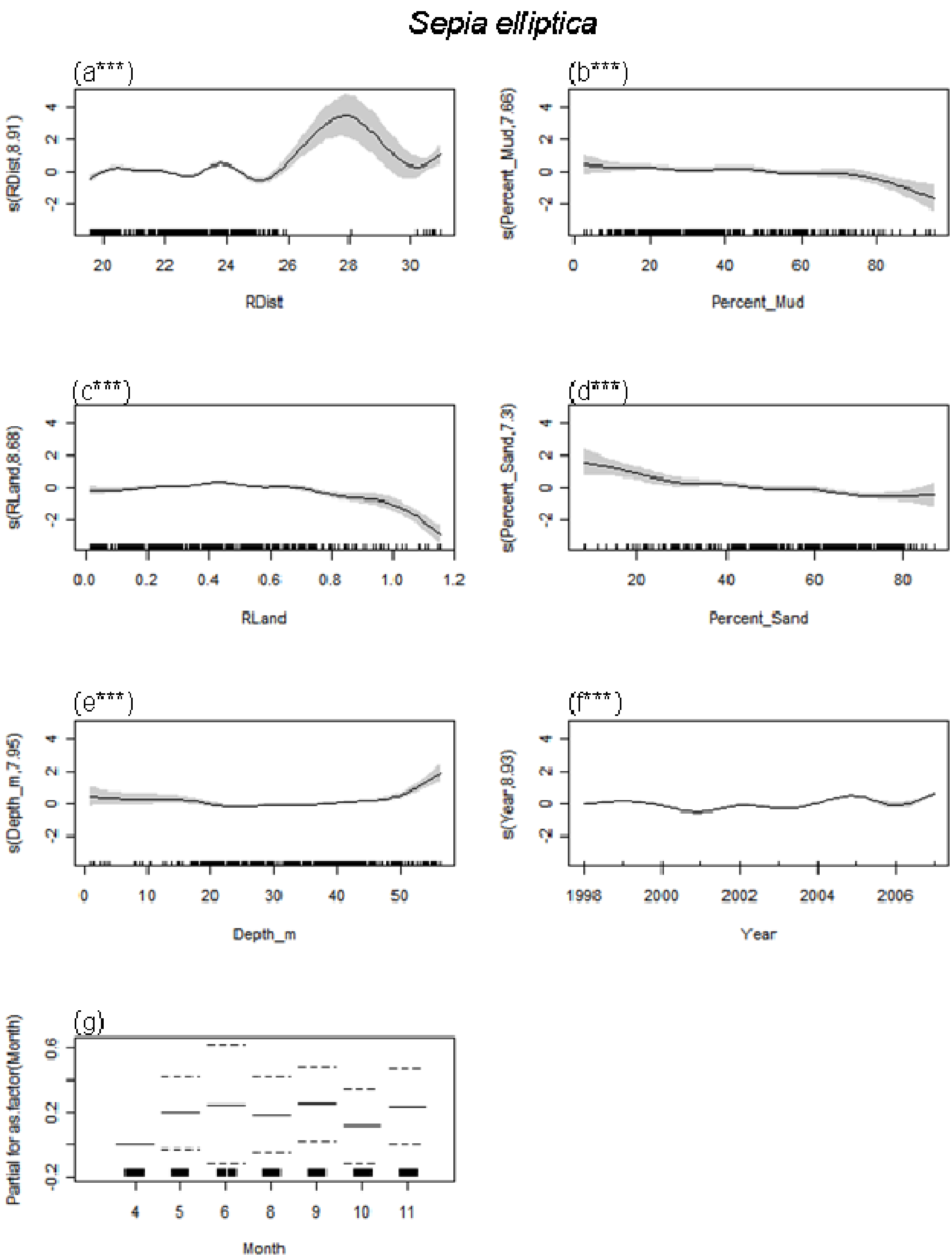


Figure 8.22. Adjusted mean cuttlefish *Sepia elliptica* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

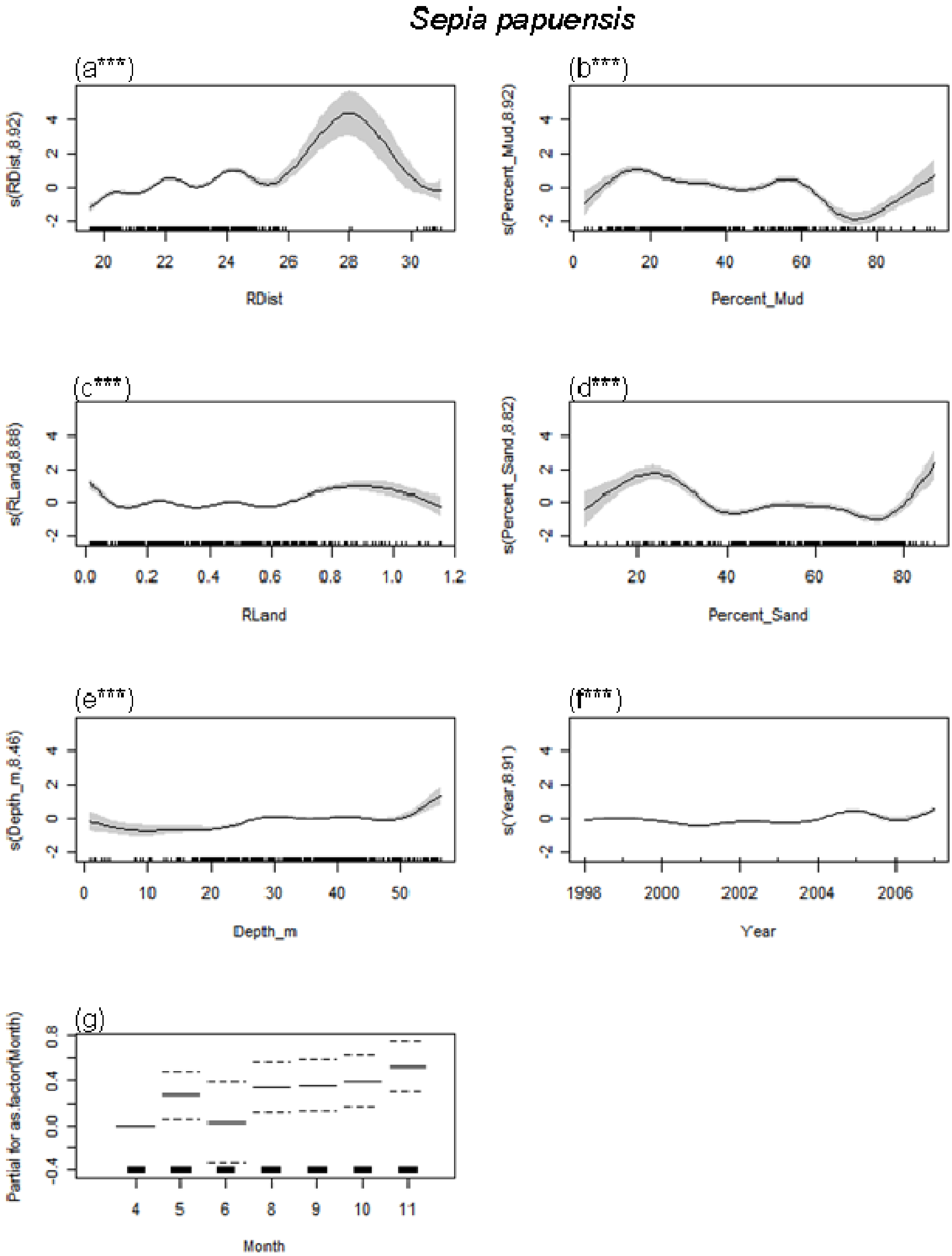


Figure 8.23. Adjusted mean cuttlefish *Sepia papuensis* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

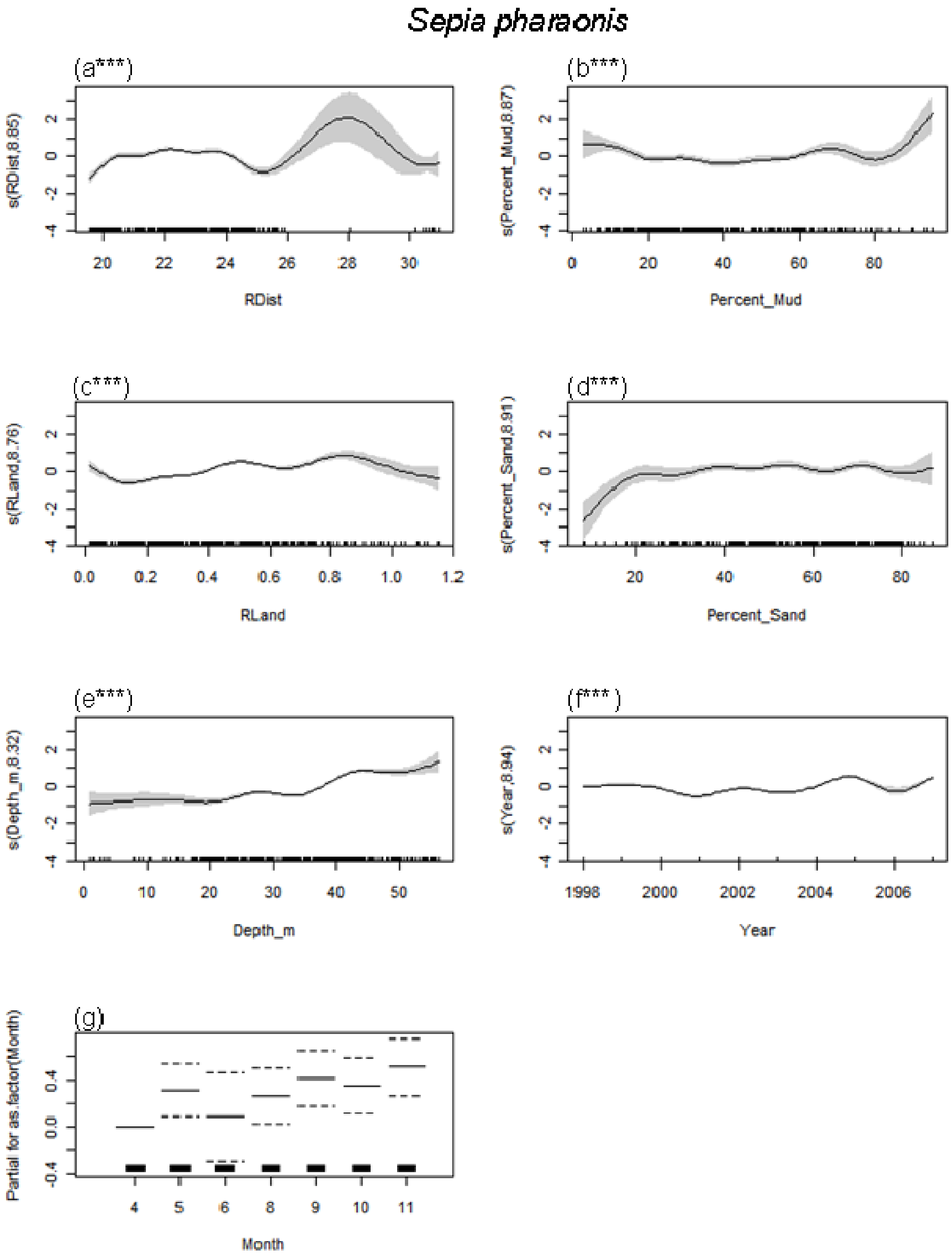


Figure 8.24. Adjusted mean cuttlefish *Sepia pharaonis* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

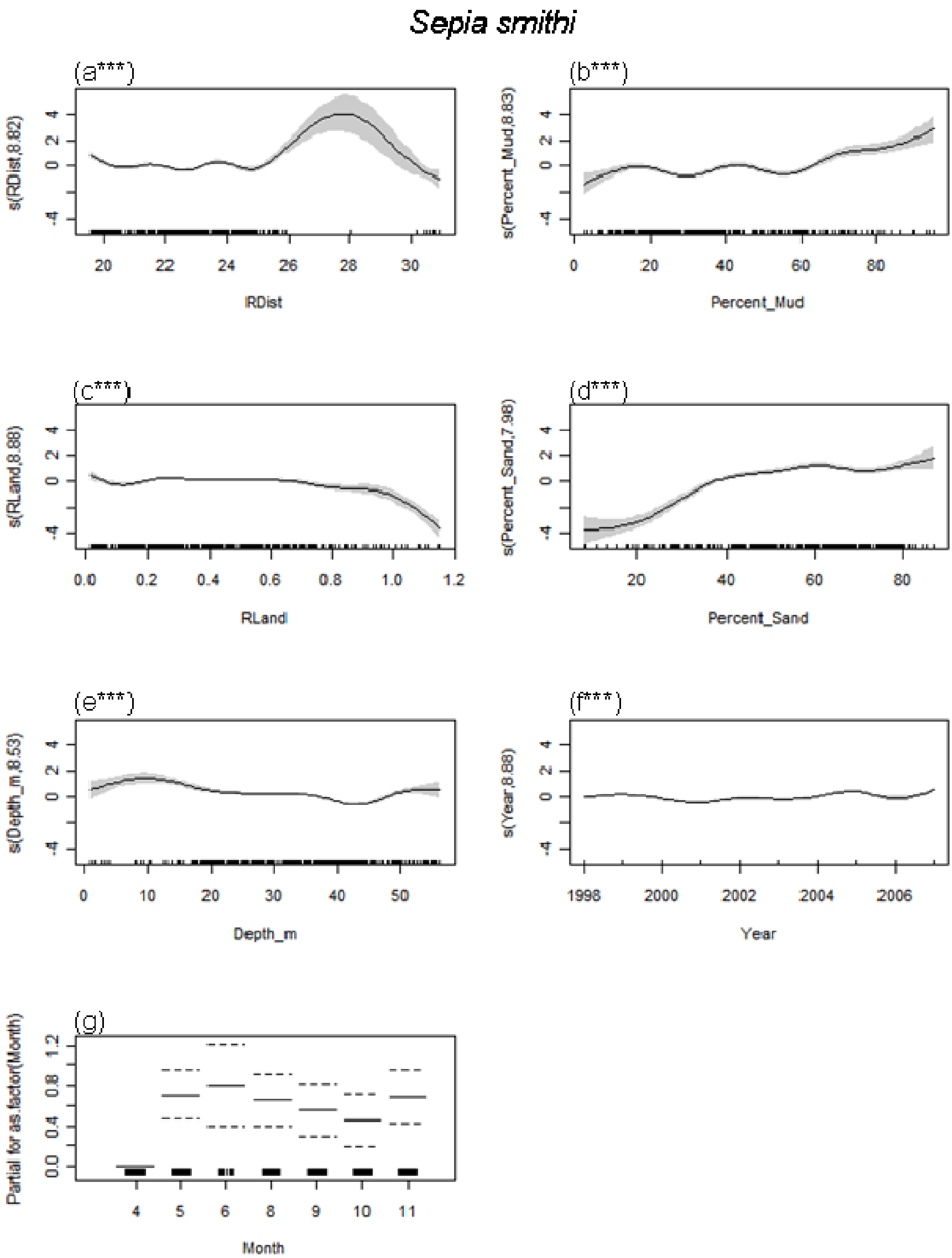


Figure 8.25. Adjusted mean cuttlefish *Sepia smithi* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

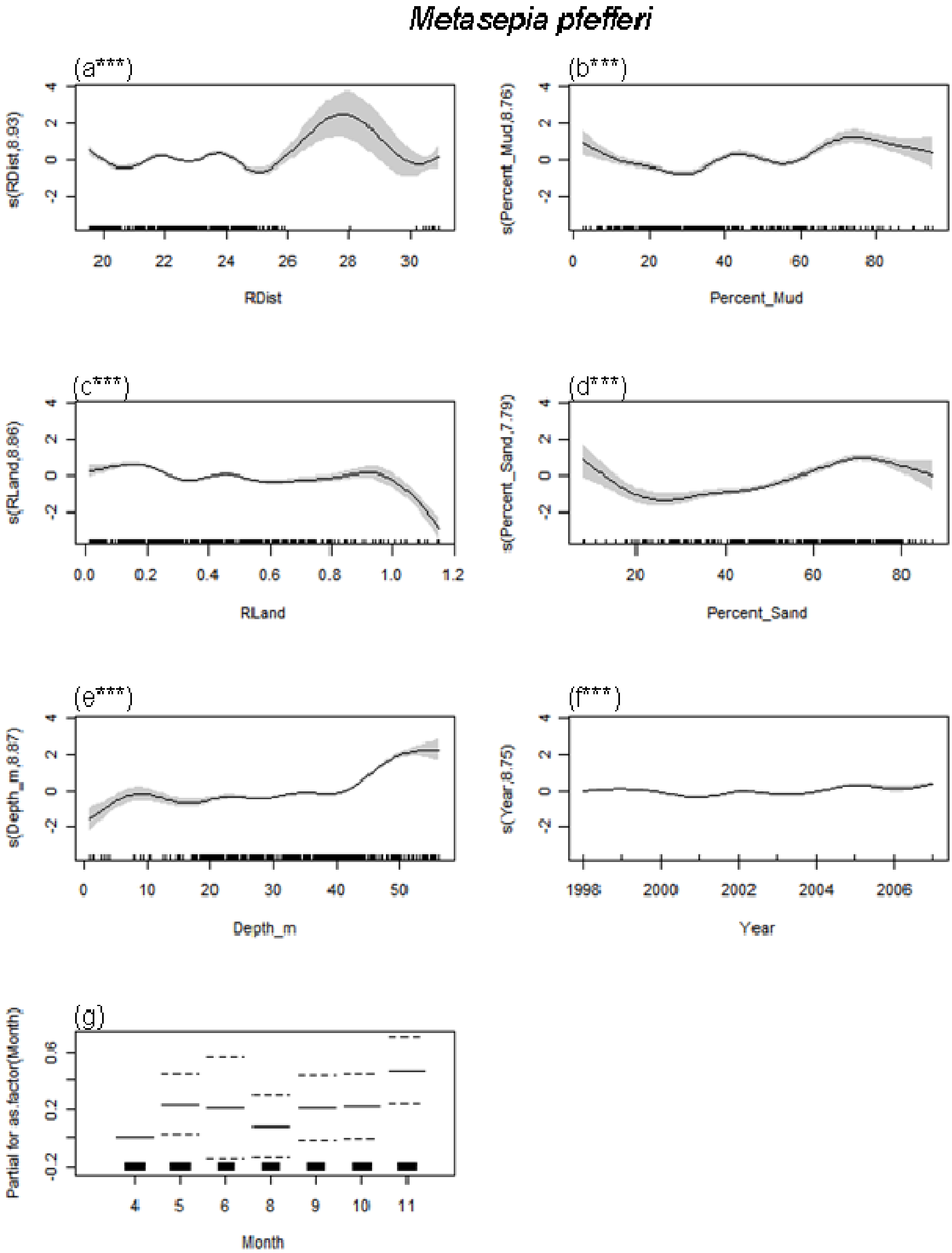


Figure 8.26. Adjusted mean cuttlefish *Metasepia pfefferi* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

Bugs

While there were no obvious annual patterns seen in the catches of the reef bugs, there were significant inter-annual differences for the mud bug caught during the NPF prawn monitoring surveys (Figure 8.27, Figure 8.28). The mean catch rate of mud bugs declined from 2002 through to a low in 2006, and then increased to their highest mean annual catch recorded in 2008. The mean annual catches of the reef and mud bugs from the CSIRO scientific and observer surveys and NPF commercial vessels did not show a similar pattern to the NPF prawn monitoring survey data. Catches of mud bugs fluctuated slightly between years but remained mostly stable across the period of 1993 to 2005 (CSIRO scientific and observer surveys) and 1998 to 2007 (commercial vessels) (Figure 8.29 – Figure 8.32). There was also no obvious seasonal pattern in the catches of either species of bugs from the NPF prawn monitoring surveys or CSIRO scientific and observer surveys apart from the months of April – May and September – October where catches were slightly lower (Figure 8.29, Figure 8.30). There appeared to be a distinct seasonal pattern in the commercial catches where greater quantities of mud bugs were retained earlier in the year (April – August) and a greater proportion of reef bugs recorded during September to November compared to other months (Figure 8.31, Figure 8.32).

From the NPF prawn monitoring and CSIRO scientific and observer surveys, highest catches of the mud bug (*T. parindicus*) were recorded when the substrates comprised 20 to 60% mud. Catch rates declined when the percentage of mud increased or decreased beyond this range (Figure 8.27, Figure 8.29). This was also supported by the NPF commercial logbook data where the greatest numbers of mud bugs retained were from areas where the mud composition of the substrates were between 10 and 60% (Figure 8.31). The total weights of mud bugs in NPF commercial catches were also significantly lower when the substrate was greater than 40% sand. For the reef bugs caught during the NPF prawn monitoring surveys, high percentages of sand and low mud in the substrate were generally associated with higher catches (Figure 8.28, Figure 8.30). However, high but variable catches were also associated with low sand and high mud substrate composition. There was no clear pattern with substrate type and reef bug catches recorded in the NPF commercial logbook data. The large catches of reef bugs were recorded on grounds where substrates comprised of either low (< 20%) or high (> 60%) sand or 50 – 80% mud (Figure 8.32).

There were very distinct differences in abundance with depth and distance offshore between the two bug species caught during the NPF prawn monitoring and CSIRO scientific and observer surveys. The mud bug (*T. parindicus*) showed highest catch rates within the 15 – 35 m depth zone (Figure 8.27). Mean catches were lowest in the inshore coastal area (< 10 m) and deeper than 40 m. Catch rates appeared to be similar with distance offshore (RLand) except for a few trawls further offshore where catches were high. The reef bug (*T. australiensis*) showed a distinct preference for deep offshore waters, greater than about 35 – 40 m and more than 60 nautical miles (> 1.0 RLand) from the Gulf coastline (Figure 8.28, Figure 8.30). The catches of mud and reef bugs from the commercial vessels were also closely related to depth and distance from shore (Figure 8.31, Figure 8.32). The catches of mud bugs recorded by NPF commercial fishers in the Gulf were relatively consistent from shallow to about 30 m but dropped steeply when vessels fished in deeper waters or more than 60 nautical miles offshore. Further, the pattern for the reef bug was similar to that found in the NPF prawn monitoring surveys; increasing catches with increasing depth and distance from shore (Figure 8.32).

The highest catches of the mud bug (*T. parindicus*) within the Gulf were recorded around the Mornington and Karumba regions during the NPF prawn monitoring surveys and from NPF commercial logbooks (Figure 8.27). This contrasted with the reef bug catches where highest abundances recorded from the surveys and logbooks were around the Vanderlins and Weipa regions (Figure 8.28, Figure 8.32).

Scallops

The predicted catches of mud scallops (*Amusium pleuronectes*) from the NPF prawn monitoring surveys remained relatively stable from 2002 to 2008, except for a steep decline in 2006 (Figure 8.33). While catches also remained relatively stable through most months of the year, there were significantly higher catches in the months of September and October. A similar pattern was seen in the annual catches of the fan scallop, *Annachlamys flabellata*. However, the monthly catch rates for *A. flabellata* were less variable with slightly higher catches made early and late in the year (Figure 8.34). This pattern was not reflected in the CSIRO scientific and observer survey or the NPF commercial logbook mud scallops data. Catches of this species were more variable during the CSIRO scientific and observer surveys, especially in 2003. That year showed the highest mean catch rate but also had the lowest trawl effort (Figure 8.35). The annual retained catch of mud scallops by the NPF commercial vessels tended to show an inverse pattern to the NPF prawn monitoring survey catches. The highest weights of scallops retained on NPF commercial vessels were in the 1998 – 2000 and 2005 – 2006 periods (Figure 8.36). The mean monthly catch rates for *A. pleuronectes* also showed a different pattern to the NPF prawn monitoring surveys with highest catches recorded in mid-year months rather than at the end of the year. There was no data for the fan scallop (*A. flabellata*) from the CSIRO scientific and observer surveys or the NPF commercial logbook data.

In the NPF prawn monitoring surveys, the mud scallop did not appear to have a distinct sediment preference. Highest catches were made on either mostly sand or mud substrates. Lowest catches were found in areas where the sediment more gravely (low mud and sand) (Figure 8.33). There were few obvious catch patterns in relation to sediment types from the retained catch records of the NPF commercial logbook data, except that greater quantities of scallops are generally retained by commercial operators in areas where the substrate is mostly mud or mostly sand (Figure 8.36). In contrast, data from the CSIRO scientific and observer surveys found that this species appeared to be more abundant when the percentage of mud and sand in the substrate was low (Figure 8.35).

The catch rates for the mud and fan scallop species were generally similar among each of the NPF prawn monitoring survey regions and CSIRO scientific and observer survey regions in the Gulf, except for slightly higher abundances in the south Groote region (Figure 8.33 – Figure 8.35). Catches of the mud scallop were significantly lower in the shallow inshore waters, less than 15 m depth (Figure 8.33). This was also supported by the NPF commercial logbook data. However, the highest retained catches of mud scallops were recorded from outside the NPF prawn monitoring survey area; northwest of Gove and in waters deeper than 50 m (Figure 8.36).

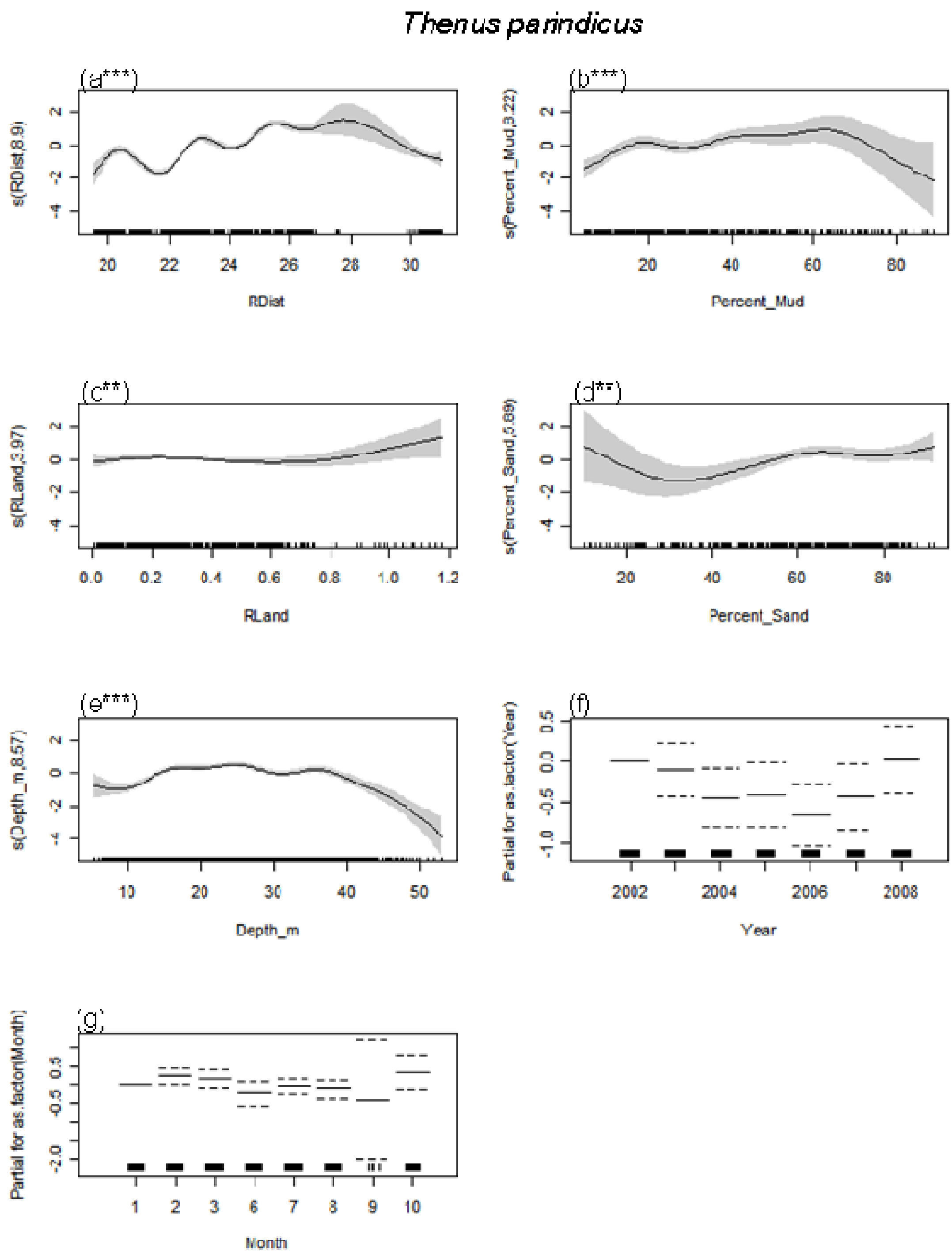


Figure 8.27. Adjusted mean bug *Thenus parindicus* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

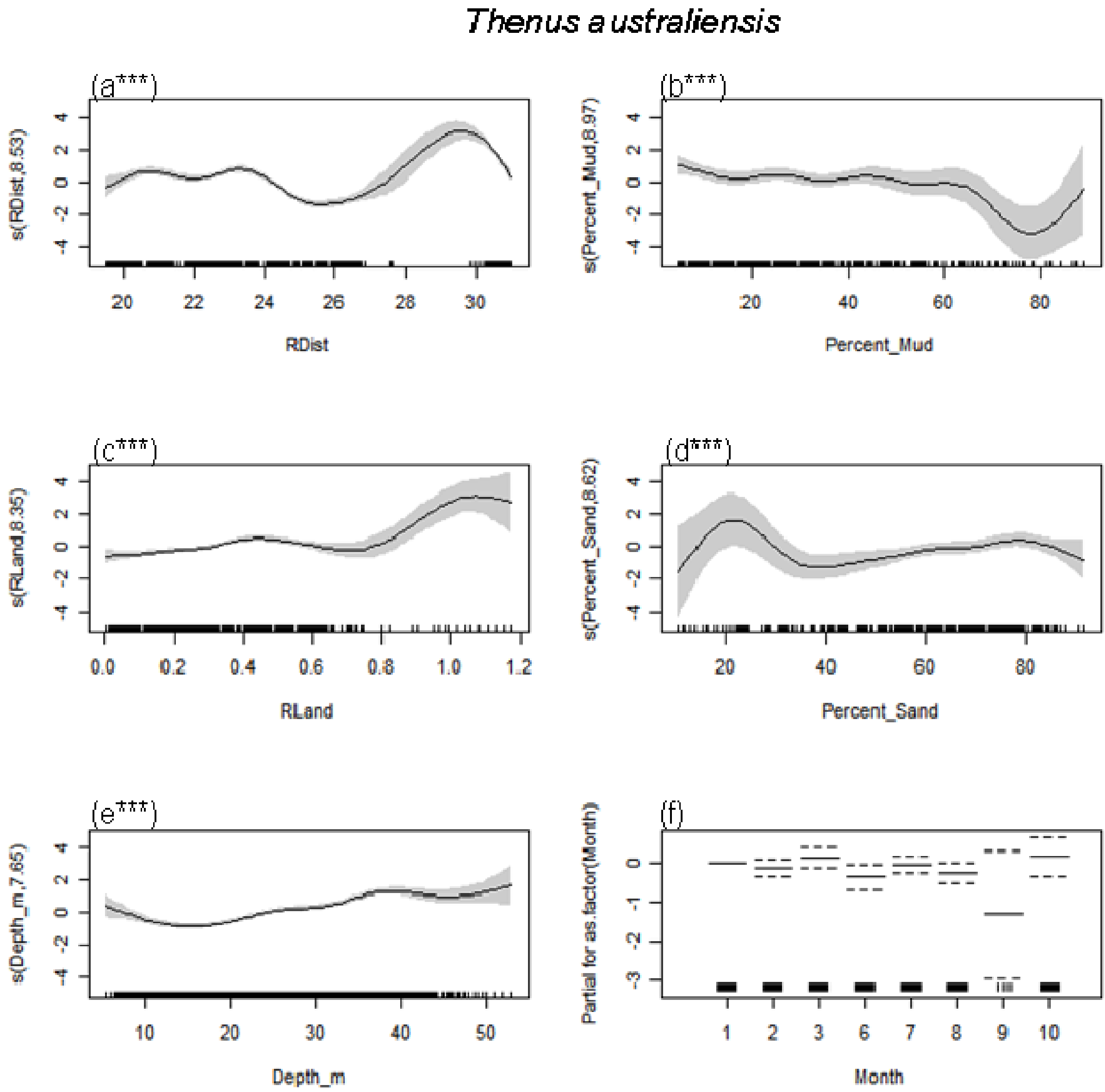


Figure 8.28. Adjusted mean bug *Thenus australiensis* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

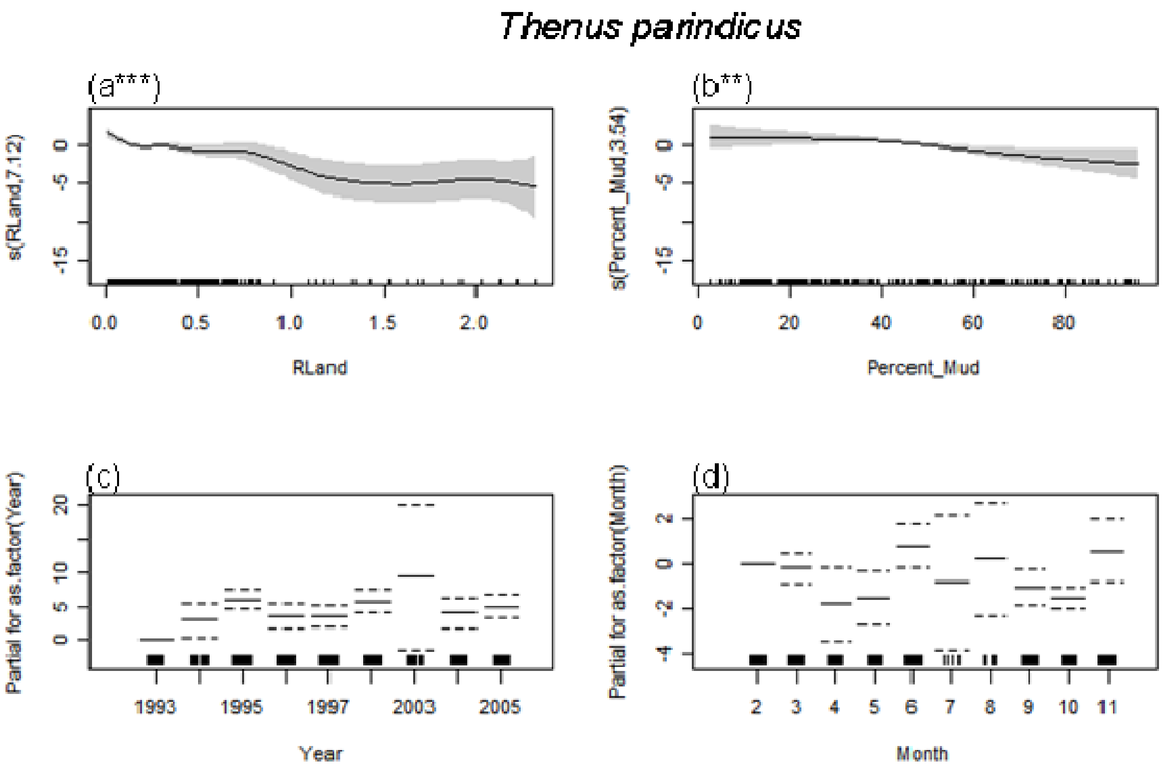


Figure 8.29. Adjusted mean bug *Thenus parindicus* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria (Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

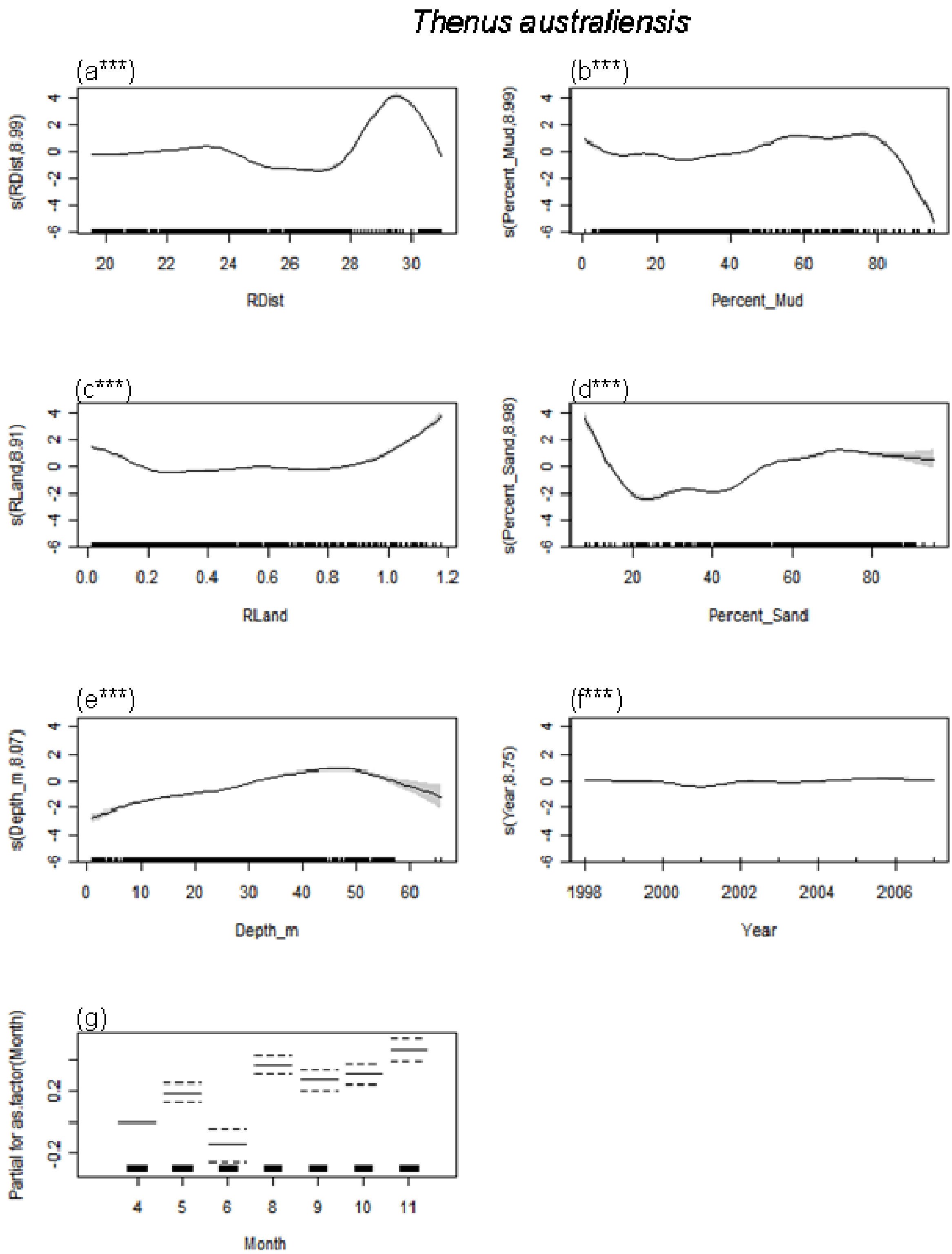


Figure 8.30. Adjusted mean bug *Thenus australiensis* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

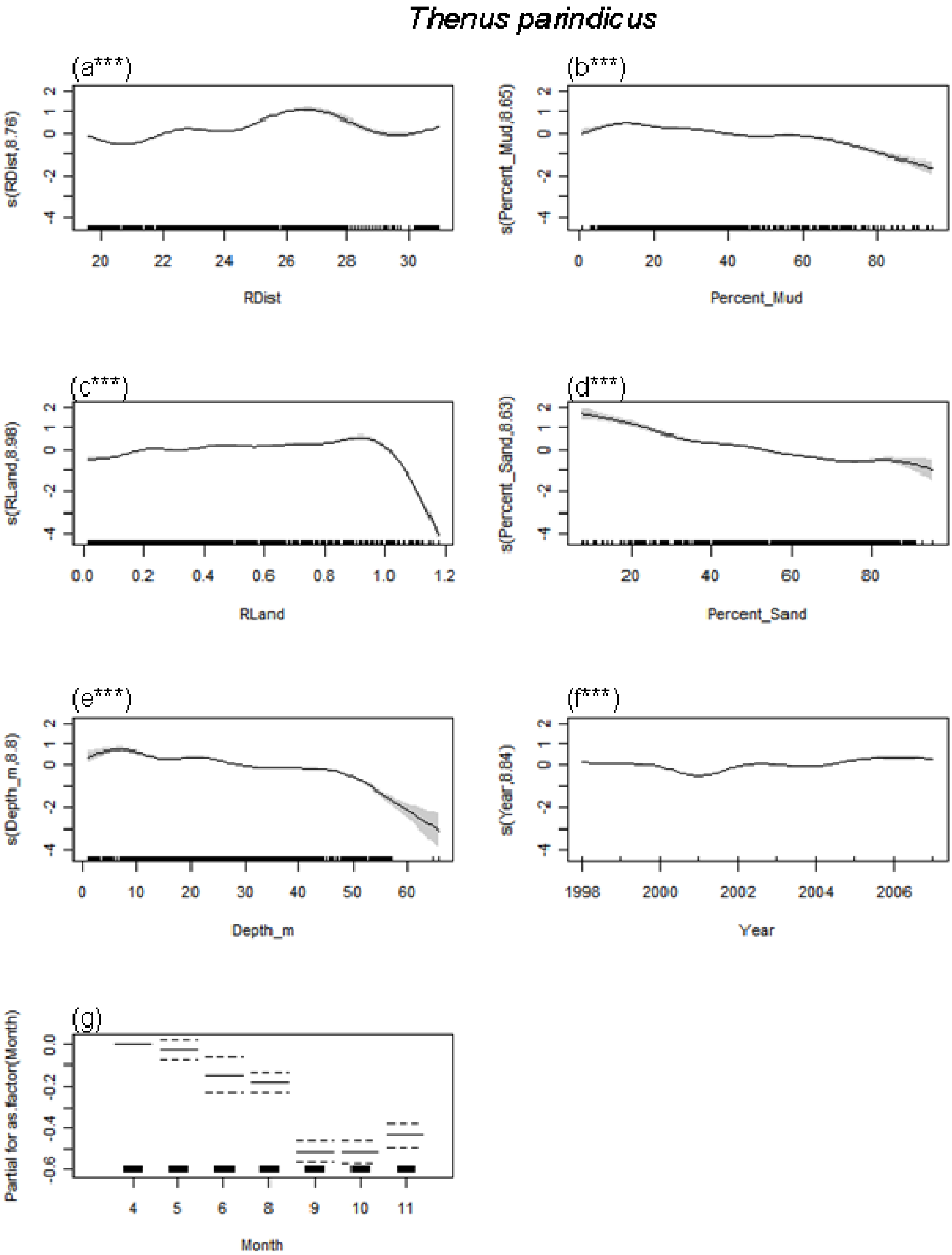


Figure 8.31. Adjusted mean bug *Thenus parindicus* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

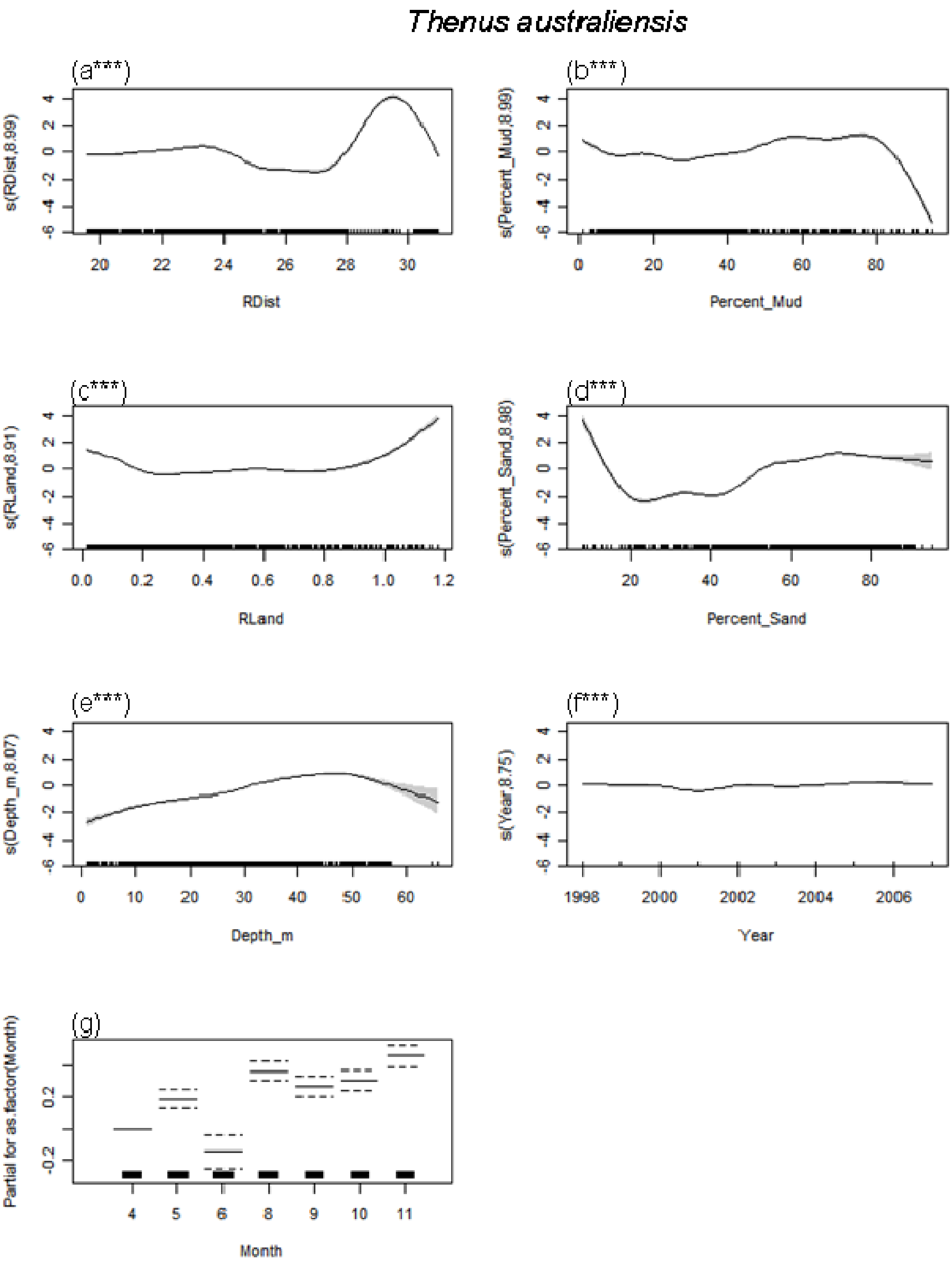


Figure 8.32. Adjusted mean bug *Thenus australiensis* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria. (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

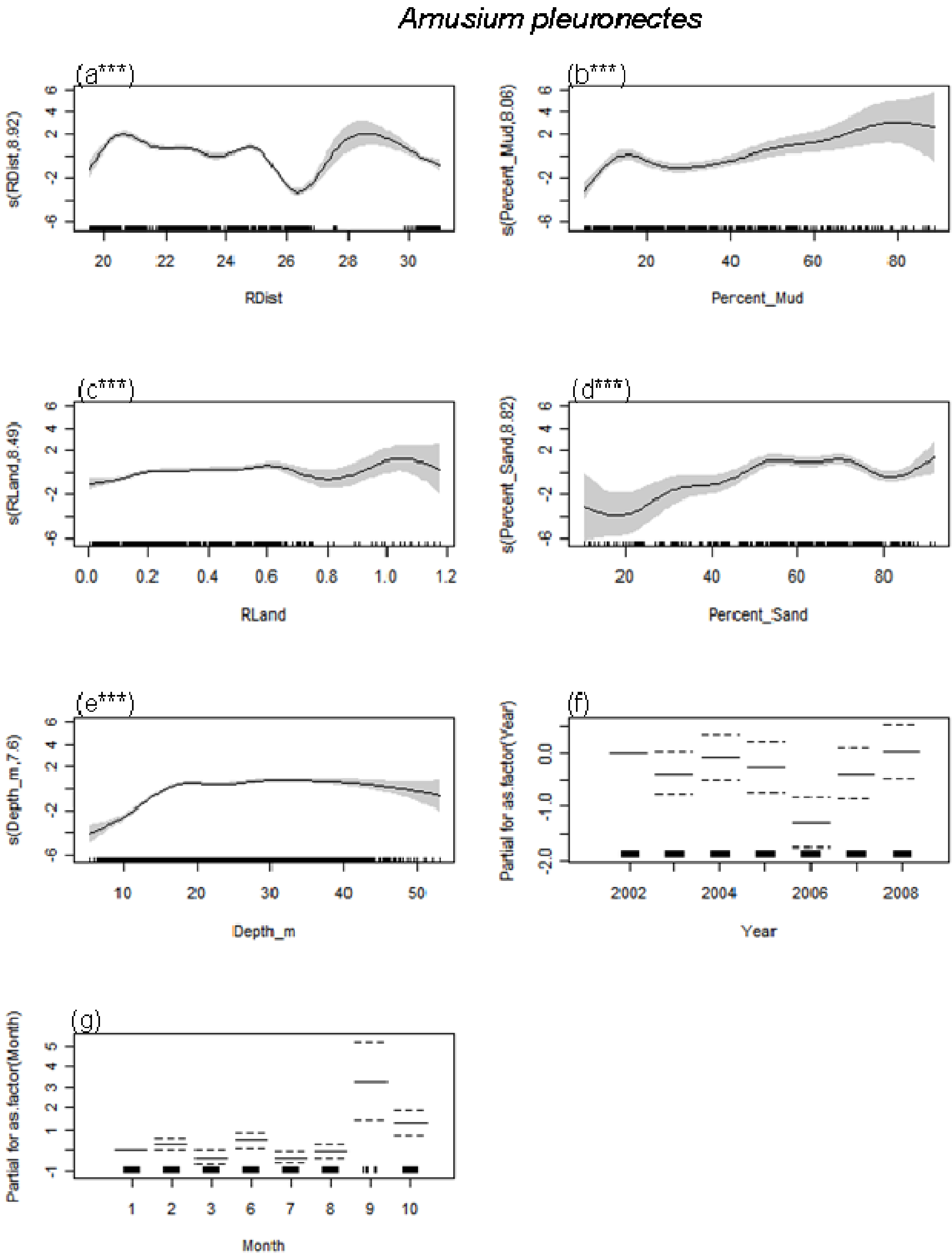


Figure 8.33. Adjusted mean scallop *Amusium pleuronectes* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

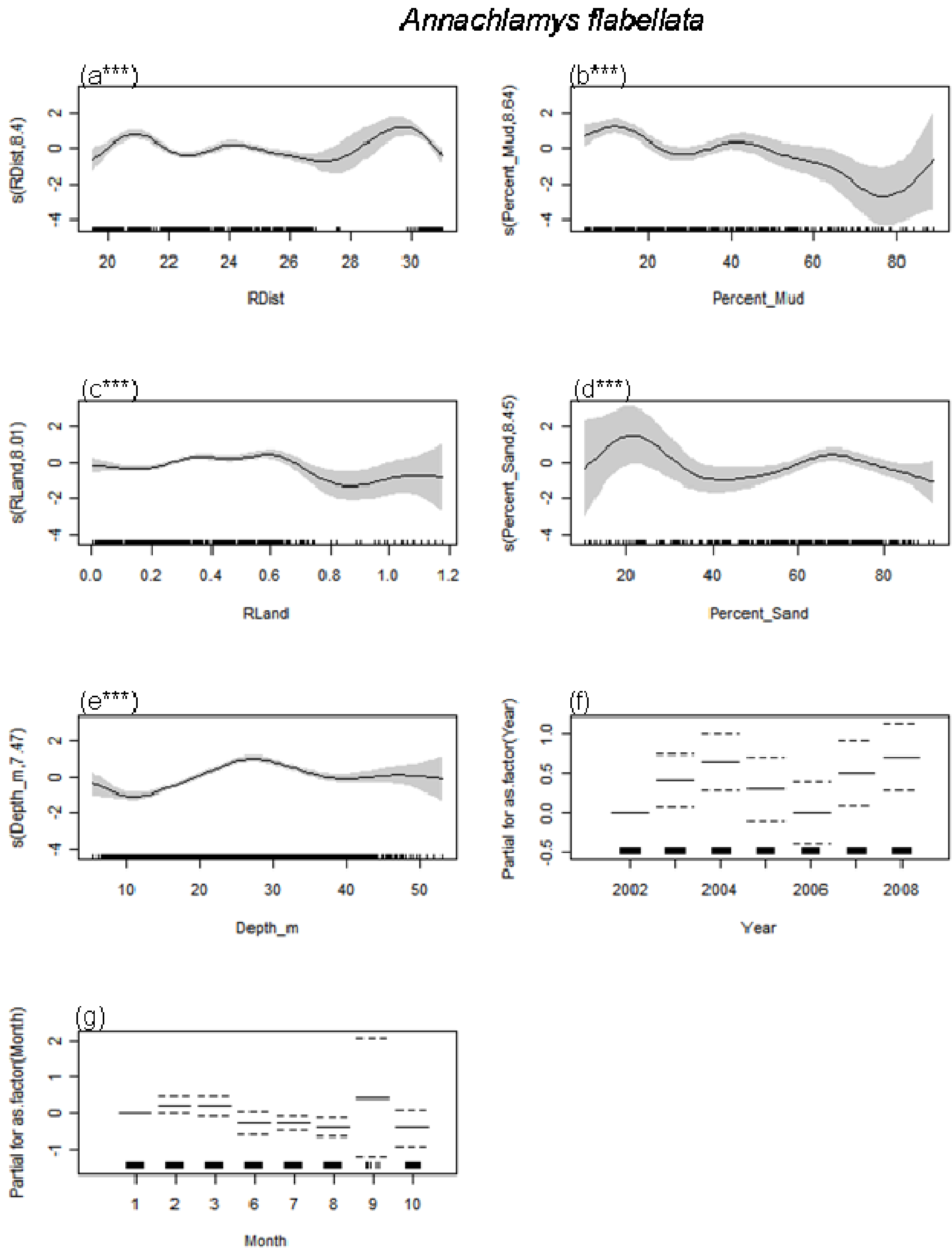


Figure 8.34. Adjusted mean scallop *Annachlamys flabellata* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from the NPF prawn monitoring surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

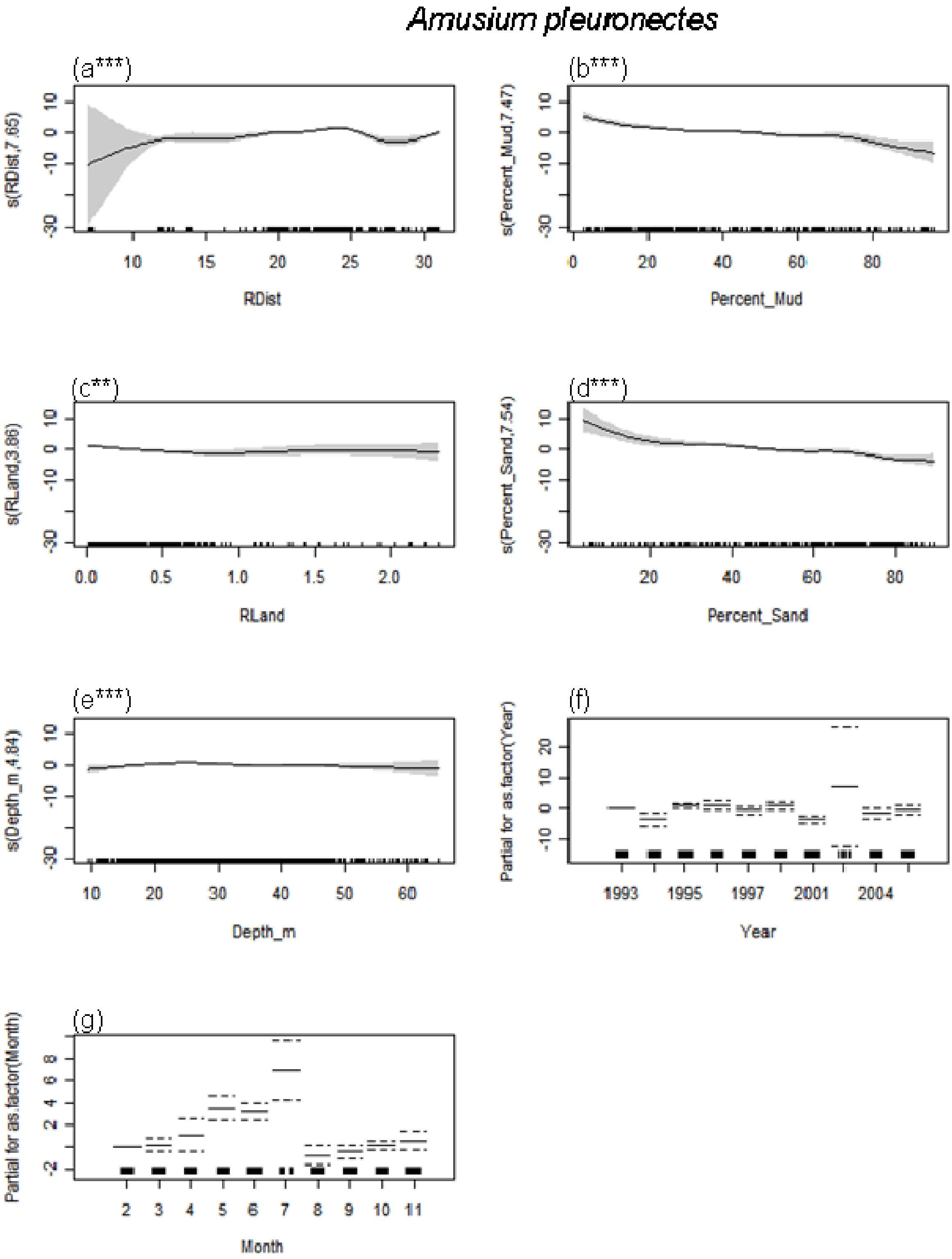


Figure 8.35. Adjusted mean scallop *Amusium pleuronectes* catch rates (Log CPUE in g.ha^{-1}) ± 95% confidence interval of significant effects in models from CSIRO scientific and observer surveys in the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

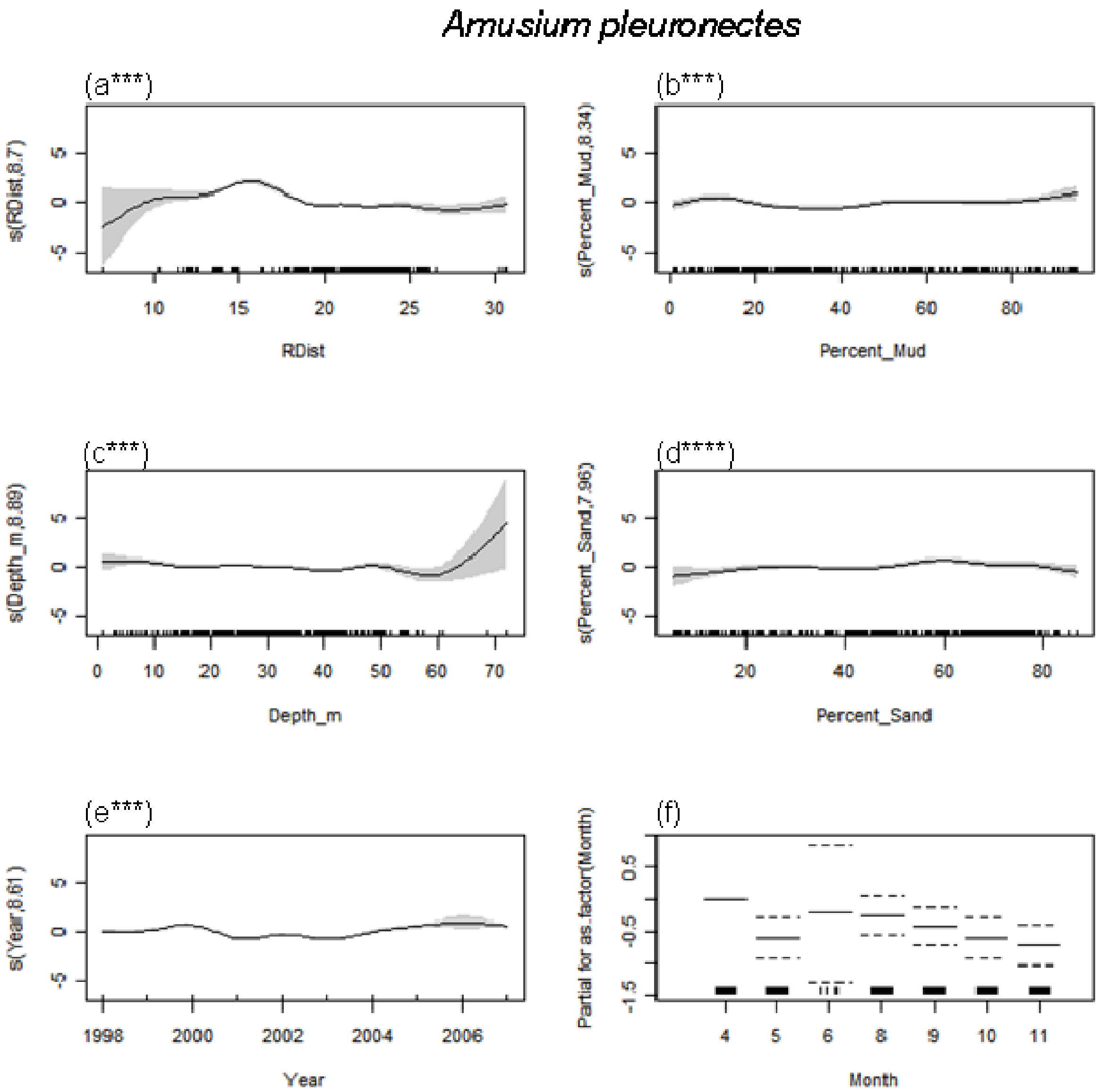


Figure 8.36. Adjusted mean scallop *Amusium pleuronectes* catch rates (Log CPUE in $g.ha^{-1}$) ± 95% confidence interval of significant effects in models from NPF commercial logbook records from the Gulf of Carpentaria (RDist is low at Groote Eylandt and high in Weipa; Significance levels: *** < 0.0001; ** < 0.01; * < 0.05).

8.5 Discussion

The NPF prawn monitoring survey had a similar byproduct species composition, distribution and relative abundances comparable with the NPF commercial fishery. We used these data as a proxy for predicting the species compositions of the NPF commercial catches that were recorded in logbooks only to broad byproduct group levels (Chapter 9). This however assumed that the proportion of each species within a byproduct group that was retained by the commercial fleet was also similar to the catch proportions of the NPF prawn monitoring surveys. This may not have been the case as the commercial sector generally only retains the larger-sized animals and therefore the larger-growing species.

The relationship between the spatial, temporal and environmental variables and the abundance of the byproduct species may have also been influenced by the sampling designs of these surveys. As these byproduct groups are mostly incidental catch of prawn trawling, the majority of catch data (NPF prawn monitoring surveys and NPF commercial logbooks) was collected from areas of importance for targeted prawn species. Therefore, CSIRO scientific and observer survey data was included to provide species catch and composition information from different areas, habitats and times not covered in the NPF prawn monitoring surveys or the NPF commercial fishery. However, for some surveys the catches of byproduct groups, especially for squid, were not identified to a species level and therefore only used in the overall mean catch rate comparisons. This reduced the number of data records available for the correlation analysis and resulted in poorer model fits (larger standard errors) in the predicted catch rates for each of the spatial, temporal and environmental variables.

8.5.1 Squid and cuttlefish

The species compositions of squid and cuttlefish catches in the Gulf of Carpentaria appears to have remained stable from earlier research surveys of the Gulf of Carpentaria in 1990 – 1991 (Dunning et al. 1994) to the 2002 – 2008 NPF prawn monitoring surveys. Dunning et al. (1994) recorded five taxa of loliginid squid and seven taxa of cuttlefishes from CSIRO scientific surveys across the Gulf in 1990 and 1991. They reported that the squid catches were dominated by *Photololigo* cf. *chinensis* (split and renamed: *Uroteuthis* sp 3 and 4) (75 – 80%) and *Photololigo* cf. *edulis* (split and renamed: *Uroteuthis* sp 1 and 2) (17 – 20%). For the cuttlefish catches; he found *S. elliptica* was the most abundant (50 – 57%), followed by *S. pharaonis* (29 – 36%) and *S. papuensis* (9%). In our study, *Uroteuthis* sp 3 and *Uroteuthis* sp 4 together also comprised between 60 and 94% of the overall squid catch. However, unlike in these previous 1990 and 1991 surveys, *Uroteuthis* sp 2 was relatively abundant around the western region of the Gulf of Carpentaria where it was between 17 and 38% of the total squid catch. Furthermore, *A. noctiluca* was caught in most regions during the recent NPF prawn monitoring surveys, but was not recorded in the 1990 or 1991 surveys (Dunning et al. 1994). *Aestuariolus noctiluca* is a small species that was found to prefer the very shallow coastal waters. Due to the larger size of the survey vessel used during the earlier survey; this shallower habitat (< 7 m) was not sampled in the 1990 and 1991 study. Lu et al. (1985) recorded catches of *A. noctiluca* from trawls in depths of 3.5 – 7 m around the southeast Gulf, where it was also recorded at its highest proportion of the squid catch during the NPF prawn monitoring surveys. Dunning et al. (1994) also found that highest catches of *P.* cf. *chinensis* were from the east and south regions of the Gulf and lowest in the north western Gulf and catches of *P.* cf. *edulis* were most common around the Weipa region. Most of the squid species in our study showed little difference in catch abundances across the regions in the Gulf, except for *Uroteuthis* sp 3 where mean catches were lowest around Weipa.

The most common species of cuttlefish caught in the NPF prawn monitoring surveys, *S. elliptica*, had a wide distribution in the Gulf of Carpentaria, from Groote Eylandt in the west to Weipa in the east. This species was also the most widely distributed and abundant cuttlefish in the 1990 – 1991 research surveys (Dunning et al. 1994). The two other common cuttlefish species, *S. pharaonis* and *S. papuensis* were most abundant in the south to southeast Gulf and east Gulf regions, respectively, during the earlier surveys in 1990 – 1991 (Dunning et al. 1994). In this study, these two species were widely distributed throughout the Gulf. Furthermore, highest abundances for *S. pharaonis* were also found around the south and southeast Gulf (Mornington and Vanderlins) but also Weipa and for *S. papuensis* around Weipa and Mornington. From the NPF prawn monitoring survey, the region around Karumba appeared to be markedly different in species composition to the other regions; almost exclusively comprising a single cuttlefish species, *S. elliptica*.

Cephalopod fisheries world-wide, predominantly in temperate waters, show marked inter-annual and seasonal fluctuations in squid and cuttlefish landings (Georgakarakos et al. 2002; Schön et al. 2002; Pierce and Boyle 2003; Chen et al. 2006; Glazer and Butterworth 2006). There is also much evidence to suggest that these fluctuations are strongly correlated with their migratory and spawning behaviours and changes in environmental conditions (Boletzky 1983; Bartol et al. 2002; Schön et al. 2002; Valavanis et al. 2002; Pierce and Boyle 2003; Zuur and Pierce 2004). The overall mean catches of squid landed during the NPF prawn monitoring surveys appeared to decline from 2002 to 2008. However, individual species showed inter-annual variations in the catch. There were higher than average catches recorded during several years followed by a sharp decline in catch abundance in the following years. This pattern was seen in catches from both the NPF prawn monitoring surveys and NPF commercial fishery. Reiss et al. (2004) suggested that temperature was one of the dominant mechanisms affecting the abundance of *Loligo opalescens* in southern California Bight. They showed that the abundance of this species varied with changes in El Nino conditions. Prior to the El Nino in 1997 – 1998, squid were found all along the coast from Point Conception to Vancouver, British Columbia. During the summer of the 1998 El Nino, squid abundance in trawl samples was very low with a considerable fraction of their trawl sites containing no squid at all. No evidence for a shift in the abundance of squid to the more northern areas was observed, nor was there any apparent shift to slope waters from shelf waters. Following this in 2001, when the water temperatures returned to normal, squid were again abundant all along the coast. They proposed that the decrease in abundance of this species was a result of a decline in the production of offspring during the El Nino when the sea temperature was warmer than normal, rather than a shift in habitat (Reiss et al. 2004). There was no clear relationship in the peaks or troughs in squid catches from the NPF prawn monitoring surveys or NPF commercial fishery and the recorded El Nino (1997, 2002 – 2003, 2006 – 2007) or La Nina (1998, 2000, 2008) events in Australia.

In the squid fishery in Scottish waters, *Loligo forbesi* showed consistent seasonal patterns in catches with peak landings of maturing and mature squid between October and November from coastal waters (Bellido et al. 2001). They reported that the seasonal abundance of this species was related to their annual life cycle: highest landings were when squid were recruiting to the fished area when the population were approaching breeding condition (in winter). The catches were lowest after winter when the squid disappeared from their spawning grounds. In Chesapeake Bay of the United States, catches of the commercially-important squid, *Lolliguncula brevis*, increased when higher salinities and water temperatures occurred within the bay (Bartol et al. 2002). They reported that these variables had a profound influence on both annual and seasonal variability in the species distribution. Squid were more abundant in summer and autumn compared to spring and winter (Bartol et al. 2002). The squid, *Loligo vulgaris reynaudii* is the main species of the South African cephalopod fishery and it also shows inter-annual and seasonal fluctuating landings (Schön et al. 2002), similar to *Uroteuthis* species in the NPF. This has significant economic impact on the fishery and management of this resource. Peak summer catch rates were reported in shallow water depths (< 30 m), and decrease with depth, with the opposite trend occurring during winter (Schön et al. 2002).

Highest mean catches of squid from the NPF prawn monitoring and CSIRO scientific and observer surveys were generally associated with shallower water and during January to February and June to August. However, there were few squid caught outside of the main months sampled during the NPF prawn monitoring surveys (January – February and August – September). Thus, these surveys may be unable to detect a strong seasonal pattern. Rainer (1984) reported highest squid catches were mostly in the winter months, and lowest in autumn and spring, in the shallow coastal waters (10 – 19 m) of the southeast Gulf of Carpentaria. Although Dunning et al. (1994) found that most squid were caught in waters less than 30 m, he reported that they occurred across the entire depth range sampled (7 – 63 m) and there was no clear relationship between abundance in trawls and depth. He suggested that this was possibly a reflection of the slight depth gradients within the Gulf of Carpentaria. In the Gulf St. Vincent, South Australia, juvenile and sub-adult populations of the southern calamary (*Sepioteuthis australis*) predominantly occur offshore in waters greater than 10 m, while the mature adults migrate and aggregate inshore around their shallower spawning grounds (Steer et al. 2007).

According to NPF commercial fishers, squid appear to be more abundant at certain times of the year in the Gulf of Carpentaria; possibly coinciding with their breeding cycle (Dunning et al. 1994). Similar to that study, we found no obvious aggregations of mature squid or spawning aggregations during the NPF prawn monitoring survey or CSIRO scientific and observer surveys. There was a depth and seasonal relationship evident for squid catches in the NPF commercial fishery with highest mean catches recorded in the shallow waters early in the year. However, the highest trawl catches of squid, up to 12 t d^{-1}, were in the deeper waters (> 21 m) around Mornington. Squid are known to aggregate immediately prior to spawning (Dunning et al. 1994; Wang et al. 2003; Bower and Ichii 2005; Semmens et al. 2007) and in the NPF, squid egg cases were observed during these large hauls (G. Fry pers. comm.). Therefore it is likely that the waters around Mornington are an important area in the Gulf for squid aggregating and spawning (see details in Chapter 7).

Abundances of the cuttlefish *Sepia officinalis* in the English Channel were correlated with depth and sea surface temperatures, expanding their distribution further north in the spawning season in warm years, and shifting further south in cooler years (Wang et al. 2003). *Sepia officinalis* is the main cephalopod species caught in the French Atlantic fishery in northeast Atlantic (Denis and Robin 2001). Landings of this species in the fishery showed seasonal catch variability with a decrease in summer (June – July), and highest catches in winter and spring. This seasonal catch trend followed the migration cycle of *S. officinalis*. Denis and Robin (2001) reported high commercial landings when adult cuttlefish were concentrated on coastal spawning grounds in spring and lowest catches in summer corresponding to their minimum levels of stock after the death of spawners and the migration of the remaining stock towards their wintering areas in deeper offshore waters in autumn.

The catches of cuttlefish from the NPF prawn monitoring surveys and NPF commercial fishery were relatively stable through 1998 to 2008. Most species of cuttlefish caught in the Gulf of Carpentaria did show a preference for deeper offshore waters. However, there was no clear seasonal pattern in catches, except for an increase in landings through the year for the NPF commercial fishery. This may be due to their life history or the size-selectivity in cuttlefish retained by the NPF commercial fishery. Most cuttlefish species are known to be short-lived and fast growing (Wang et al. 2003). It may be that there is a greater proportion of larger or mature cuttlefish on the NPF prawn trawl grounds late in the year. However, only two species of cuttlefish, *S. smithi* and *S. papuensis*, showed clear seasonal spawning patterns (Chapter 7). It is possible that during certain times in the prawn season where commercial fishers are landing the most prawns, it is not economical or practicable to retain cuttlefish. Alternatively, there may be a trend for commercial fishers to trawl in deeper waters later in the year, when cuttlefish are more abundant.

8.5.2 Bugs

From a previous study in the southeast Gulf of Carpentaria, Jones (1988) compared population structures of *Thenus parindicus* from 1963 (prior to the establishment of the NPF) to 1983 and found that significant changes occurred that are likely to be attributable to commercial fishing activities. Catch per unit effort for *T. parindicus* in 1983 was 1.8 bugs.ha^{-1}; 44% lower than the 3.2 bugs.ha^{-1} recorded in the 1963 – 1964 period. There was also a 15% reduction in mean size of bugs, resulting in a 65% reduction in the exploited standing stock of *T. parindicus* in the Gulf over a 20 year period (Jones 1988). Similarly, the abundances of bugs caught in the NPF prawn monitoring surveys and NPF commercial fishery had also decreased over time. It is possible that this decline may be a result of long-term commercial fishing pressure. However, the NPF commercial fishery is regulated to only retain bugs greater than 75 mm carapace width and restrictions on berried females. It was shown that the length at maturity for the mud bug, the more common of the two species, was considerably lower than this size (Chapter 7). Furthermore, there is evidence that the survival rate of bugs caught and discarded is very high, 98% of bugs survive post-trawl (Wassenberg and Hill 1993). While there was about 30 to 50% decline in the catches between 1998 and 2007, the mean catch rate recorded in the NPF prawn monitoring surveys in 2008 had increased to the levels recorded during the earlier survey years (2002 – 2004). It is possible that, like the squid and cuttlefish, their abundances are spatially and temporally variable across the Gulf of Carpentaria. Also, the NPF commercial effort distribution is continually changing over the last few years. It may be that the commercial fishery is no longer fishing in areas where bugs are abundant.

These two *Thenus* species are known to have highly aggregated or patchy distributions in northern Australia with significant seasonal variability in their catches (Jones 1993). Jones (1993) reported that *T. parindicus* were more abundant in the south eastern Gulf during the months of February to June and October. However, off Townsville in north eastern Australia, catches of *T. australiensis* were more uniformly distributed through the year. There was a strong seasonal pattern in the NPF commercial fishery bug catches, where mud bugs were predominantly caught in the early part of the year and the reef bugs later in the year. This pattern was similar to the catches of cuttlefish and may also indicate that the NPF commercial fishery is shifting effort from the shallow waters in the start of the year and into deeper waters closer to the end of the year or possibly concentrating more effort in the Vanderlins or Weipa regions at that time.

Jones (1993) also found differences in the habitat characteristics between the species, suggesting sediment type and water depth were the most influential factors. He reported that the mud bug, *T. parindicus*, was most abundant in relatively shallow, inshore waters (10 – 30 m) with predominantly mud and silt sediment. In contrast, the reef bug, *T. australiensis*, was more abundant in deeper offshore waters (40 – 50 m) with coarser sand sediment. In our study, the distribution and abundance of the two bug species in the Gulf of Carpentaria clearly separated by depth and sediment type. *Thenus parindicus* was more abundant in the 15 – 35 m depth zone on muddy substrates in the south eastern Gulf region. *Thenus australiensis* was mostly restricted to the Vanderlins and Weipa regions in waters deeper than 35 – 40 m with mostly sandy substrates.

8.5.3 Scallops

The saucer scallop, *Amusium japonicum balloti*, forms a major fishery resource along the eastern Queensland coast of Australia. This species supports both a targeted dredge fishery and is a byproduct of the Queensland East Coast Otter Trawl Fishery (Jebreen et al. 2003). They are known to have an aggregated distribution along the eastern coast. Both fisheries have seasonal peaks in catch from January to March and show inter-annual catch fluctuations (Jebreen et al. 2003). The most common scallop species in the Gulf of Carpentaria was the mud scallop *A. pleuronectes* which is smaller in size compared to the east coast species. Although the catch rate for this species during the NPF prawn monitoring and CSIRO scientific and observers surveys was high compared to other byproduct groups in the Gulf, the retained catches of mud scallops by the NPF commercial sector between 1998 and 2007 was low. The NPF commercial landings were also relatively stable between years. Anecdotal evidence from fishers suggests that this species does not grow to a marketable size in the Gulf of Carpentaria.

8.6 Conclusion

Spatial, temporal and environmental variables were found to be important factors influencing the distribution and abundance of the squid, cuttlefish, bug and scallop species in the Gulf of Carpentaria. We examined their influence on catches in three datasets and found consistencies among many of the factors. This was especially true for the NPF prawn monitoring surveys and the NPF commercial fishery logbooks. This was not surprising as both the NPF prawn monitoring surveys and NPF commercial fishery data were collected from similar regions within the Gulf and the catches were made at similar times of the year.

The squid and bug groups showed a steady decline in their catch rates from NPF prawn monitoring surveys between 2002 and 2008. There was also relatively high inter-annual and seasonal variability in their abundances. No clear temporal patterns in abundances were evident for the cuttlefish and scallop groups in the Gulf of Carpentaria. Squid were more abundant in the shallower waters while cuttlefish and scallops had higher catches in deeper waters. The two bug species showed the clearest differences in distribution, with species being separated on depth and substrate type. There were also strong regional differences in catch rates of each of the byproduct species.

An understanding of these relationships between abundances and the spatial, temporal and environmental variables is critical to forecast catches and fluctuations and may also be a valuable tool in the successful assessment and management of these byproduct stocks by providing reliable predictors for their abundances and population distributions outside of the current NPF commercial fishery areas or seasons.

9. PREDICTING SPECIES COMPOSITION OF BYPRODUCT IN NPF LOGBOOK RECORDS

9.1 Abstract

Byproduct records in the NPF fishery logbooks are grouped into about 30 multi-species categories. In order to be able to examine the fishery impacts on species' populations, we need to be able to estimate catch rates of each species. We explored two statistical techniques for modelling the species composition of the catch of each byproduct group taken during NPF prawn monitoring surveys. The first method was a generalised additive modelling (GAM) approach based on previous work by Venables and Dichmont (2004). The second was a bagged classification tree that predicts byproduct species composition from aggregated predictions formed from classification tree models built on bootstrap samples of the data. Models were developed for all byproduct groups except scallops. We found that after removing small scallops from the NPF prawn monitoring survey data to reflect what is retained commercially, only one scallop species remained.

Predictors of species composition of byproduct were grouped into the following categories: spatial (latitude, longitude, distance along the coast, distance from land, depth), temporal (seasonal, long-term trend), and environmental data (percent mud, sand and gravel). The models produced for each byproduct group highlighted a large spatial component followed by a slight temporal influence and some influence of sediment composition.

In summary, the squids *Uroteuthis* sp 3 and sp 4 dominate catches throughout the NPF prawn monitoring survey regions. High proportions of *Uroteuthis* sp 3 were caught in shallower waters irrespective of sediment type. Whereas, a higher proportion of *Uroteuthis* sp 4 occurred in deeper, sandy regions. The Ovalbone cuttlefish *Sepia elliptica* was the dominant species caught, occurring in high proportions in muddy regions, particularly shallow areas. Pharaoh cuttlefish *(Sepia pharaonis*) were more abundant in deeper waters. A higher proportion of Smiths cuttlefish (*Sepia smithi*) were found in sandy, deeper waters. Both the Papuan *S. papuensis* and Flamboyant cuttlefish *Metasepia pfefferi* occurred in low proportions across the region. High proportions of mud bugs (*Thenus parindicus*) were observed right across the NPF prawn monitoring survey region and their distribution appeared to be influenced by both spatial and temporal variables and the presence of mud. In contrast, Reef bugs *Thenus australiensis* tended to be located in deeper waters where the sediment was typically sandier.

9.2 Introduction

9.2.1 Overview of the species-split problem

One problem associated with placing restrictions on byproduct catches is determining how many of each species are caught. Although byproduct species are regularly caught in the NPF, logbook information is limited to simply the byproduct group name (e.g. cuttlefish or squid) as the focus is generally on the target catch. Furthermore, the identification of byproduct species is difficult and time consuming, often requiring close examination in the laboratory.

CSIRO and AFMA scientific observers on board commercial fishing vessels have been able to collect catch data on byproduct species. We developed a statistical model for four byproduct species groups (squid, cuttlefish, bugs and scallops) that will enable prediction of species composition based on spatial, temporal and environmental characteristics of six regions in the Gulf of Carpentaria. We apply these predictions to NPF commercial logbook data, to enable these data to be available for individual byproduct species stock assessments.

9.2.2 Existing methods for the species-split problem

The species-split problem involves “catch allocation”, where a catch group (e.g. squid) is divided into species according to explanatory variables. Often the information available for building a predictive model is limited and this presents many challenges, particularly when more than two species exist for a particular fishery group as in the case of squid, and cuttlefish.

Little information exists on catch allocation for fishery-related species (Venables and Dichmont 2004). They developed a generalised additive model for predicting the proportion of catch allocated to a particular prawn species. Other predictive species composition models have used genetic tagging studies and focussed on allocating fish stocks to different regions (Shaklee et al. 1999).

The approach adopted by Venables and Dichmont (2004) relied on applying generalised linear and additive modelling to the NPF prawn monitoring survey data. They predicted the proportions of prawn species (either tiger, endeavour or banana) comprising the total catch. The approach considered a quasi-likelihood for modelling the proportion of each prawn species by weight in the catch as a function of smoothed terms in the model. The smoothed terms consisted of a combination of spatial, temporal and environmental variables (Venables and Dichmont 2004). Although their approach was successful at predicting the species proportion from logbook data, their approach is limited to situations where only two species exist. In cases where a particular biological group consists of more than two species, the problem becomes much more complex. This problem requires an alternative approach, which we explore for up to six species of squid and cuttlefish.

Where the response consists of more than two categories, many approaches adopt either to: (1) assemble first, predict later or (2) predict first, assemble later strategies (Ferrier and Guisan 2006). In these approaches, clustering algorithms are coupled with generalised linear or additive models to predict species assemblages or explore assemblage relationships depending on the approach used. Multivariate methods such as that proposed by De’Ath (2002) aim to predict and assemble together. In this approach, environmental variables are used to partition the assemblage data into similar groupings according to a deviance criterion. An alternative strategy for situations where the number of species groups is small is a classification tree. Here, weights can be set to reflect the total weight of each species caught. The latter approach is explored further in this chapter for the multi-species squid and cuttlefish catches.

9.3 Methods and materials

9.3.1 Species composition

Byproduct species (squid, cuttlefish, bugs and scallops) were collected from annual January and July – August prawn monitoring surveys between 2002 and 2008 in the NPF. For the analyses in this chapter we have defined five regions and have lumped north and south Groote compared with Chapter 7 (Figure 9.1). Regions fished include Weipa (purple), Groote (red), Mornington (green), Vanderlins (blue) and Karumba (orange) (Figure 9.1). Details of field sampling and identification of species are described in Chapter 7.

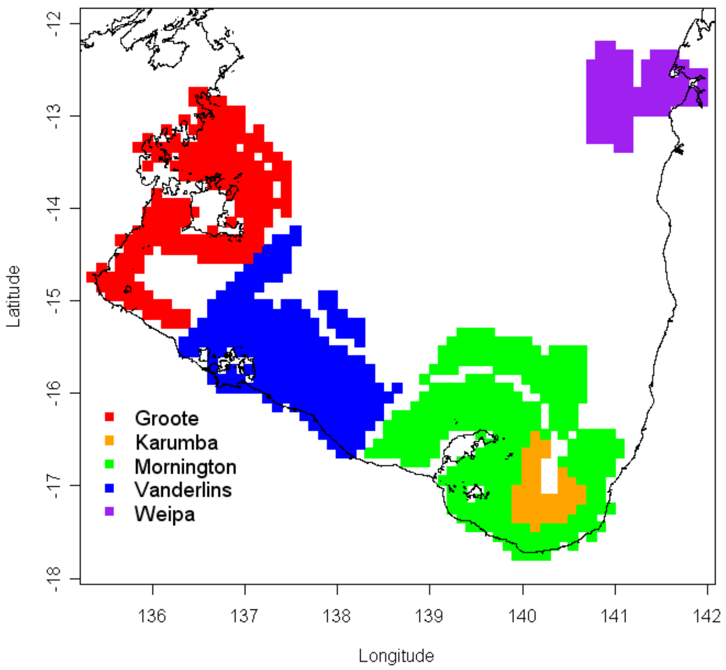


Figure 9.1. Map of regions in the Northern Prawn Fishery that the NPF prawn monitoring survey catch data were allocated.

In the laboratory, it was not possible to process all cuttlefish and squid samples due to time constraints. A strategy was undertaken to obtain the best representation of species both spatially and temporally (refer Chapter 7) (Table 9.1).

Species composition of the byproduct groups are described in detail in Chapter 8. The byproduct catches made during the NPF prawn monitoring surveys were widely distributed throughout the monitoring region in the Gulf of Carpentaria (Table 9.1, Figure 9.2). It is clear from these maps that each region was not visited consistently through time. For example, the Vanderlins region was visited in August in 2002 and 2003 but in the remaining years, sampling in the region occurred in January, February, June and July.

Table 9.1. Summary of the frequency (%) each species occurred in samples for each byproduct group collected from each region during the NPF prawn monitoring surveys between 2002 and 2008.

Byproduct group	Species	Region (%)				
		Weipa	Groote	Mornington	Vanderlins	Karumba
Squid	*Aestuariolus noctiluca*	12.5	5.1	14.5	9.8	48.2
	Uroteuthis sp 1	1.4	0	0	0	1.2
	Uroteuthis sp 2	5.6	27.4	13.8	6.6	7.1
	Uroteuthis sp 3	41.7	70.9	61.4	57.4	76.5
	Uroteuthis sp 4	52.8	37.6	55.2	62.3	20.0
	Sepioteuthis lessoniana	1.4	0	2.1	0	0
Cuttlefish	*Sepia elliptica*	89.9	96.8	88.8	93.0	97.0
	Sepia smithi	33.7	35.4	59.3	52.0	41.6
	Sepia pharaonis	29.6	22.8	45.0	66.0	2.0
	Sepia papuensis	20.7	9.5	37.6	34.0	4.0
	Metasepia pfefferi	5.9	7.0	13.2	14.0	0
Bugs	*Thenus parindicus*	98.5	99.7	99.6	99.2	100
	Thenus australiensis	39.0	4.0	23.7	35.8	1.2
Scallops	*Amusium pleuronectes*	99.7	99.6	97.5	100	99.0
	Annachlamys flabellata	26.0	13.3	50.1	22.8	5.2

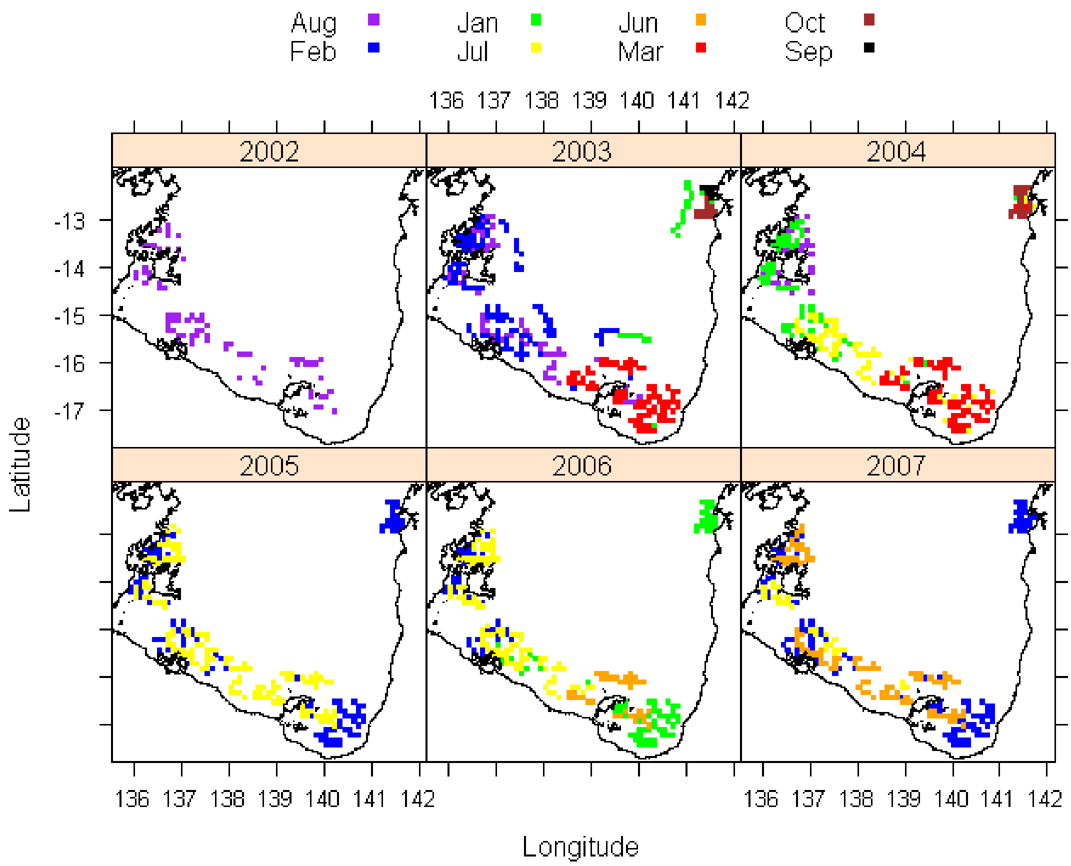


Figure 9.2. Spatial distribution of sampled byproduct catches from trawls made during the NPF prawn monitoring surveys sorted by year and month.

9.3.2 Environmental variables

Several explanatory variables were expected to influence species distribution and thus predict species composition for each byproduct group. These included spatial and temporal terms (Table 9.2). These variables were grouped into the following categories: spatial, temporal and environmental data. Subsets of these variables are mapped in Figure 9.3 and Figure 9.4. A more detailed description of the variables is provided below.

Spatial variables included grid coordinates, latitude and longitude, depth, NPF area, or a more coarse classification such as NPF region (e.g. Karumba, Mornington, Groote). As well, derived spatial coordinates such as RLand and RDist, represent the distance from the coastline in degrees and the distance along the coastline in degrees respectively. RDist in particular is useful for capturing changes along the coastline which may show a difference in species composition.

The spatial variable, RLand tried to capture changes in species composition as boats fished in deeper waters and is therefore related closely to depth (Figure 9.3 a, c). These spatial variables have been found useful in models of prawn species composition in previous studies of northern Australian fishing regions (Venables and Dichmont 2004). In that study, a spline term of RDist in particular was important in predicting the species composition of tiger prawns that showed significant differences across the NPF.

Table 9.2. Summary of explanatory variables used in developing the models of species composition.

Variable Type	Variable Label	Interpretation
Spatial	Latitude and Longitude	Geographical co-ordinates
	RDist	Distance along the coastline in degrees from a fixed point
	RLand	Distance from the coastline in degrees (1 degree ~ 111 kilometres (60 nm))
	Depth	Depth in metres
	Area	Fishing Region
Temporal	Month	Fishing month
	Year	Fishing year
	Day	Long-term trend: Number of days since 1st January 1970
	BDay	Byproduct Day: Day in fishing year when byproduct was caught
Environmental	Mud	Percent mud (%)
	Sand	Percent sand (%)
	Gravel	Percent gravel (%)

Temporal variables included month, year, a long-term trend that we refer to as “Day” and a seasonal term called “BDay”. The long-term trend is calculated as the number of days since the 1st of January 1970, while the seasonal term represents the day number within a byproduct fishing year ranging between 1 and 365. The time series for this dataset consists of six years from 2002 to 2007, with only a subset of months being surveyed within a particular year (Figure 9.2).

The months in which samples were collected, were not consistent from year to year. For example, in 2002, data from the month of August was the only month where data was obtained for byproduct species as it was the start of the NPF prawn monitoring survey project. In 2003 and 2004, samples was collected in January/February, March and then in July and October. For the three most recent years samples were collected in February, June and July.

Sediment type was the only environmental variable available for this analysis. Fishers do not record sediment type in their logbooks but do record location. Using data from other studies, where sediment type has been mapped in the NPF, we obtained sediment composition for locations in the logbooks.

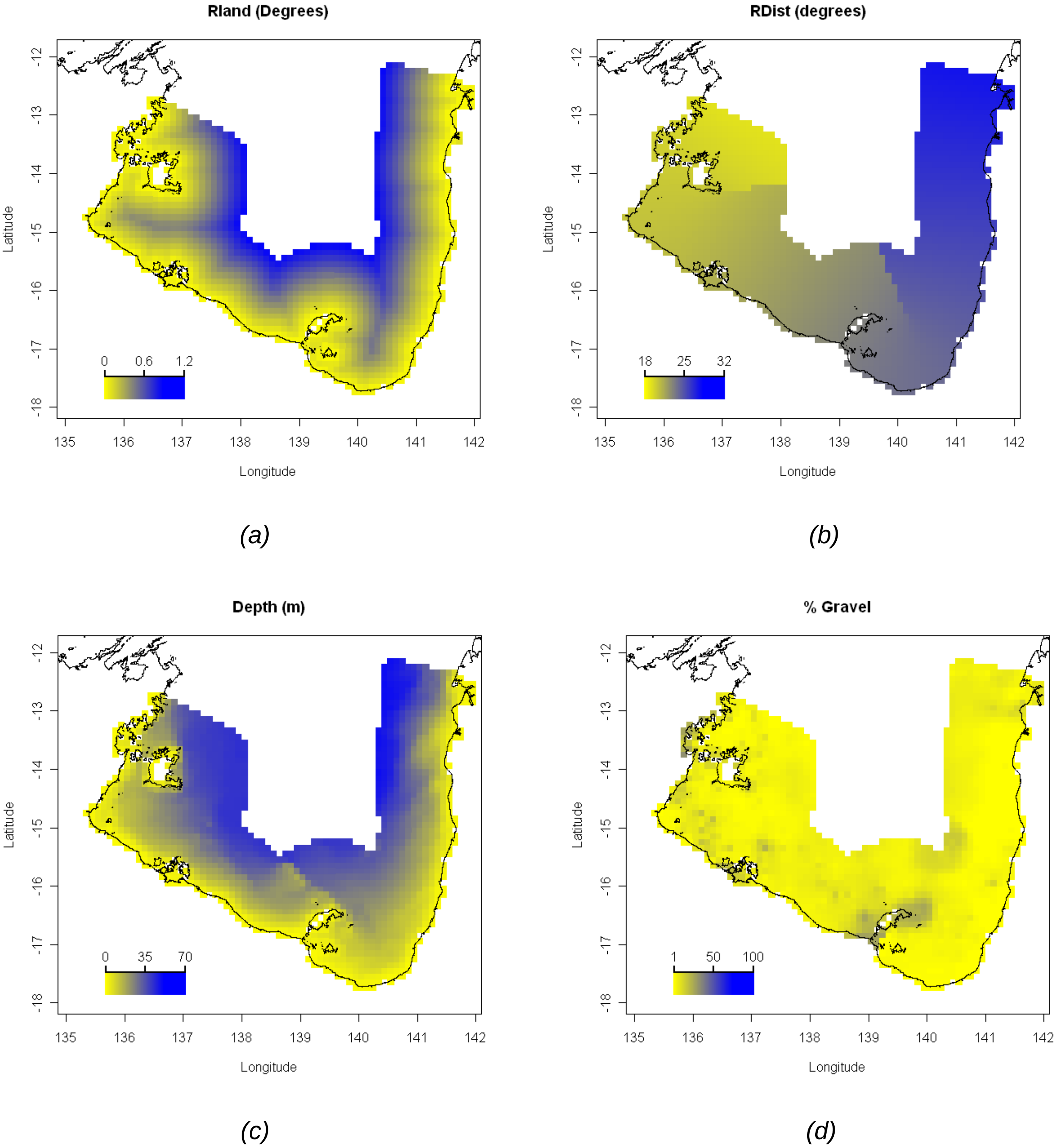


Figure 9.3. Map of explanatory variables showing (a) RLand: distance from the coastline in degrees, (b) RDist: distance from a specific point along the coastline (lat = -16.925°, long = 122.113°), (c) depth in metres and (d) percentage gravel.

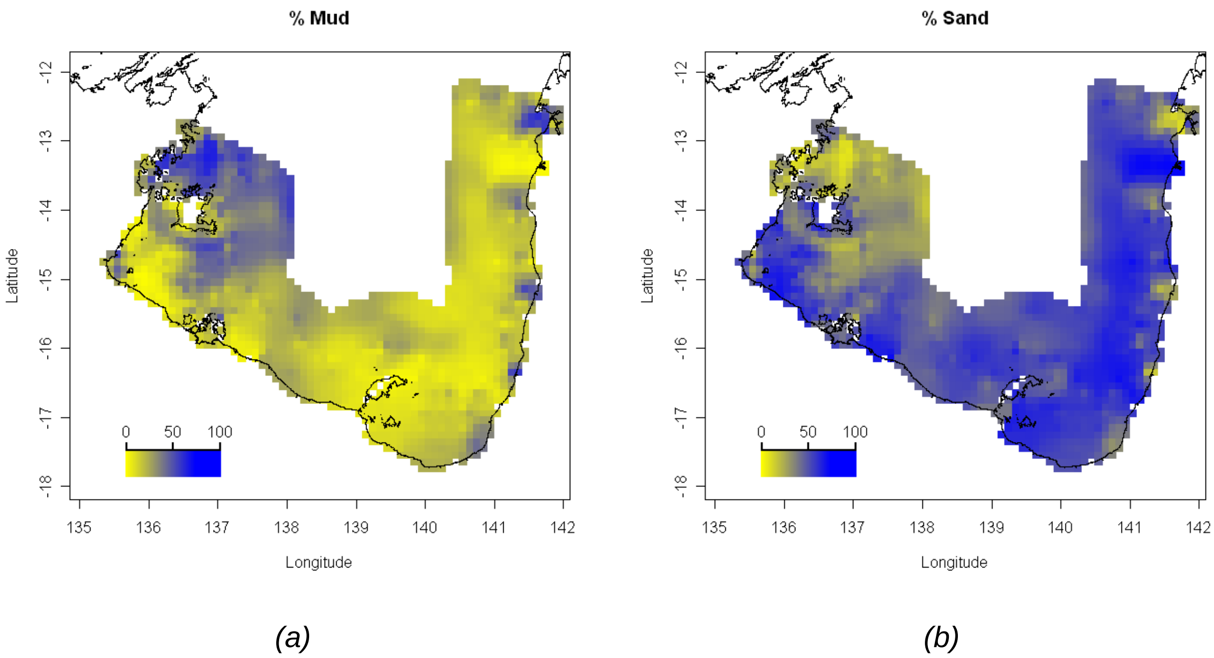


Figure 9.4. Map of explanatory variables showing (a) percentage mud and (b) percentage sand within the Northern Prawn Fishery fishing zones.

9.3.3 Data analysis

Byproduct catches from the NPF prawn monitoring surveys used in the predictive models contained all individuals caught and thus were not directly comparable with catches reported in commercial logbooks. The discrepancies between the two sources arose for two reasons and these are outlined below.

Discrepancy 1: Size threshold

The commercial logbooks report the total weight of all byproduct retained by fishers. Fishers usually only retain animals that exceed an economic size threshold. For most byproduct groups, small individuals were discarded. This is a problem only if the discard proportion survives. If the discarded byproduct survives, the NPF prawn monitoring survey catches will be biased. They will contain an unknown proportion of the true catch that would be discarded under commercial conditions. For bugs and scallops, the discarded proportion was assumed to survive. To build an accurate model to predict species composition, we need to separate small from the large individuals in the NPF prawn monitoring survey dataset to reflect the proportion kept commercially. The size restrictions for the byproduct groups (Table 9.3) were not officially recorded (except bugs) and we based them on typical commercial fishing practices communicated by industry.

During the NPF prawn monitoring surveys, the bugs (*Thenus* species) were measured for carapace length (in mm). The NPF is regulated by a minimum legal size (MLS) of 75 mm carapace width and a restriction on retaining egg-bearing females. Determining the bug discard proportion in the NPF prawn monitoring survey data can be undertaken by examining length-width relationships of a subsample of individual species, and predicting the widths of individuals that are over a certain carapace length (40 mm) and adjusting for the proportion berried in the sample. Those that have a length less than the size limit (Table 9.3) represent those animals in the NPF prawn monitoring survey dataset that would have been discarded under commercial practices and were therefore discarded from the analysis. In addition to predicting widths, individual weights of animals given their length can also be predicted and used to determine a total weight per catch. For the squid, cuttlefish and scallop groups, the small individuals caught during the NPF prawn monitoring surveys that were under the minimum commercial size threshold were also discarded from the analysis.

Table 9.3. Size limits set for byproduct species in the Northern Prawn Fishery. + = mantle length (in mm), * carapace width of males and non-berried females, ^ = shell width (in mm).

Byproduct Group	Size Limit	Survival of Smaller Individuals
Bugs	75 mm*	Yes
Scallops	63.5 mm^	Yes
Squid	125 mm+	No
Cuttlefish	~100 mm+	No

Discrepancy 2: Null reporting

As the commercial logbook records only report animals over a certain size threshold, there will be situations where the entire catch contained individuals below the nominated threshold level. As a result, a zero or null value will be reported in the logbook. It is difficult to disentangle the interpretation of a zero in these instances as (a) all animals were below the size threshold, (b) or no animals were caught during that night of fishing, (c) or the volume of byproduct catch did not warrant animals being retained and processed.

Unlike the size threshold issue, determining the true total weight of the catch in the commercial logbook data is much more complicated. We initially considered trying to estimate the weight of the catch missing using a joint model of the form,

$$[W_i] = [W_i \mid l \le t] + [W_i \mid l > t] \quad (9.1)$$

where W_i represents the total weight of the i-th trawl, l represents the length of individuals caught in the trawl, t represents the size limit (Table 9.3) and $[\ ]$ represents a suitable probability distribution in which to model the catch weight. The NPF prawn monitoring survey data provides all three sources of information shown in Equation 9.1. However, the NPF commercial logbook data only provides information on the second distribution shown on the right hand side of Equation 9.1. As a result, estimating the first component in this equation is a complex task. We could consider fitting a zero-inflated model to the NPF prawn monitoring survey data to estimate the components of the joint model shown in Equation 9.1. However, the trawling intensity is quite different for both types of surveys. The NPF prawn monitoring surveys are typically 30 minute trawls compared to commercial trawls of duration around three hours. This makes the estimation task a difficult one and for that reason, we have chosen to concentrate only on "Discrepancy 1" (accommodating the size threshold) in this report but acknowledge a possible bias in predicted proportions when estimated from the commercial logbook records.

Length-Weight and Length-Width Relationships for Thenus spp

The development of length-weight and length-width relationships for the bugs was necessary to determine weights of individual animals and the proportion of animals discarded respectively. This allowed for the development of a more plausible and accurate predictive model of species composition that could be applied to the commercial dataset. Two types of models were fitted to size related data collected for specific byproduct groups where length-weight and length-width relationships were required.

The first model developed a relationship between weights of individuals (w_{F_i}, w_{M_i}) and their corresponding lengths (l_{F_i}, l_{M_i}) for females (*F*) and males (*M*) as shown in Equation 9.2. This model was used to predict weights of individual animals which can be summed to find a total weight that is used in the model. In Equation 9.2, the index i represents the index for individual bugs.

$$\begin{aligned} \log(w_{F_i}) &= \alpha_{F_0} + \alpha_{F_1}\log(l_{F_i}) + e_{F_i} \\ \log(w_{M_i}) &= \alpha_{M_0} + \alpha_{M_1}\log(l_{M_i}) + e_{M_i} \end{aligned} \qquad (9.2)$$

The second model formed a relationship between the width (wd_{F_i}, wd_{M_i}) of an individual and its length (l_{F_i}, l_{M_i}) for each sex (Equation 9.3). This type of model was necessary for certain byproduct groups such as bugs, where the size restriction relates to the width of the animal and not the length. In the NPF prawn monitoring survey data, only lengths are recorded.

$$\begin{aligned} \log(wd_{F_i}) &= \alpha_{F_0} + \alpha_{F_1}\log(l_{F_i}) + e'_{F_i} \\ \log(wd_{M_i}) &= \alpha_{M_0} + \alpha_{M_1}\log(l_{M_i}) + e'_{M_i} \end{aligned} \qquad (9.3)$$

Errors were appropriately included in both equations.

For each type of relationship explored, a robust linear model was fitted to the log transformed data. The log transformation was necessary to provide a relationship that is approximately linear, and distributions that are approximately normal.

Robust regression is a statistical method useful for modelling data containing outliers or influential points, which are sometimes reflected in the relationships described above. The concept is analogous to using the median as a measure of location, instead of the mean, for data with outlying observations. The median is a more resistant measure of location than the mean. Robust regression differs from standard statistical regression methods such as least squares because it attempts to down-weight highly variable observations occurring at the tails of the distribution that might influence the estimates from the regression model.

The aim of this type of analysis is to obtain a predictive model with realistic standard errors that is highly efficient and not heavily influenced by outlying points. Occasionally these outlying points are the result of errors made through the data entry process but more often, these outlying points are correct. In the latter situation it is important not to remove the outlying observation, but adjust the model accordingly to avoid underestimating coefficients and variance estimates. The `lmRob` function from the robust package in R was used to fit these types of models.

Two Species Split

For byproduct groups consisting of two species, we adopted an approach consistent with that described by Venables and Dichmont (2004). The model assumes that the proportion, Y is a random variable with mean and variance of the form

$$E(Y) = \mu, \ \ \mathrm{Var}(Y) = \frac{\mu(1-\mu)}{T/\varphi} \qquad (9.4)$$

where μ represents the ideal proportion about which the response is distributed, T represents the total weight of the byproduct species caught, and φ is an unknown scalar constant. The expression for the variance in Equation 9.4 is structured such that the variance is at a maximum when μ is equal to 0.5 and is at a minimum when μ is close to either 0 or 1.

In this model the predictor variables relate linearly to Y via the ideal proportion, μ through a logistic link. The linear predictor, which is shown in Equation 9.5, may consist of a combination of linear and non-linear terms. A more flexible model that we consider however is a generalised additive model (GAM) as implemented in Venables and Dichmont (2004).

$$\log\left(\frac{\mu}{1-\mu}\right) = \eta = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p \qquad (9.5)$$

where β_i is the slope parameter for the range of environmental and spatial predictors x_i. Like Venables and Dichmont (2004), we considered an isotropic spline to estimate the relationships between latitude and longitude, and RDist and RLand and smoothed terms for sediment, temporal terms and depth. In some situations we considered fitting a tensor spline to investigate the interaction between temporal variables such as BDay and spatial variables such as RDist.

We implemented this model in R with the `mgcv` package and in particular the `gam` function with a quasi-likelihood that specifies explicitly, the mean-variance relationship shown in Equation 9.4. Validation of each model was performed with cross-validation or alternatively, using a test dataset with the Hellinger distance computed between the predicted and actual proportions. The Hellinger distance is an ideal metric for comparing vectors of proportions as it requires that each vector has positive or zero elements. For the current problem, the vectors represent the actual and predicted species proportions. One attractive property of the Hellinger distance is that the vectors of these proportions represent points on a sphere. Points that are close together indicate similarities between the predicted and actual species composition, while those further apart suggest differences between the predicted and actual composition. The distance metric d_H (Rao 1995) is defined as

$$d_H(a,b) = \left[\sum_{j}^{J} \left(\sqrt{a}_j - \sqrt{b}_j \right)^2 \right]^{\frac{1}{2}} \qquad (9.6)$$

where J represents the number of observations from which a distance is calculated and a and b are the observed and predicted values.

Multi-Species Split

We investigated a range of models for predicting the species composition of byproduct groups with more than two species. Models investigated included neural networks, a multinomial model and classification trees with and without bagging. After some initial exploration, we found the bagged classification tree to perform the best, followed by a pruned classification tree. Consequently, subsequent analyses focused on the model development of the classification tree. We evaluated each type of model using the Hellinger distance, which was used to compare the actual and predicted species composition.

Classification trees have become a popular tool in ecology for classifying species into classes according to a suite of important predictor variables. The approach, which is based on the ideas of Breiman et al. (1984) is non-parametric in the sense that the input data does not need to be of a specific parametric form and can be ordinal, categorical, continuous or binary, or even a mixture of these different data types. Missing values are also allowed, which make analysis flexible and case weights can be added to reflect differences in catch size. For byproduct, in particular squid and cuttlefish, the classes modelled represent the species caught in each trawl.

Classification trees operate by partitioning the data into similar groups according to the gini criterion. The gini criterion is a type of misclassification error and therefore partitioning is conducted in such a way as to reduce the overall misclassification rate. Once a large tree is grown, the tree is pruned back using cross-validation, from which, an optimal tree is selected. This is typically the tree yielding the lowest cross-validated error rate. However, other trees of slightly smaller size but comparable in accuracy (or within one standard error) could also be selected. Predictions are formed by running data down the branches of the tree until a terminal node is reached and a classification is assigned. The `rpart` package in R allows for the construction of such a model and is based on the methods outlined in Breiman et al. (1984) and Therneau and Atkinson (1997).

To improve model prediction, aggregating methods have been proposed, namely bagging, which was first introduced by Breiman (1996) and later extended and implemented in R (Breiman 2001). Breiman identified instability with the classification tree model brought about by the greedy nature of the partitioning algorithm. He found that through bootstrap aggregation, otherwise termed as “bagging”, predictions could be improved by eliminating the bias inherent in the classification tree method. Here, unpruned classification trees were fitted on bootstrap samples of the data. Predictions are formed for each tree model and averaged across models to form a “bagged” prediction. Although achieving more accurate predictions, no tree is produced and this can be considered a downfall of the approach if a model is required. Despite this, other pieces of information can be retrieved from the modelling process that can aid in the interpretation of the model. These were namely, variable importance rankings and partial dependence plots that show relationships between predictor variables and the predicted class.

An implementation of the approach is available in R as part of the `randomForest` package. However the package does not implement case weights, which is important for analysing byproduct species. To overcome this problem, we implemented "bagging" the traditional way as outlined in Breiman (1996). We used the "out-of-bag" samples to form the predictions as on average, 37% of the samples will not be present in any given bootstrap. This provided an adequate test dataset on which to base the predictions (Breiman 2001).

Standard errors are not automatically produced as a result of this model and will require further investigation if they are to be incorporated in a stock assessment of byproduct species. As standard errors are not an integral part of current stock assessments of the target prawn species in the NPF, we only focused on the predictions from these types of models.

9.4 Results

9.4.1 Bugs

Determining the discard proportion

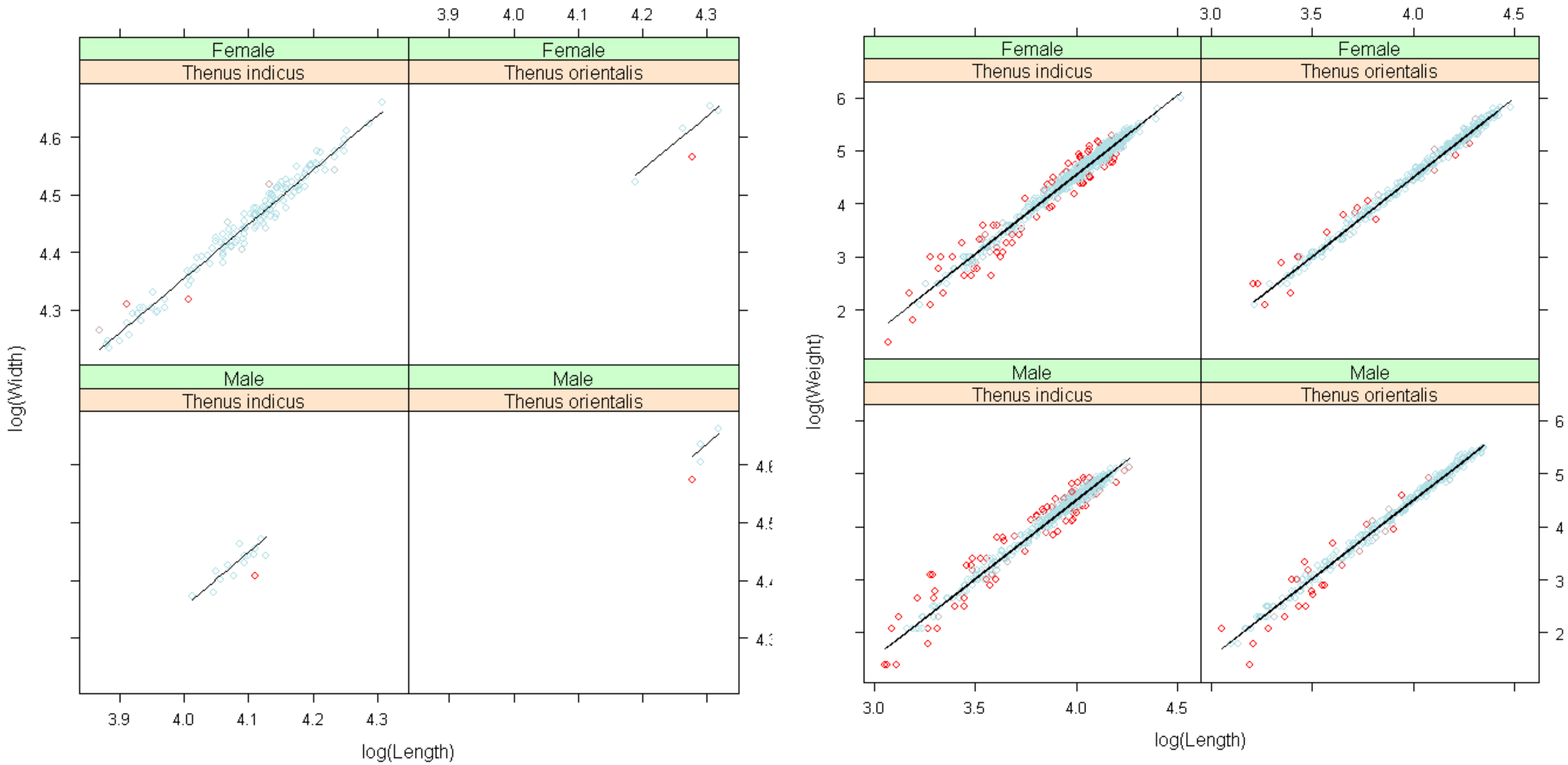
The minimum legal width (MLS) of bugs in the NPF is 75 mm and those that get discarded from a commercial catch are assumed to survive. As the catches from the NPF prawn monitoring surveys are of carapace length and do not accurately reflect the size composition of commercial catches, we converted survey carapace length to width (Table 9.4) in order to remove those animals that have a width below 75 mm.

Table 9.4. Summary of the carapace length-width relationships for the two bug species combined.

Term	Coefficients	SE	*t*-value	*p*-value
Intercept	0.5934	0.0575	10.32	< 0.001
log(length)	0.9405	0.0140	67.16	< 0.001

Figure 9.5 (a) shows the results from fitting a robust regression to the carapace length-width data for bugs. The data is overlayed on the straight line which forms the relationship between the log of the width and log of the length of individual bugs. Influential points (highlighted in red) are down weighted in the robust regression and models are fit separately for each species and each sex. Despite the limited data for the reef bug (*T. australiensis*) and male mud bugs (*T. parindicus*), the results indicate little differences between the sexes of each species. As a result, we fit a length-width relationship to bugs, ignoring sex (Table 9.5).

Carapace length-weight relationships were also examined to predict the individual weights in the NPF prawn monitoring survey data so that a total weight could be estimated from each trawl. Figure 9.5 (b) displays the results of the fit with the estimates in Table 9.5. Once again, points deemed influential are displayed in red and are therefore down weighted when estimating the fitted line. Results indicate that similar relationships exist for each species and each sex within species.



(a) (b)

Figure 9.5. Robust regression relationships for (a) the log of bug carapace width versus the log of bug carapace length broken down by species and sex, and (b) the log of bug weight versus the log of bug carapace length broken down by species and sex. Red points indicate highly influential points that are down weighted in the regression model. Note name replacements: *T. parindicus* replaces *T. indicus* and *T. australiensis* replaces *T. orientalis*.

Table 9.5. Summary of the carapace length-weight relationships for the two bug species.

Term	Coefficients	SE	*t*-value	*p*-value
Thenus parindicus				
Female: Intercept	-7.4059	0.068	-109.10	< 0.001
Female: log(Length)	2.9886	0.017	177.20	< 0.001
Male: Intercept	-7.4251	0.077	-96.35	< 0.001
Male: log(Length)	2.9825	0.019	152.22	< 0.001
Thenus australiensis				
Female: Intercept	-7.4562	0.072	-103.77	< 0.001
Female: log(Length)	2.9901	0.018	168.17	< 0.001
Male: Intercept	-7.3113	0.069	-105.42	< 0.001
Male: log(Length)	2.9543	0.018	166.15	< 0.001

Model of Species Composition

A series of generalised additive models (GAMs) were fitted to the bug data to model the proportion of mud bug caught as byproduct in the NPF. Cross-validation was used to evaluate the performance of each model in relation to the Hellinger distance. The model that produced the smallest distance in terms of cross-validation has the best fit for both spatial and temporal terms (Figure 9.6). Table 9.6 contains a smooth isotropic term for latitude and longitude, RDist and RLand, a smooth term for Mud, BDay, Day and Depth. Cross-validation results (Figure 9.6) of the series of models examined show the Hellinger distance resulting from using the training data to predict the proportion of mud bug. The figure also indicates the results when cross-validation is used (red line). The percent deviance explained for this model is 68.3% (Table 9.6).

Figure 9.7 shows plots of the actual versus the predicted proportion when cross-validation is used as opposed to just the training data. The plots reveal some discrepancies between the predicted and actual proportions.

Figure 9.8 shows termplots of the relationship between each smoothed term in the model and its relationship between the response on the logit scale. These plots are only presented for the main terms in the model. Each plot shows the smooth, flexible relationship along with its error, shown as a grey shadow around the curve and a rug plot indicating the locations of observed data.

Table 9.6. Generalised additive modelling results of the "best" model for the proportion of mud bugs in the NPF prawn monitoring survey catches. Statistics summarising the performance of the model include the percent deviance explained, adjusted R^2 and the cross-validated Hellinger distance.

Variable	Effective Degrees of Freedom	Estimate	SE	*p*-value
Intercept		6.756	0.36	< 0.0001
Smooth Terms				
s(Latitude, Longitude)	27.795			< 0.0001
s(RDist, RLand)	28.785			< 0.0001
s(Mud)	8.496			< 0.0001
s(BDay)	8.821			< 0.0001
s(Day)	8.949			< 0.0001
s(Depth)	6.637			< 0.0001
% Deviance Explained				68.3
Adjusted R^2				0.992
Cross-Validated Hellinger Distance				3.715
Number of Observations				3013

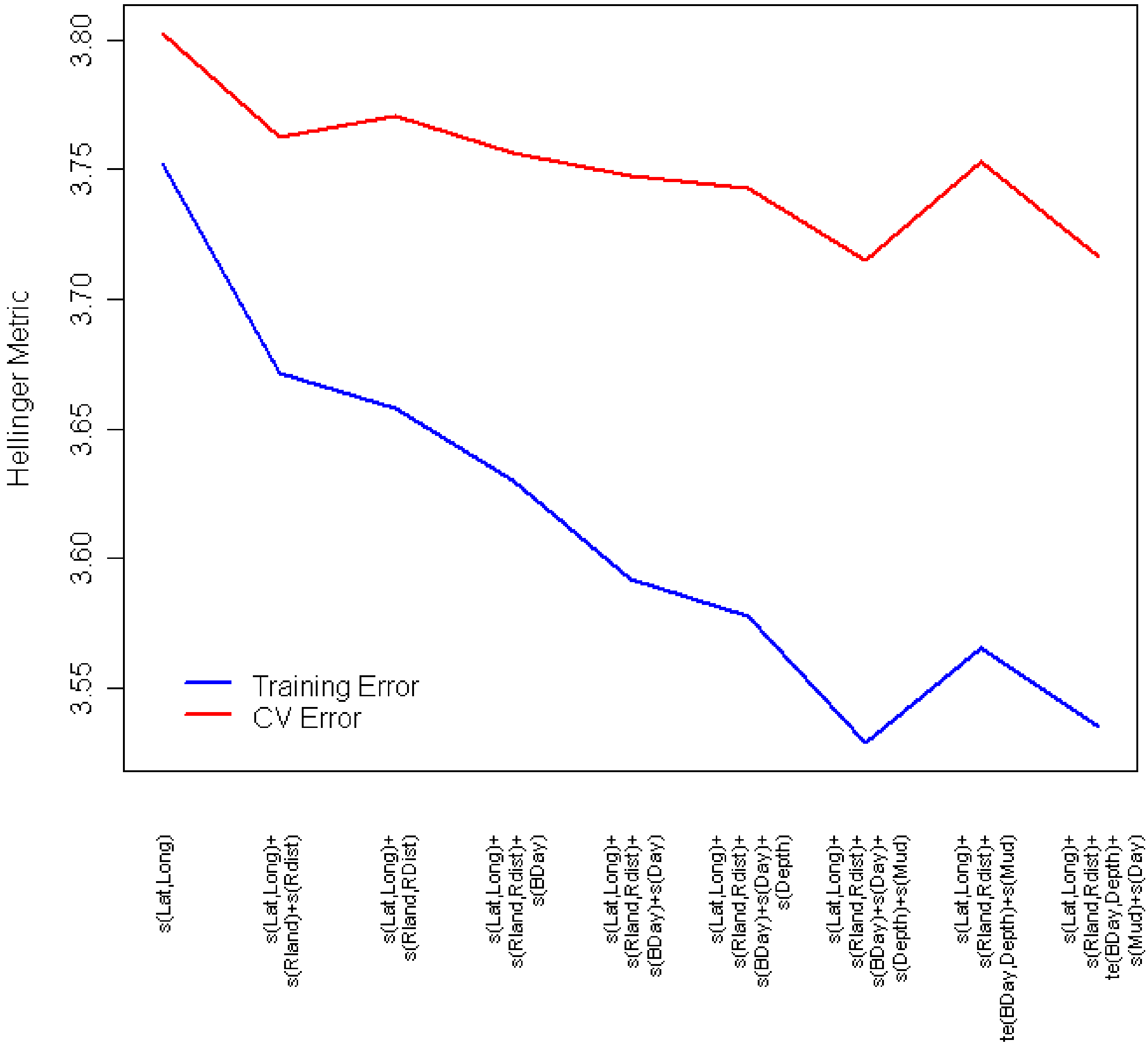


Figure 9.6. Cross-validation (red line) and re-substitution (blue line) mean square error for various additive models explored for bugs.

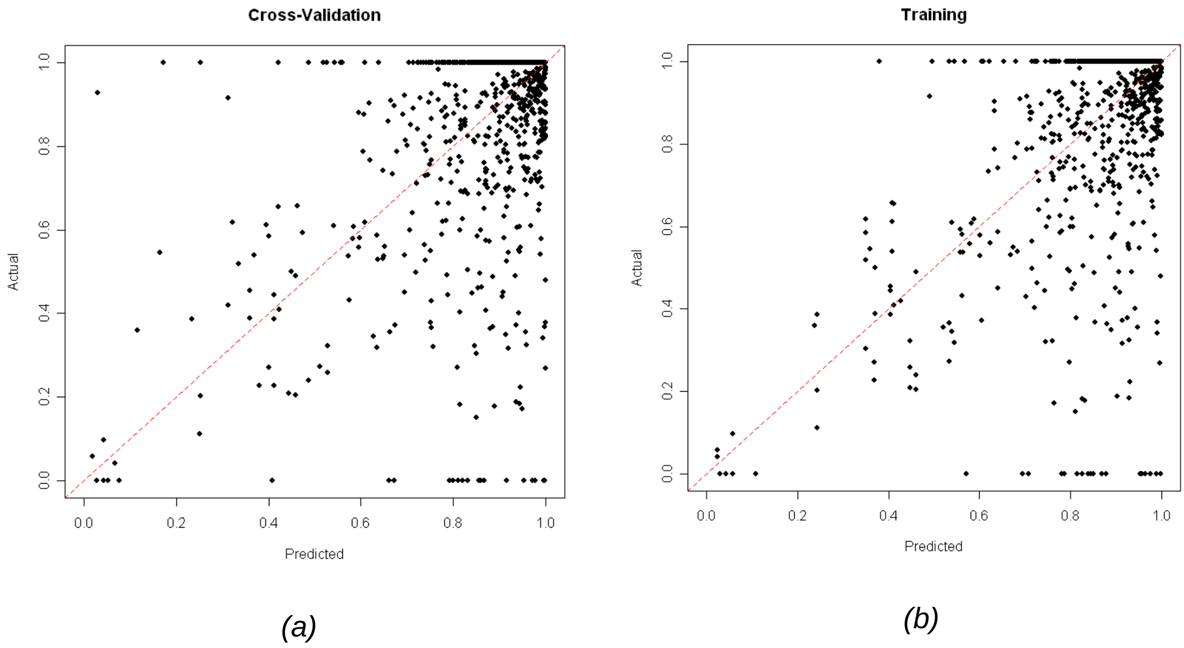


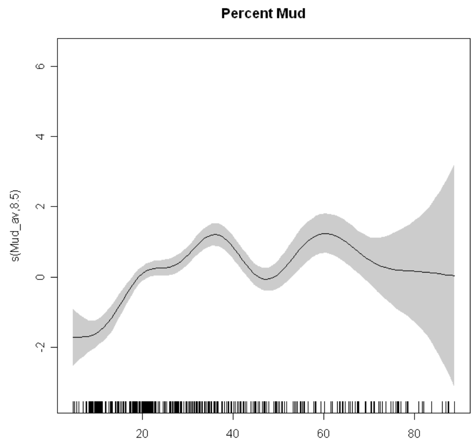
Figure 9.7. Plots showing the actual and predicted proportion of mud bug based on (a) cross-validation and (b) the training dataset.

Figure 9.8 (a) shows the termplot for Mud (percent mud in substrate) and indicates a slight decrease in the proportion of mud bugs when low percentages of mud were found, and increased when the percent mud increased to approximately 40%.

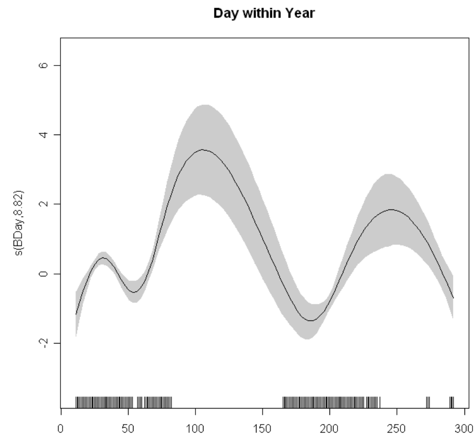
As expected, a cyclic term is apparent for BDay (Figure 9.8 b) and shows a decrease in mud bug proportions during February, March, June and July. Increases are noted during April, May, August and September, however there is large error associated with these predictions. This is largely due to the lack of data collected during these periods.

Figure 9.8 shows a steady increasing relationship through time for the long-term trend variable, Day. This suggests that as time goes by, increased proportions of mud bug were caught.

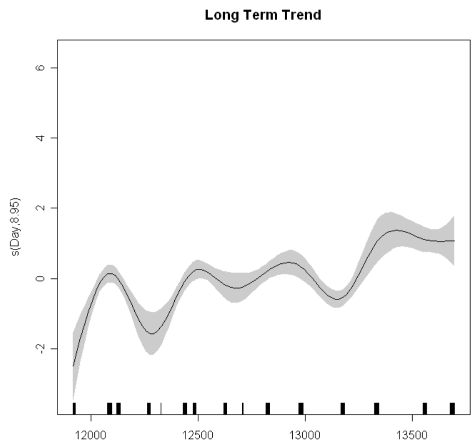
The smooth term for depth in Figure 9.8 indicates some increases in the proportion of mud bug in shallower waters, in particular, as well as in some deeper areas of the Gulf of Carpentaria. The predictions at these extremes have large errors attached due to the lack of data in these areas and therefore need to be interpreted with caution.



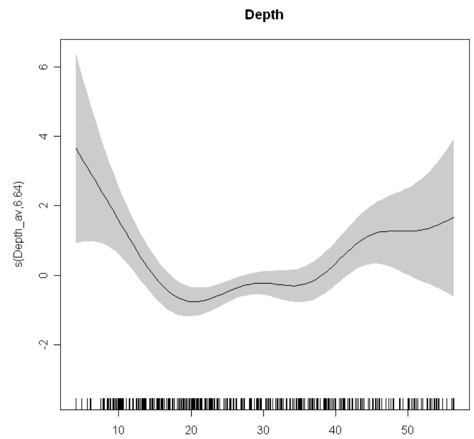
(a)



(b)



(c)



(d)

Figure 9.8. Termplot showing the relationship between (a) percent mud, (b) day within year (BDay), (c) long-term trend (Day) and (d) depth and proportion of mud bug predicted (logit-scale). Grey regions are the 95% confidence limits around the means.

Although the inclusion of these terms in the model for mud bug lead to a good predictive model, there is a very large spatial component that explains most of the variability in the data (Figure 9.9). They show the relationship between each smoothed term in the model and its relationship between the responses on the logit scale. These plots are only shown for main terms presented in the model. Each plot shows the smooth, flexible relationship along with its error, shown as a grey shadow around the curve and a rug plot indicating the locations of observed data for two periods throughout the year where it appears the prediction changes somewhat: 1st March and 1st August. For years where data was not collected on the 1st of the month, we took the earliest event recorded. Predictions and their corresponding lower and upper 95% confidence intervals are displayed in Figure 9.9 – Figure 9.12. In each series of plots, the legend reveals a graduation of colours indicating the size of the proportion. A low proportion is indicated by yellow while a high proportion is shown in red.

Figure 9.9 and Figure 9.10 show maps of the survey region in 2003 – 2007 with predictions overlayed for the 1st of March. Predicted proportions do not seem to change dramatically through time apart from some slight deviations in 2007. At this time, there is some increase in the predicted proportion of mud bug near Weipa and lower proportions in the Vanderlins and Mornington regions. Confidence intervals do indicate some variability in the predicted proportion in each year. For example, there is some uncertainty suggested throughout the Weipa region. However, some of this can be explained by the lack of data collected between Weipa and Mornington.

Figure 9.11 and Figure 9.12 show maps of the predicted proportion of mud bug in August. Compared to the March predictions, the August predictions look somewhat similar. Temporally, only slight changes in the predicted proportion are evident in 2005 and 2006 compared to the previous three years. The predicted proportion of mud bug appears to have increased across all spatial regions investigated.

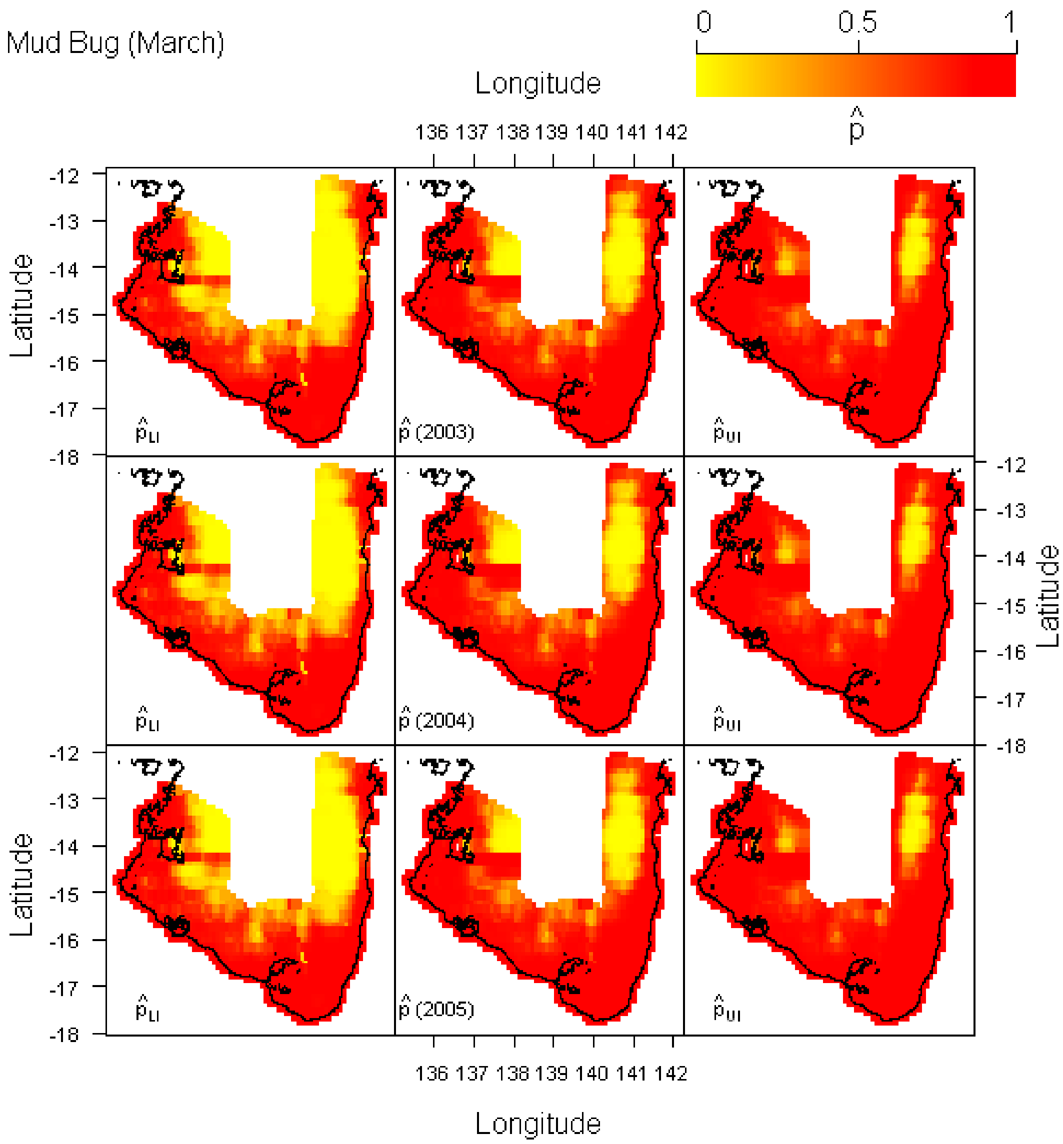


Figure 9.9. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for March 2003 – 2005. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

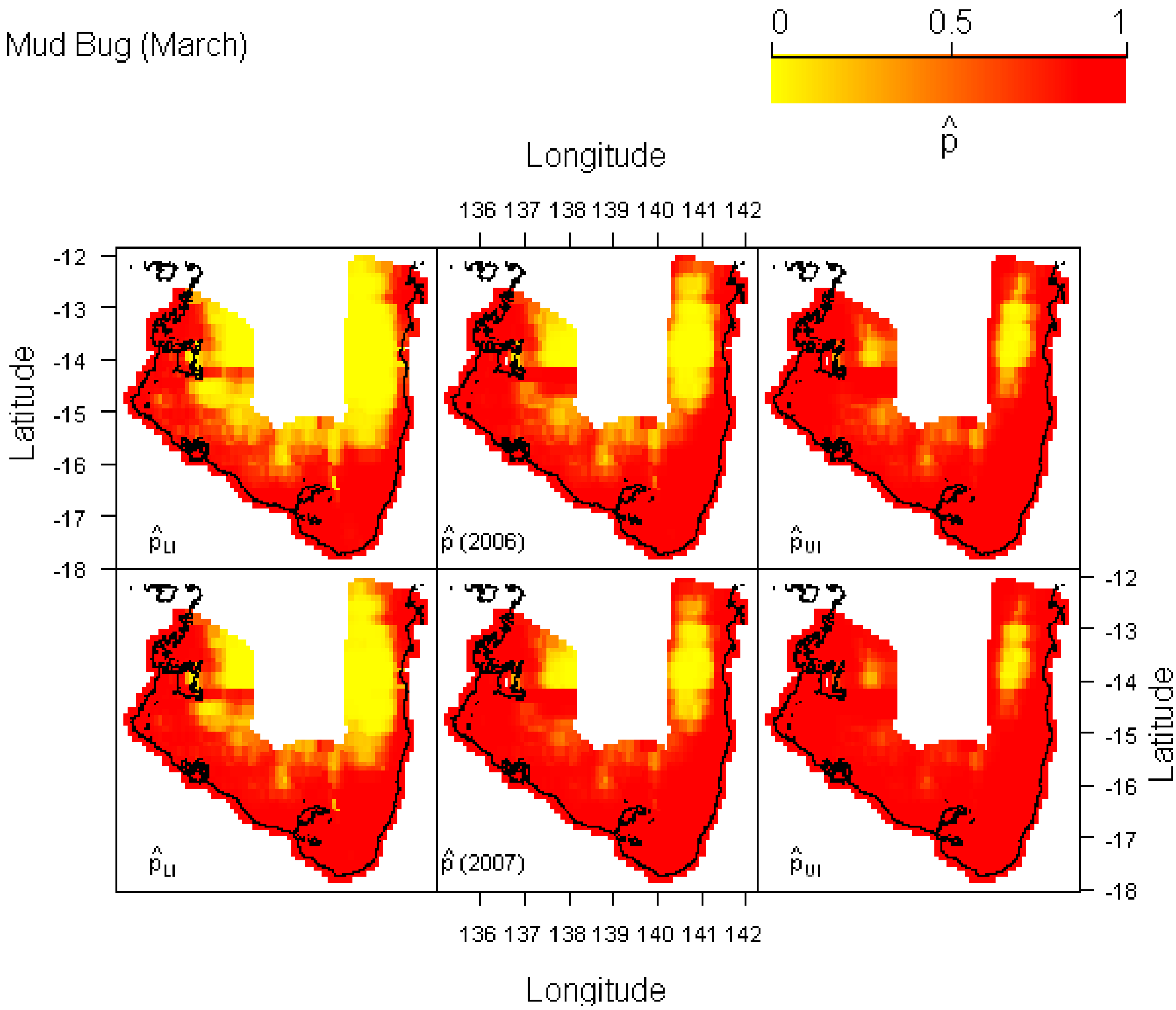


Figure 9.10. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for March 2006 – 2007. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

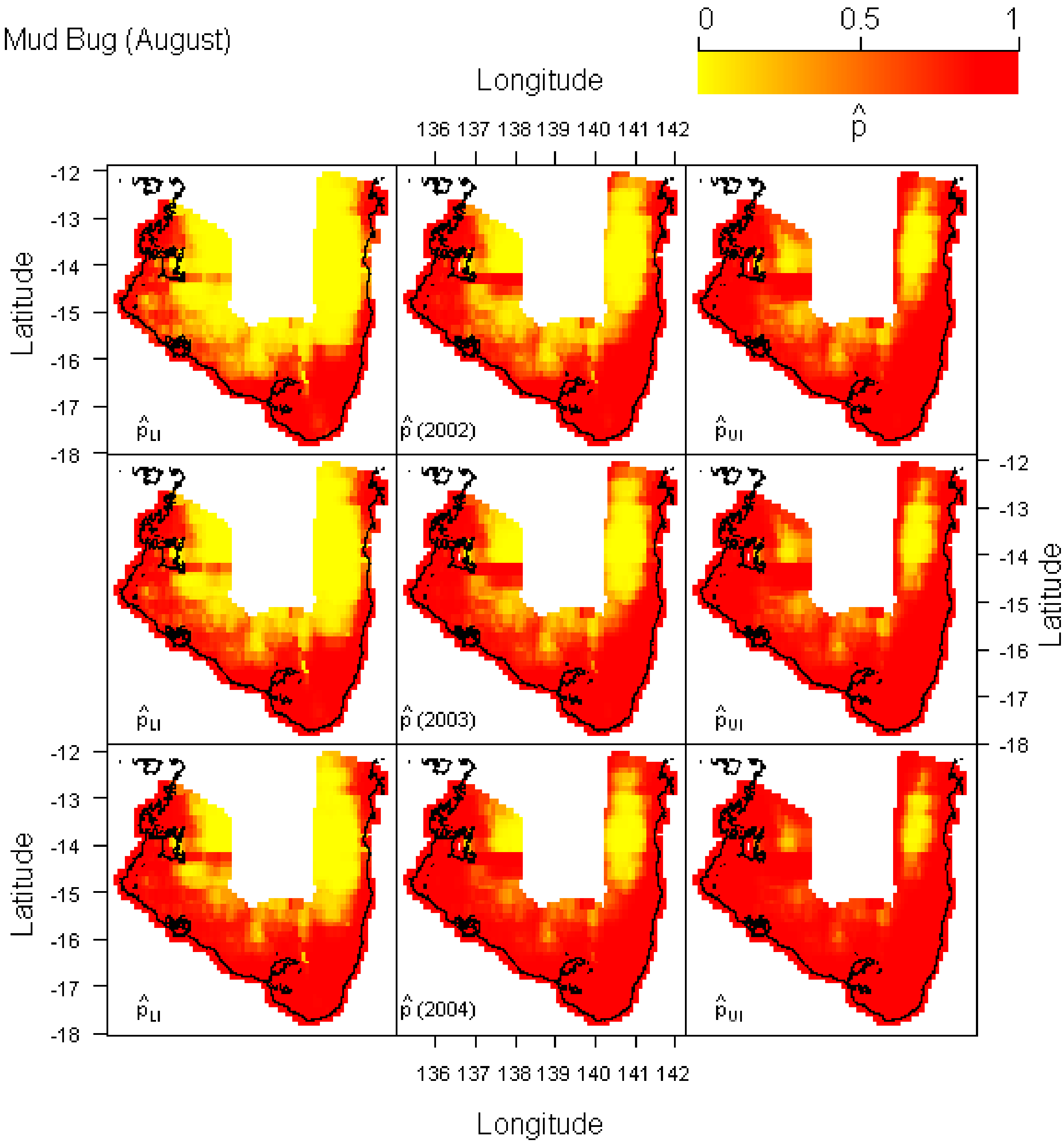


Figure 9.11. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for August 2002 – 2004. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

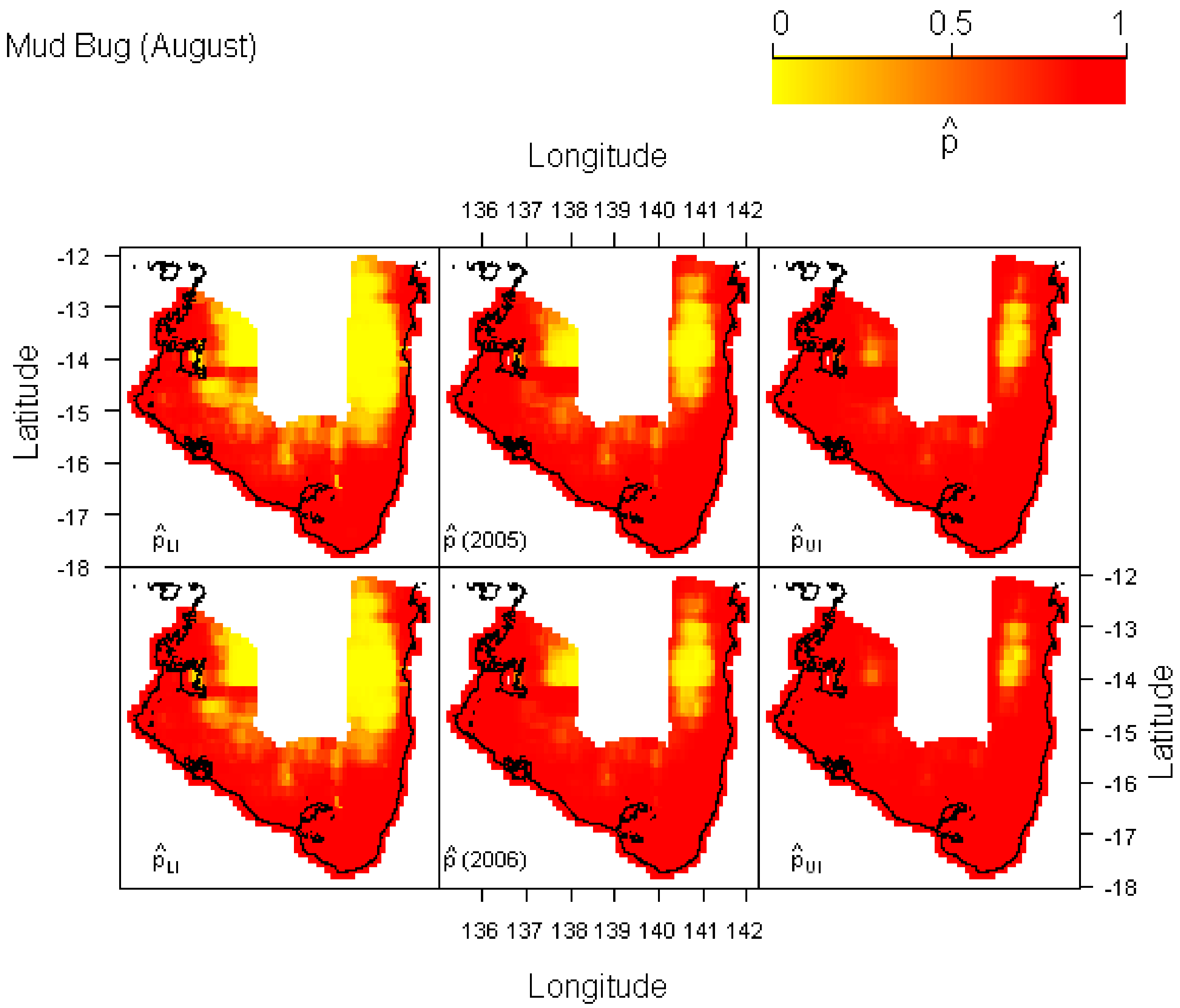


Figure 9.12. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for August 2005 – 2006. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

Table 9.7. Generalised additive modelling results for the catch allocation model that does not include Day. This model predicts the proportion of mud bug occurring in the NPF prawn monitoring survey region. Statistics summarising the performance of the model include the percent deviance explained, adjusted R^2 and the cross-validated mean square error (MSE).

Variable	Effective Degrees of Freedom	Estimate	SE	*p*-value
Intercept		6.932	0.380	< 0.0001
Smooth Terms				
s(Latitude, Longitude)	28.237			< 0.0001
s(RDist, RLand)	27.921			< 0.0001
te(BDay, Depth)	21.701			< 0.0001
s(Mud)	8.179			< 0.0001
% Deviance Explained				67.6%
Adjusted R^2				0.992
Cross-Validated MSE				0.0148
Number of Observations				3013

Including Day in the model presents an issue when attempting to split the commercial catch from year to year. Unless the model is revisited from year to year, it is difficult to determine whether the slight increasing trend (Figure 9.8) is real or whether it is purely an artefact of the data collected. The relationship to the commercial catch data for the purpose of producing a split into mud and reef bug could be problematic for this reason (Table 9.6). As an alternative, we fitted a second model (Table 9.7) that includes an isotropic term for latitude and longitude, RDist and RLand, a tensor spline for the interaction between BDay and depth, and a smooth term for mud using a smoothing spline. The choice of this model was once again determined via cross-validation (plots not shown). In this model, the deviance drops only slightly, to 67.6%.

Maps of the predicted proportion of mud bug across the survey region when Day is omitted from the model and an interaction between BDay and depth is included showed some subtle differences (Figure 9.13 – Figure 9.16). These differences are most apparent in the predicted proportion of mud bug in the deeper regions of the fishing grounds in the Gulf of Carpentaria. The previous model that included a long-term trend showed higher proportions of mud bugs in deeper water in the southern Gulf of Carpentaria (near Mornington and the Vanderlins). In the current model, these predictions are somewhat lower. There appears to be little difference between years, which is not surprising as there is no long-term trend included in this model.

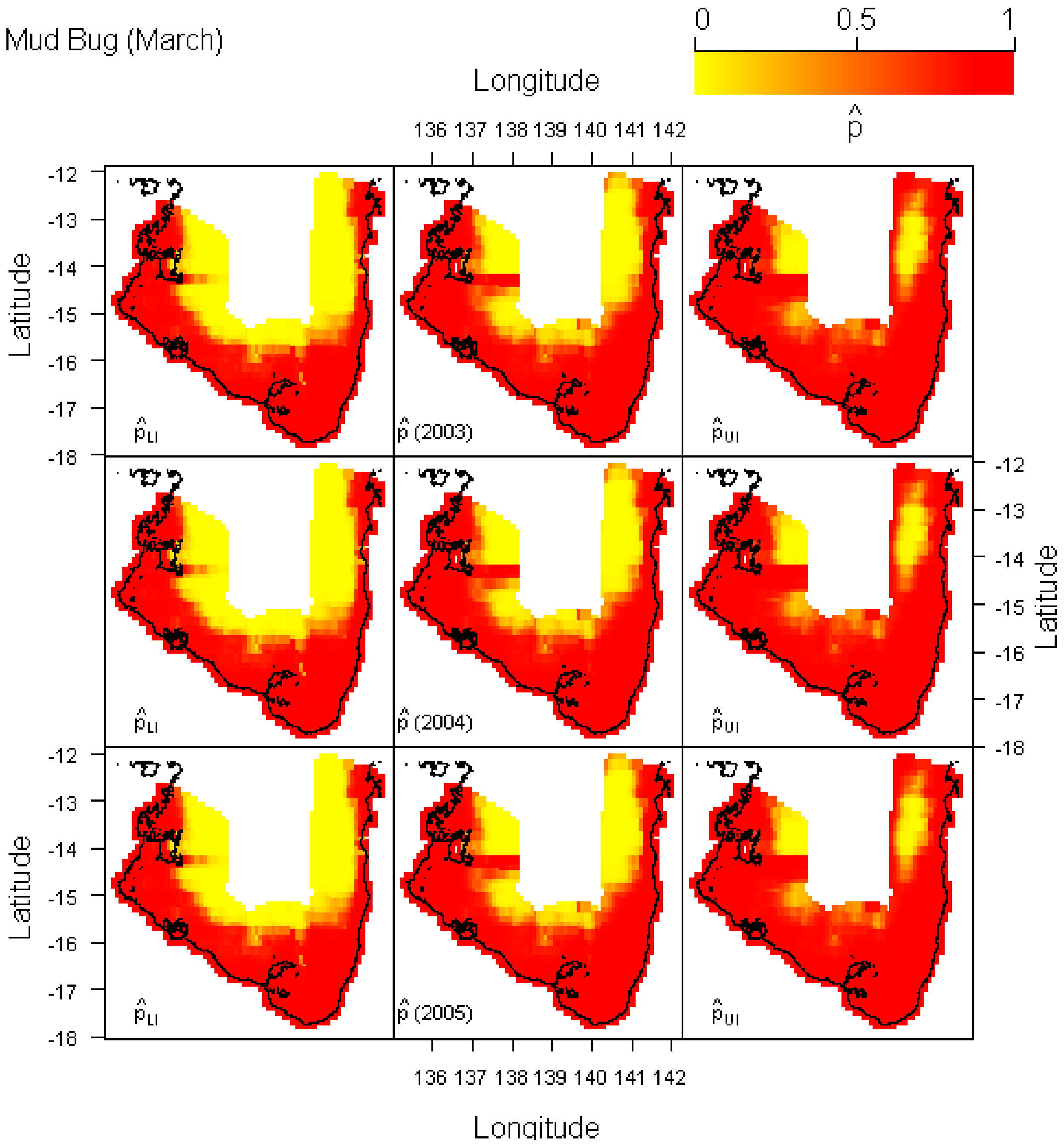


Figure 9.13. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for March 2003 – 2005 for the model that omits Day. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

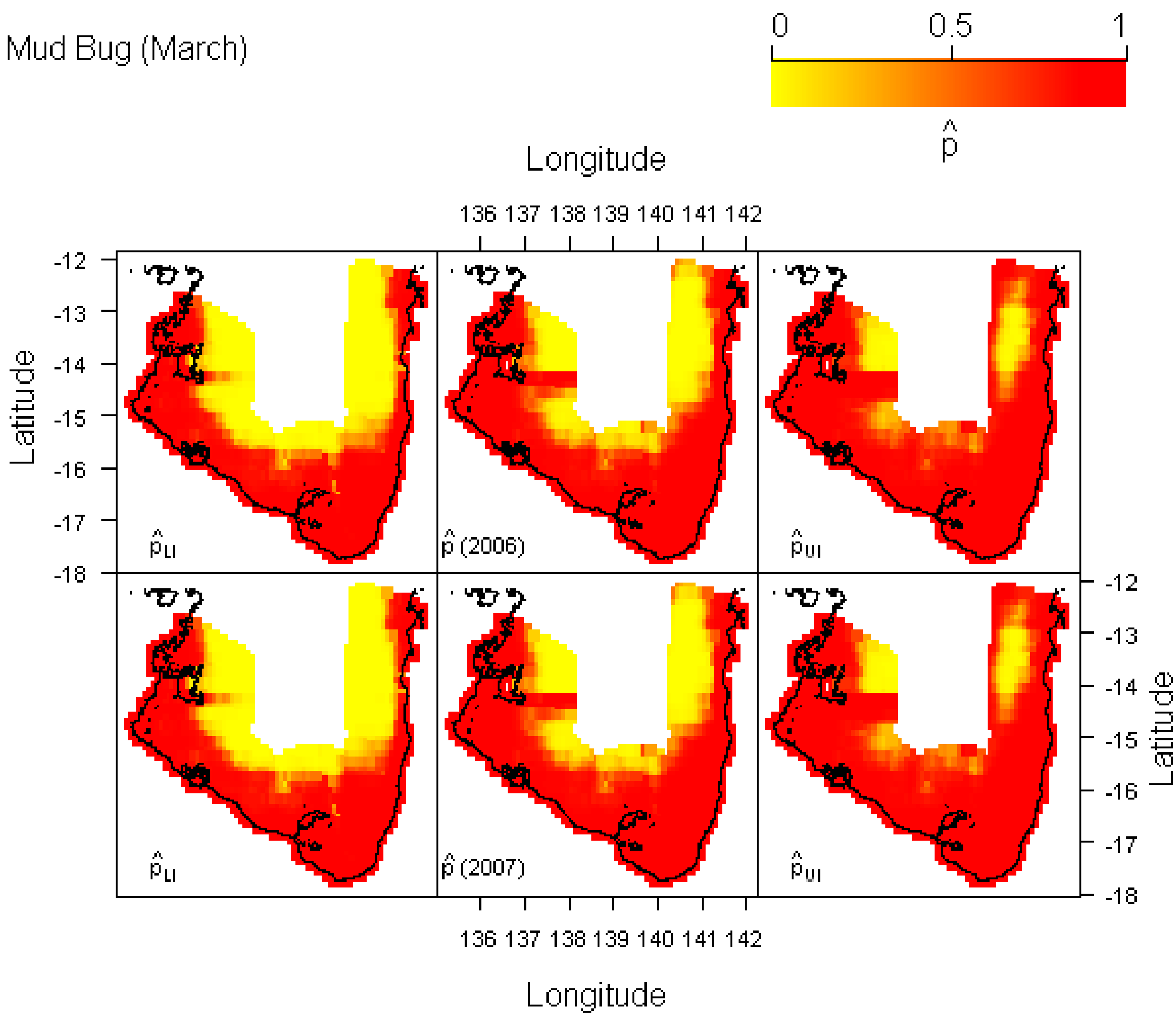


Figure 9.14. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for March 2006 – 2007 for the model that omits Day. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

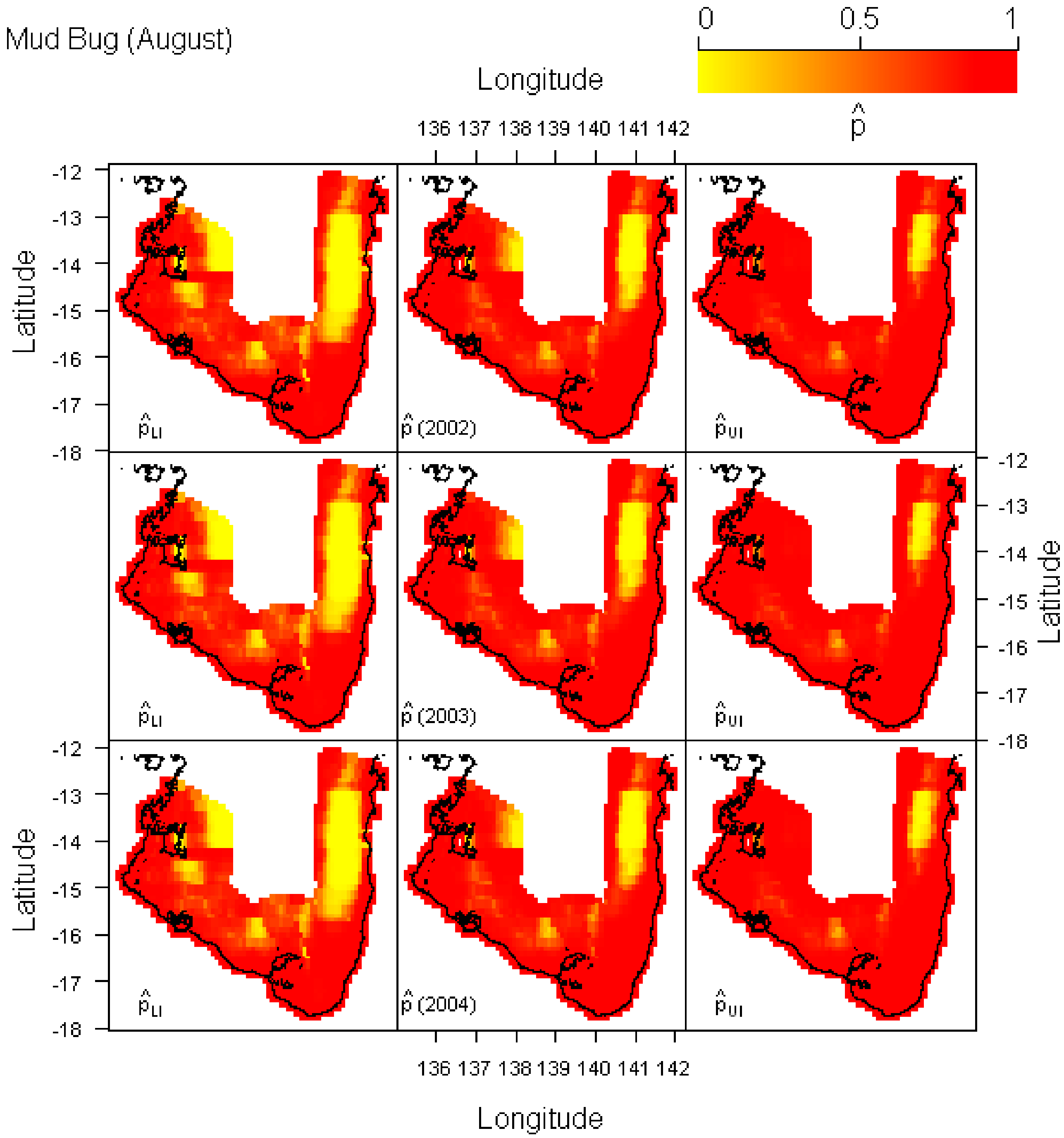


Figure 9.15. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for August 2002 – 2004 for the model that omits Day. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

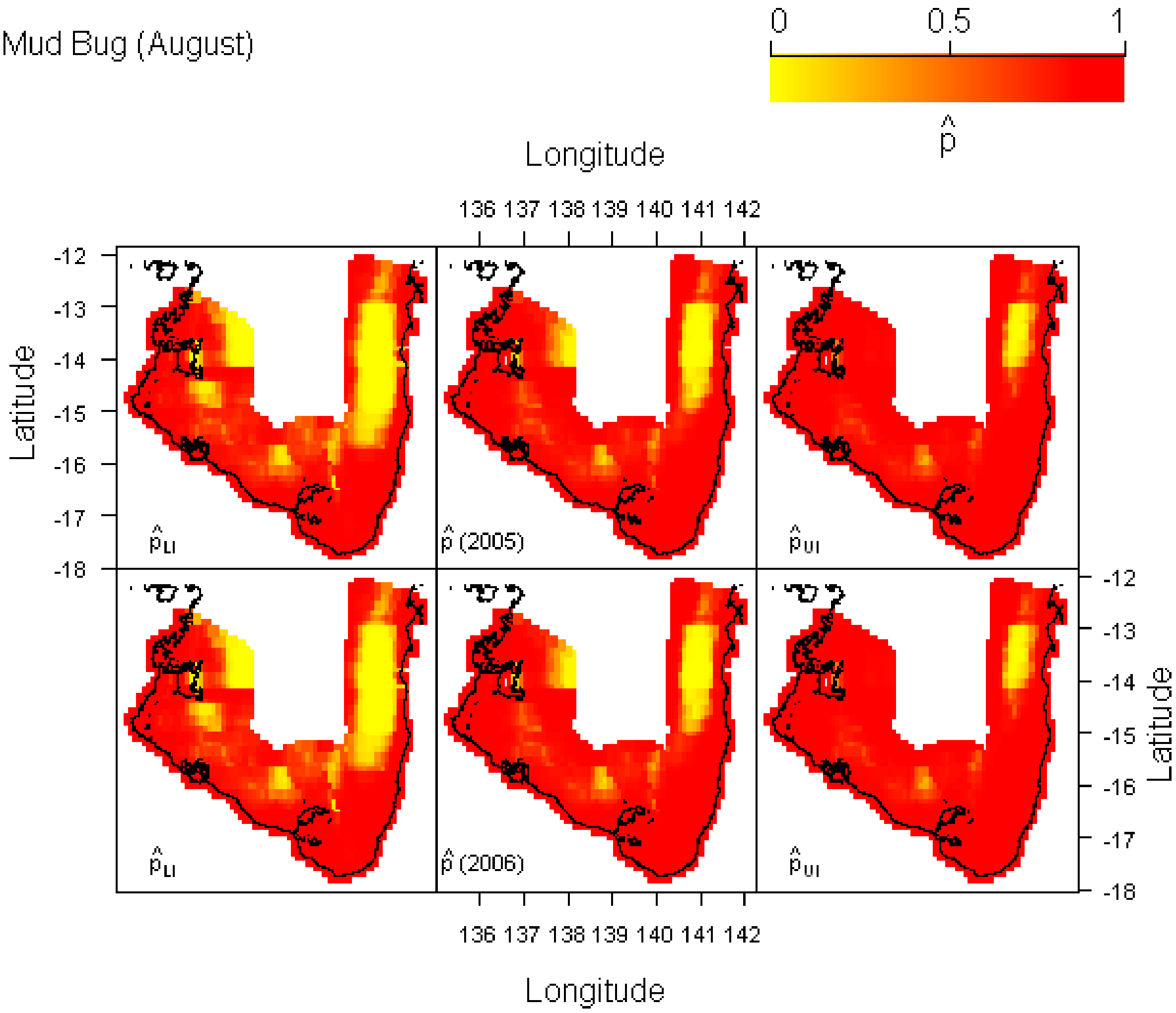


Figure 9.16. Plots showing the predicted proportion of mud bugs and corresponding 95% confidence intervals throughout the prawn fishing grounds in the Gulf of Carpentaria for August 2005 – 2006 for the model that omits Day. A higher proportion of mud bugs in the catch corresponds to a more reddish colour.

9.4.2 Scallops

Determining the discard proportion

Before formally analysing length-weight data and constructing a relationship that can be used to determine the discard proportion, we first investigated the distribution of lengths in the NPF prawn monitoring survey data. Figure 9.17 summarises these distributions of the two species of scallops investigated: mud scallop (*Amusium pleuronectes*) and fan scallop (*Annachlamys flabellata*). A red line representing the shell length at which the discard for each species is determined (63.5 mm), is overlayed on each histogram. Based on this cutoff, all but a small proportion of the fan scallops would be discarded. The remainder of the NPF prawn monitoring survey catches were mud scallops. Based on this preliminary analysis, there is no requirement for developing a model to split scallops into these two species as any attempt would result in problems with estimation due to the small number of fan scallops.

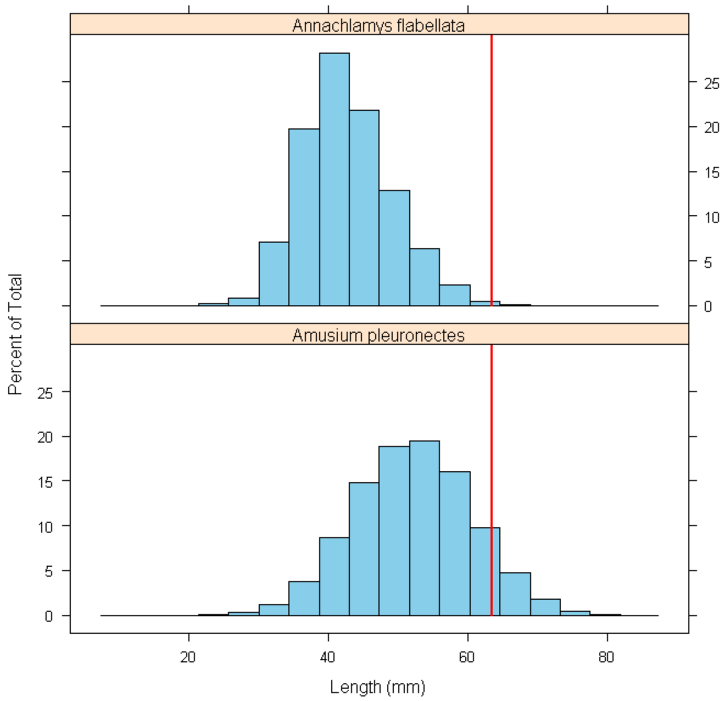


Figure 9.17. Histogram of shell lengths for each species of scallop. Size cut-off is indicated by a red line at 63.5 mm.

9.4.3 Squid

Determining the discard proportion

Information from industry indicates that any squid that is discarded during commercial fishing does not survive. Species of squid that are kept commercially typically consist of *Uroteuthis* sp 3 and *Uroteuthis* sp 4 and usually greater than 125 mm mantle length. Squid are generally not the primary target during either the banana or tiger prawn trawl seasons unless fishers find a squid mark (aggregation). Based on this information, there is no need to determine the discard proportion for this byproduct group. Therefore, the NPF prawn monitoring survey data can be considered representative of commercial fishing habits and can be used to develop a species split model.

Model of species composition

As described above, only *Uroteuthis* sp 3 and *Uroteuthis* sp 4 are typically retained in the commercial catch and this usually occurs during the tiger prawn season. Furthermore, the remaining species were rarely caught (Appendix C). Consequently, we collapsed the six species of squid identified in the NPF prawn monitoring survey data into three species groups for analysis: *Uroteuthis* sp 3 (comprising 45% of shots), *Uroteuthis* sp 4 (33% of shots) and others (22% of shots). Here, the “other” category represents the four less common species of squid (*Aestuariolus noctiluca, Sepioteuthis lessoniana, Uroteuthis* sp 1 and *Uroteuthis* sp 2).

A classification tree weighted by the size of each catch was used to predict squid species composition and therefore the proportion of each squid species caught during a trawl, based on spatial, temporal and environmental predictors. We compared a pruned classification tree with a bagged tree using the predicted and actual proportions by the Hellinger distance. We used spatial variables (latitude, longitude, RDist, RLand and depth), temporal variables (BDay) and environmental variables (percent mud, sand and gravel) in the classification tree model. We omitted the temporal variable, year, as this would prevent the model being used for data collected in future years of modelling. Our results showed some improvement in using the bagged tree model compared with the simpler pruned classification tree.

To account for any possible variation within year, we formed predictions using a test dataset from the bagged tree model for 1st March and 1st August. The test dataset was constructed such that the data reflected that in the NPF prawn monitoring survey data. In Figure 9.18 and Figure 9.19, the predictions are shown on a graduated colour scale from yellow to red with red indicating a probability of one and yellow indicating a probability of zero. The model appears to be dominated by spatial terms as there appears to be some spatial separation between *Uroteuthis* sp 3 and *Uroteuthis* sp 4. These figures also indicate that sediment may play a role.

From both figures, *Uroteuthis* sp 3 were recorded in higher proportions in shallower sites at Groote, the Vanderlins and Mornington, while *Uroteuthis* sp 4 appeared in higher proportions at sites in deeper regions of the Gulf. All other species were recorded in lower proportions apart from some shallow sites near Weipa and Mornington.

There were some differences between the predictions for March and those for August. Higher proportions of *Uroteuthis* sp 3 and *Uroteuthis* sp 4 were predicted across larger areas of the Gulf in August compared to the March predictions suggesting slight shifts in abundance of these species.

Although we do not have a model to interpret, we can still investigate the contribution of each variable to the overall fit and hence the predicted proportion through partial dependence plots. These plots show a variable’s contribution to the model, while averaging across all other variables in the model. Figure 9.20 – Figure 9.22 illustrates partial dependence for a selection of variables.

Although the contribution of sediment in the model is not as strong as any of the spatial variables, Figure 9.20 indicates that it does play a role in distinguishing between squid species groups. It is clear that areas with a high percentage of mud (and a lower percentage of sand) lower proportions of *Uroteuthis* sp 4 were caught. At these sites there was a greater proportion of other squid species. Slight increases in proportions are also noted for the mixed squid spp group when the percentage of mud is highest. Only a slight seasonal difference was found across months for all species groups (Figure 9.21 a).

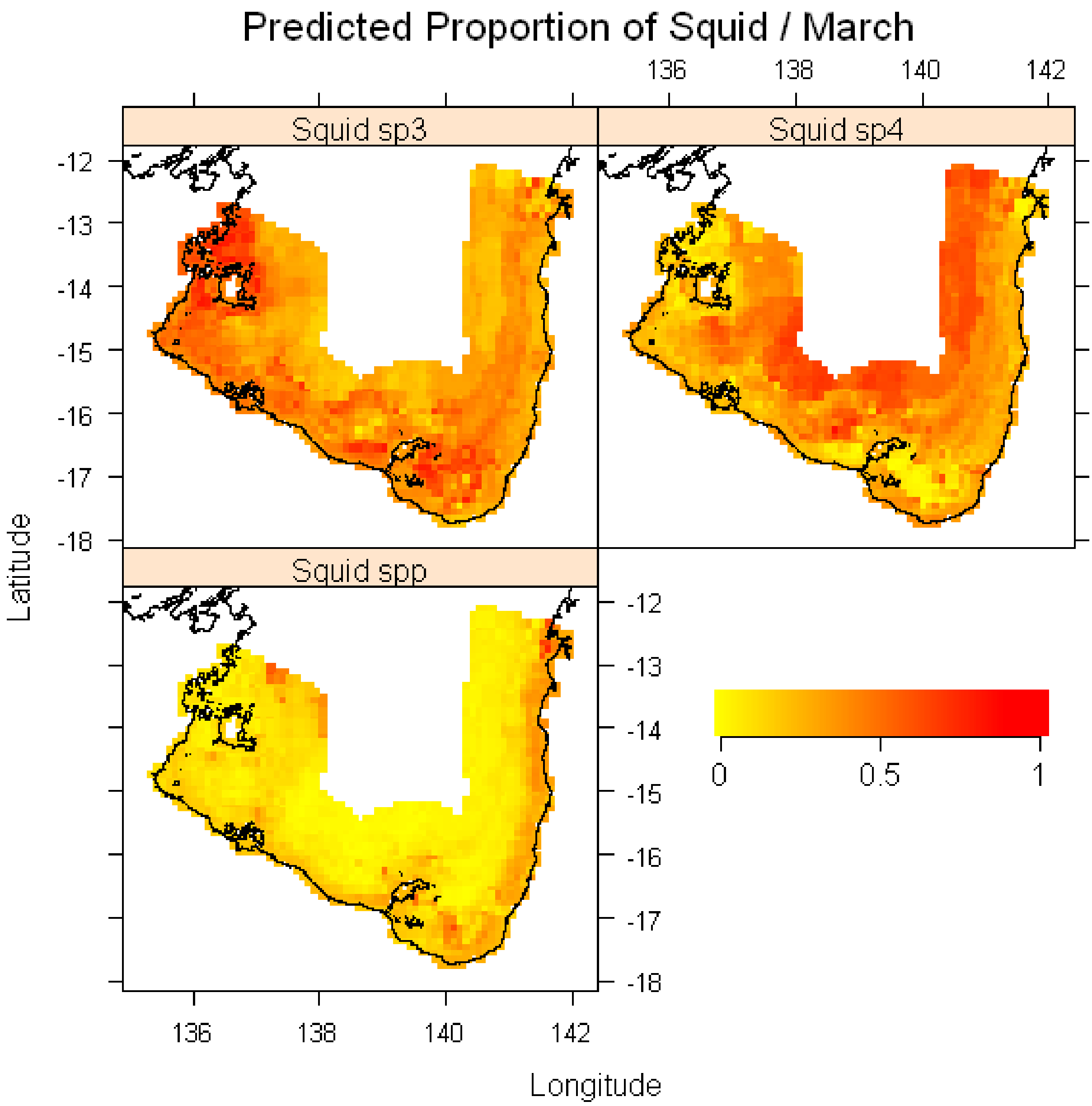


Figure 9.18. Plots showing the predicted proportion of the two *Uroteuthis* squid species (squid sp 3 and 4) and other squids (all species grouped) for March.

The partial dependence plot for depth indicates large changes in proportions with increasing depth. It is clear that as we move to deeper waters, *Uroteuthis* sp 4 is most dominant and were predicted to occur in higher proportions than *Uroteuthis* sp 3 and the other mixed squid species group.

Figure 9.23 shows the partial dependence plots for RDist and RLand. RLand shows some strong variation in proportion for the different species of squid. This probably reflects a response to changes in depth as both RLand and depth are related. The partial dependence plot for RDist (Figure 9.22 b) indicates increases in the proportion of *Uroteuthis* sp 4 as RDist becomes large at Weipa as shown in Figure 9.18 and Figure 9.19.

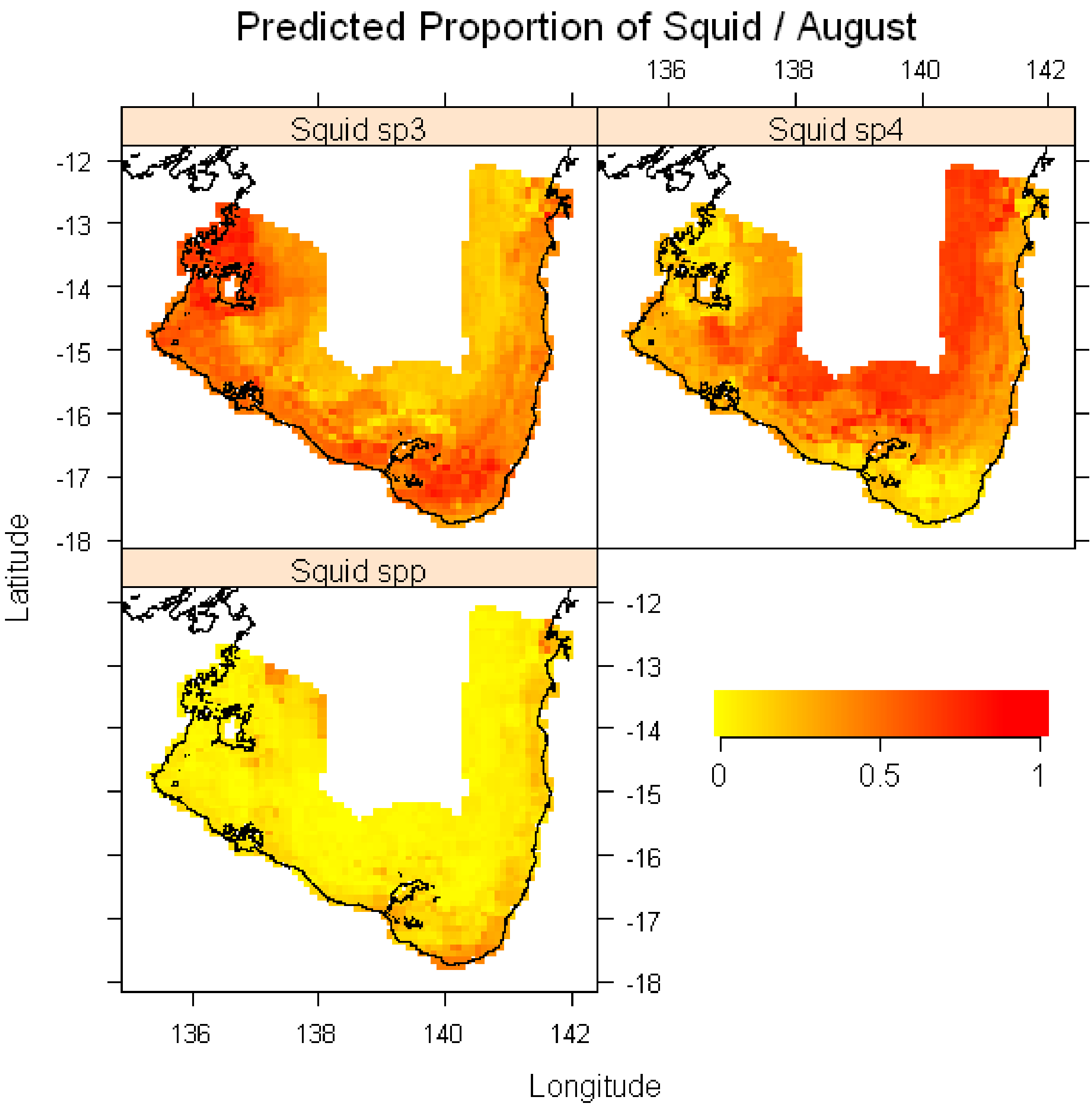
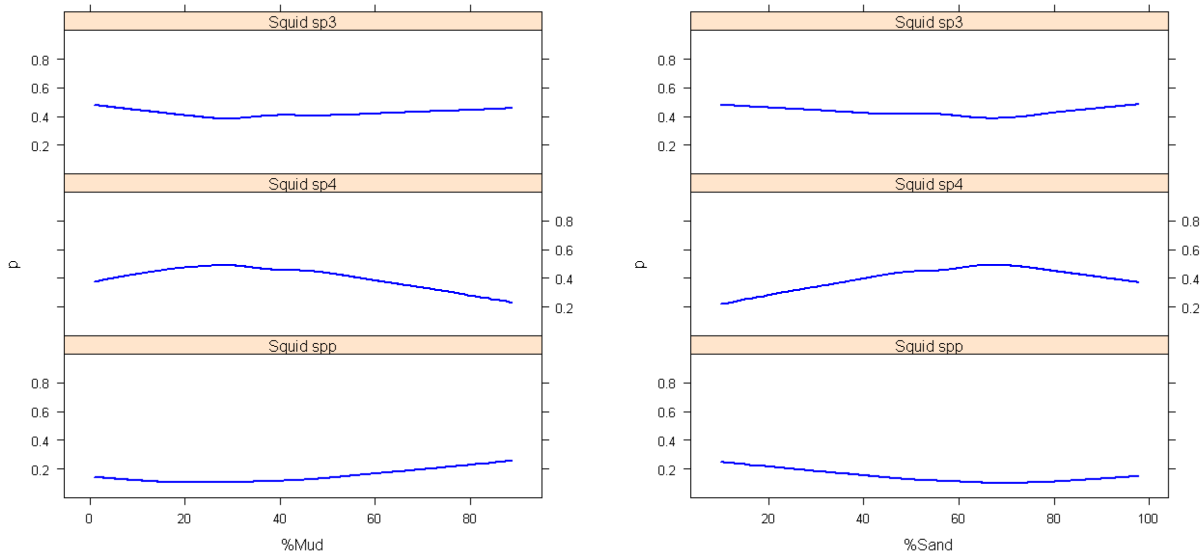
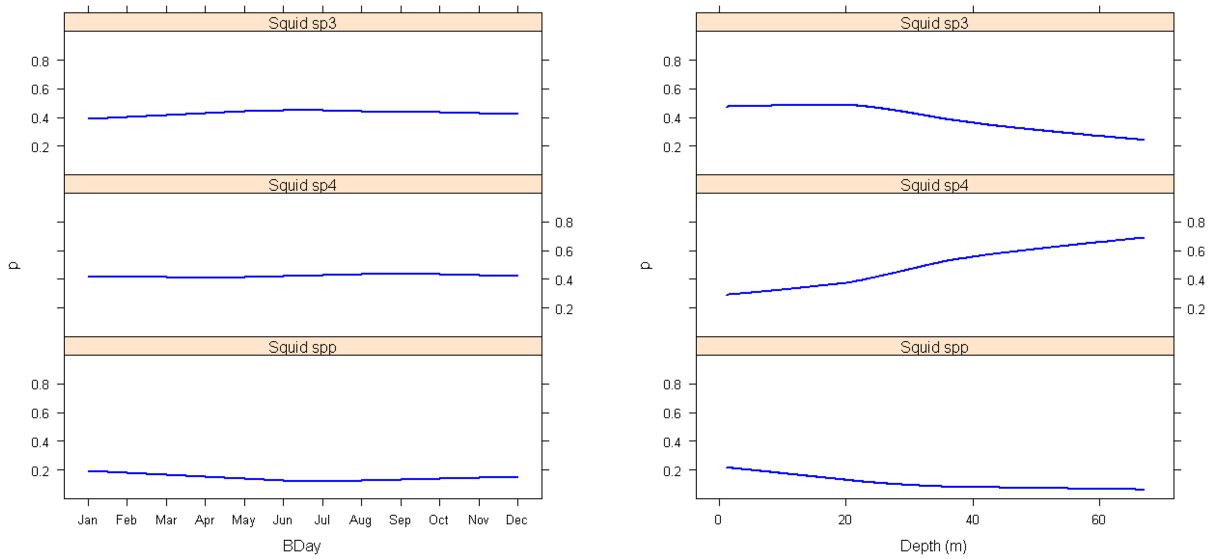


Figure 9.19. Plots showing the predicted proportion of two *Uroteuthis* squid species (squid sp 3 and 4) and other squid species (grouped) for August.



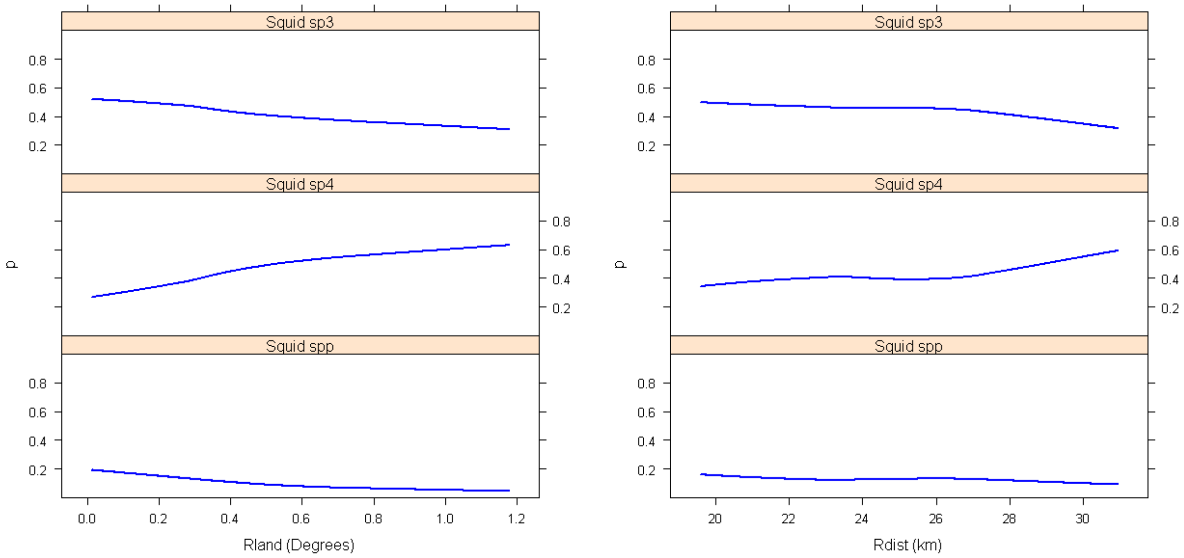
(a) *(b)*

Figure 9.20. Partial dependence plot showing the relationship between (a) percent mud and (b) percent sand versus the proportion of the two *Uroteuthis* squid species (squid sp 3 and 4) and other squids (grouped).



(a) *(b)*

Figure 9.21. Partial dependence plots showing the relationship between (a) day of year (BDay) and (b) depth with the proportion of the two *Uroteuthis* squid species (squid sp 3 and 4) and other squids (grouped).



(a) *(b)*

Figure 9.22. Partial dependence plot showing the relationship between (a) distance along the coast (RLand) and (b) distance from land (RDist) of the two *Uroteuthis* species (squid sp 3 and 4) and other squids (grouped).

9.4.4 Cuttlefish

Determining the discard proportion

Little information is available from industry or other sources on discarding practices for cuttlefish. The general consensus from industry is that cuttlefish are discarded if the majority of the catch consists of animals of less than 100 mm in mantle length. As cuttlefish do not survive once discarded, there is no requirement to separate out the NPF prawn monitoring survey catch into small and large individuals. Based on this information we assumed that cuttlefish species recorded in the NPF prawn monitoring survey catches were representative of what commercial fishers catch and report in their logbooks.

Model of species composition

A preliminary analysis of the cuttlefish data reveals that four species are fairly dominant across most sites in the Gulf of Carpentaria. These species were Ovalbone (*Sepia elliptica* – 45% of shots), Smith's (*Sepia smithi* – 22% of trawls), Pharaoh's (*Sepia pharaonis* – 17% of trawls) and Papuan (*Sepia papuensis* – 11% of trawls). The Flamboyant cuttlefish (*Metasepia pfefferi*) is the least abundant across regions, recorded in 4% of trawls. In total, five species were classified in a classification and regression tree model to determine species composition using the predictor variables (Table 9.2). Similar to squid, we did not incorporate year into this model.

Predictions from a pruned classification tree were compared with those produced from a bagged tree model by the Hellinger distance. The comparison indicated a slight improvement in prediction performance using the bagged tree model. Similar to the analysis for squid, we produced maps of the predictions for two seasons, March and August, to examine possible seasonal changes. Mapped predictions show very little difference between the two time periods suggesting little seasonal effect (Figure 9.23, Figure 9.24). This is also demonstrated by the partial dependence plot (Figure 9.26 a).

The prediction maps show a strong spatial separation of the three most dominant species of cuttlefish, namely the Ovalbone, Smiths and Pharaoh with the Ovalbone cuttlefish being the most dominant across the region. This cuttlefish appears to be in higher proportions in muddy and/or shallow areas of the Gulf while the Pharaoh cuttlefish are in higher proportions in deeper areas. This is also reflected in the partial dependence plots of sediment and depth shown in Figure 9.25 and Figure 9.26 (b) respectively. As RLand is closely related to depth, Figure 9.27 (a) also reflects these differences.

Both the Papuan and Flamboyant cuttlefish species were recorded in low proportions across the region. However, there are slight increases in the proportion of the Papuan cuttlefish in some deeper areas off Weipa and Mornington (Figure 9.24 b).

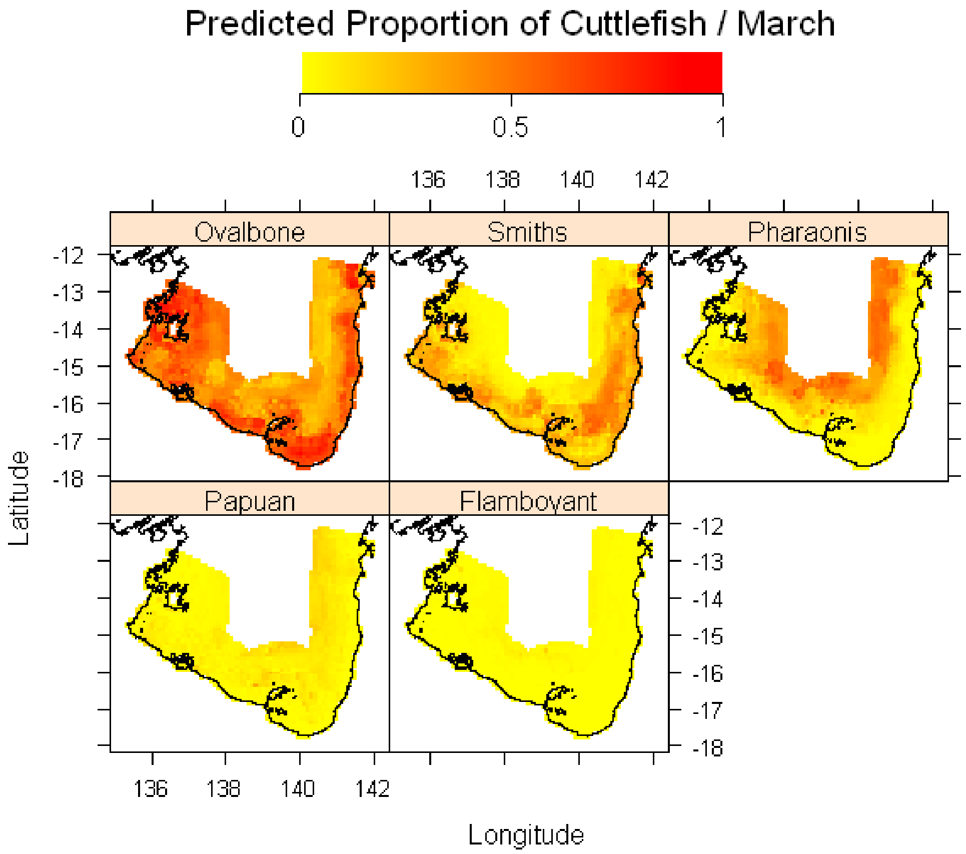


Figure 9.23. Plots showing the predicted proportion of five cuttlefish species for March.

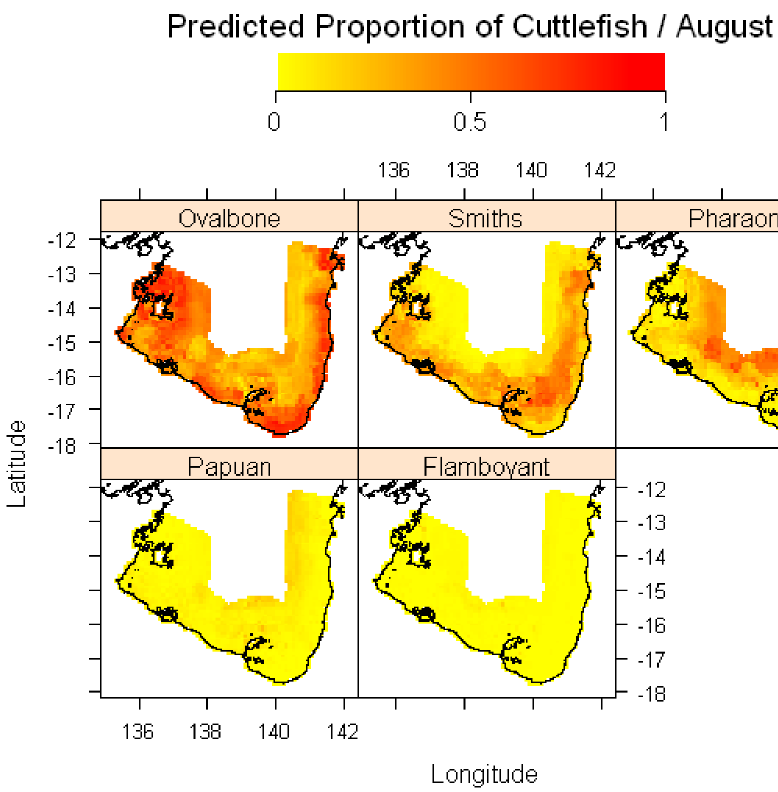


Figure 9.24. Plots showing the predicted proportion of five cuttlefish species for August.

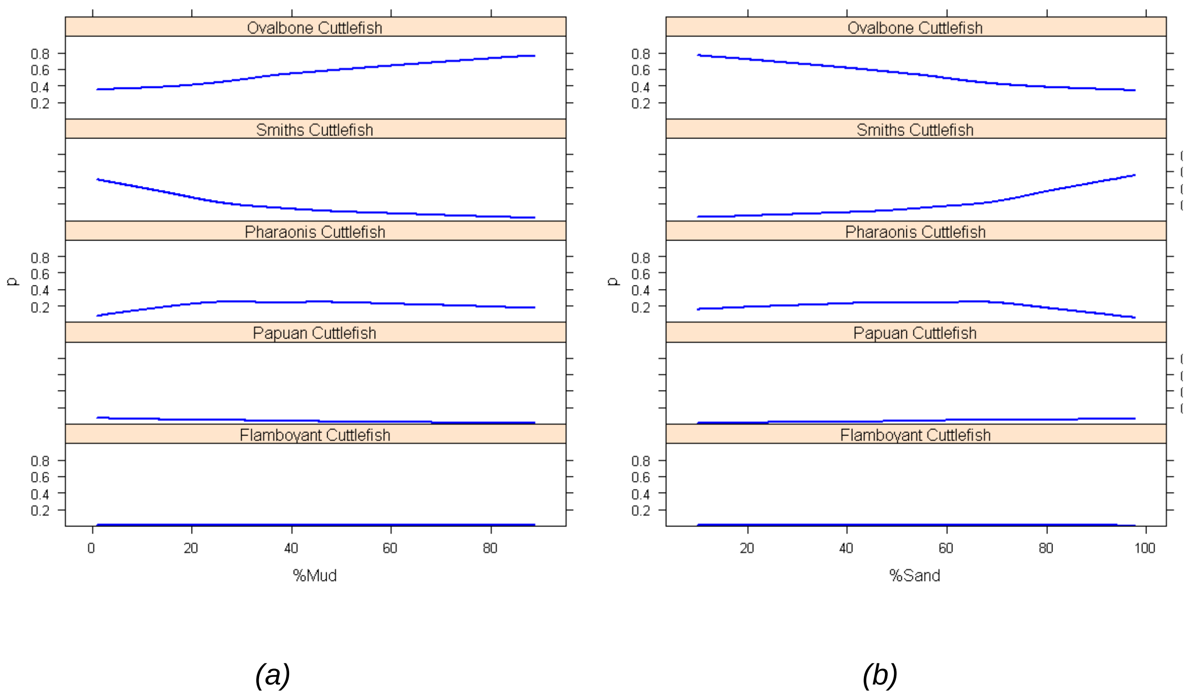
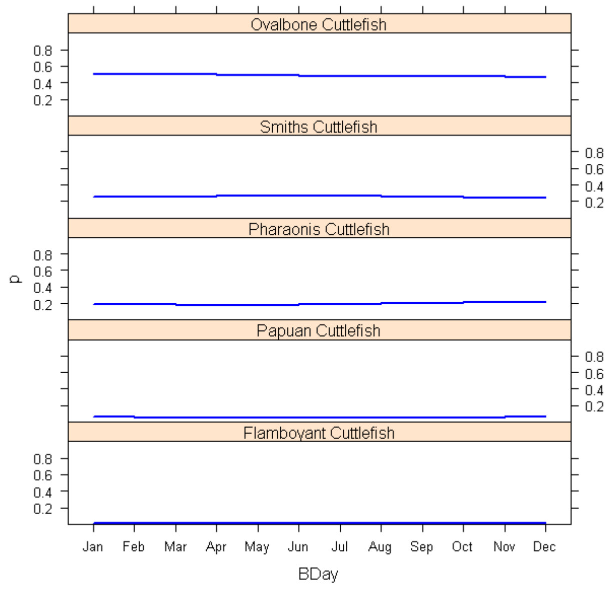
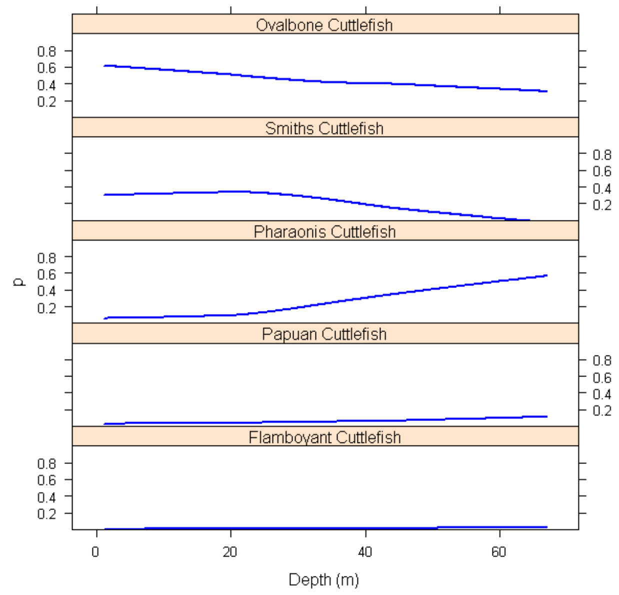


Figure 9.25. Partial dependence plot showing the relationship between (a) percent mud and (b) percent sand versus the proportion of each species of cuttlefish.

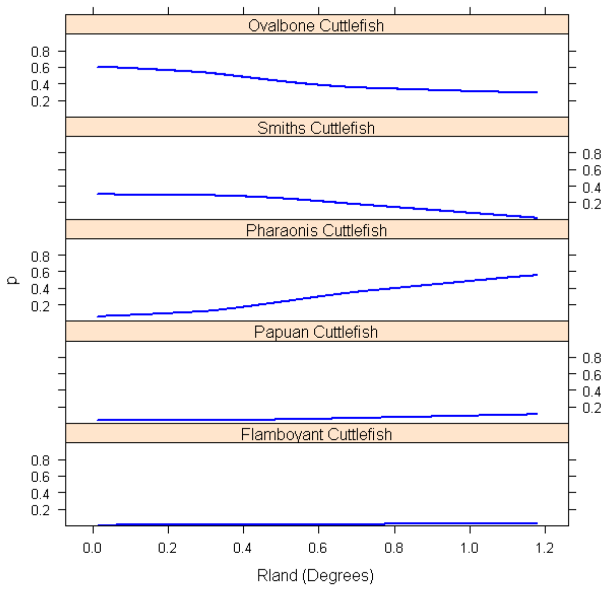


(a)

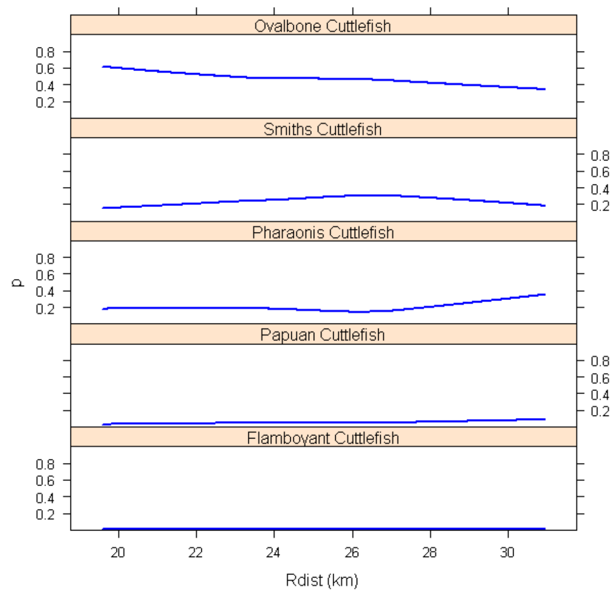


(b)

Figure 9.26. Partial dependence plot showing the relationship between (a) day of year (BDay) and (b) depth versus the proportion of each species of cuttlefish.



(a)



(b)

Figure 9.27. Partial dependence plot showing the relationship between (a) distance along the coast (RLand) and (b) distance from land (RDist) versus the proportion of each species of cuttlefish.

9.5 Conclusions

The NPF covers a large proportion of northern Australia but most logbook records of byproduct come from the Gulf of Carpentaria. The AFMA-funded NPF prawn monitoring project has been collecting prawn and byproduct data from a large number of trawl sites in the Gulf of Carpentaria since 2002. We were able to use these data to develop statistical models of the proportion of byproduct species in commercial catches in these regions. We found generalised additive models and ‘bagged’ classification trees to be the most appropriate methods to develop statistical models capable of estimating catch composition based on these spatial, temporal and environmental predictors. Models were developed for all byproduct groups investigated, except scallops. For this byproduct group, the commercial size limit of the scallops retained meant that only one species was represented in the commercial logbooks. Thus, we decided not to develop a statistical model for predicting scallop composition.

The models produced for all byproduct species highlighted a large spatial component followed by a slight temporal influence and some compositional changes due to sediment. High proportions of the mud bug *T. parindicus* were observed across the NPF prawn monitoring survey region and appeared to be influenced by spatial and temporal terms and the presence of muddy substrates. Reef bugs (*T. australiensis*) tended to be located in deeper waters where the sediment is typically sandy.

The squid species, *Uroteuthis* sp 3 and *Uroteuthis* sp 4 were dominant in the NPF prawn monitoring survey region compared with the other four species. Higher proportions of *Uroteuthis* sp 3 occurred in shallower regions irrespective of sediment type while a higher proportion of *Uroteuthis* sp 4 occurs in deeper, sandy regions.

Ovalbone cuttlefish (*S. elliptica*) was the dominant cuttlefish recorded in the monitoring dataset. It occurs in high proportions in muddy regions and in particular, shallow areas of the Gulf. *Sepia pharaonis* were more dominant in deeper waters, while higher proportions of *S. smithi* tend to be found in deeper, sandy regions. Both the *S. papuensis* and *Metasepia pfefferi* occurred in low proportions across the region.

These models have been applied to the commercial logbook records to estimate the species composition of the commercial catch since t became necessary to records byproduct in logbooks in 1998. It will allow an assessment of the status of the populations of each byproduct species. Management scenarios can then be explored to ascertain the species most impacted by fishing (see Chapter 11).

While the data for these models were based was collected in the Gulf of Carpentaria, the models would also be relevant for other parts of northern Australia, including the rest of the NPF. Similar approaches may also be applicable for other species of concern in the NPF and other fisheries that were not currently separated in logbook records.

10. ESTIMATING THE ACCEPTABLE BIOLOGICAL CATCH OF BYPRODUCT IN THE NORTHERN PRAWN FISHERY

10.1 Abstract

Formal fisheries stock assessment methods that rely on commercial logbook records are almost impossible to apply to non-targeted catch. This is because logbook records are not a reliable index of abundance of these groups. We used the data from the NPF prawn monitoring surveys to estimate the biomass of the main byproduct groups: squid, cuttlefish, bugs and scallops in the Gulf of Carpentaria. From these biomass estimates, we developed a new catch limit reference value for each byproduct group. We have termed this reference point the ‘acceptable biological catch’ (ABC). We compared the recent catch recorded in NPF commercial logbooks with our estimates of ABC. We found that the recent catches are only a small proportion of the estimated ABC of bugs, scallops and cuttlefish. This suggests that the catches of these groups do not need close monitoring by managers unless fishing practices change dramatically.

For squid, the recent catches were similar to the estimated ABC and could need further analyses. However, historical catches of squid from areas within the NPF, but outside the current commercial prawn fishing grounds, suggest that our biomass value for squid may be an underestimate. If commercial squid catches increase dramatically in the NPF, further studies may be required to improve our estimate of the true biomass of squid in the Gulf of Carpentaria. Until that occurs, squid catches should continue to be monitored.

The new ABC catch limit references provide an index of the sustainable catch of each species group and can be used as an indicator of the limit of commercial catches. In order for the ABC estimate to be updated, the current fishery-independent NPF prawn monitoring surveys need to be maintained. Continuing these surveys will provide an index of the biomass of each byproduct group on the main commercial prawn fishing grounds in the Gulf of Carpentaria.

10.2 Introduction

Stock assessments of byproduct species are extremely rare due to the nature of its incidental catch in a fishery targeting other species. As a consequence, there are often little data available for rigorous analysis. This makes formal stock assessment of byproduct species very challenging. In the early stage of this project, we attempted to conduct a stock assessment using biomass dynamics models for byproduct species. These models failed to produce reliable and reasonable results. The main difficulties included: (1) we only have a very short data time-series (1998 – 2007) in the commercial logbooks; (2) commercial logbook records are not a reliable proxy for species occurrence because fishers may not always retain these byproduct when they catch them; (3) as non-target species, the catch and CPUE of these byproduct groups varies greatly between years for some species such as squid so that CPUE may not be a reliable index for abundance; and (4) CPUE lacks contrast for some species such as cuttlefish.

These difficulties have led us to develop alternative methods for assessing byproduct resources. In this chapter we (1) describe methods for estimating byproduct species biomass from NPF prawn monitoring surveys, (2) develop an exploitation rate proxy for maximum sustainable yield (MSY) based on life-history traits of each byproduct species and (3) estimated an acceptable biological catch (ABC) based on the estimated biomass and exploitation rates.

10.3 Methods

Two NPF prawn monitoring surveys were undertaken each year at up to 300 sites, in the Gulf of Carpentaria since 2002 (Milton et al. 2008). The details of the prawn monitoring surveys have been described elsewhere (Chapter 7). Byproduct abundance appeared to vary between seasons. As the July – August survey is closer to the tiger prawn fishing season that generally catches the majority of the byproduct groups, we used the survey data from the mid-year surveys to estimate biomass. However, surveys were undertaken in all areas in the Gulf at mid-year only in the last three years (2005 – 2007). Therefore, the analysis in this chapter has been limited to the period from 2005 – 2007.

A key step in undertaking an assessment of the acceptable biological catch is to estimate spawning biomass for each byproduct group. The current MLS for bugs retained by the NPF commercial fishery is 75 mm CW (52 mm CL). There are no size restrictions on the other three byproduct groups for the NPF. However, a commercial size threshold for scallops was set at 63.5 mm shell width (Chapter 9), as smaller individuals would be both uneconomical to retain and likely to survive once trawled and released. As most squid and cuttlefish do not survive trawling, we assumed that the commercial fishery catches all individuals. Bug and scallop sizes were assumed to approximate sexual maturity in these groups (Chapter 7). We first estimated the proportion of the NPF prawn monitoring survey catch equal to or larger than the MLS from their length measurement in the surveys. Then we estimated the proportion of mature individuals by weight according to the following relationship between weight w and length l:

Bugs: $\ln(w) = 0.59 + 0.94\ln(l)$ (Chapter 9)

Mud scallop: $w = -25.1 + 0.707l$ (n = 112, r^2 = 0.96)

Fan scallop: $w = -24.1 + 0.922l$ (n = 61, r^2 = 0.98)

We stratified the surveyed area into six regions corresponding to prawn stock regions. We also stratified the surveyed area into four depth ranges to estimate the mean weight per unit of area similar to the method used in the prawn surveys (Milton et al. 2008):

$$\bar{D}_{R,y} = \frac{1}{nm}\sum_{d}^{m}\sum_{i=1}^{n}\frac{W_{R,y,d,i}}{a_{R,y,d,i}}, \qquad (10.1)$$

where $W_{R,y,d,i}$ = weight of particular byproduct group in region R, year y, depth range d and sample i, n = number of samples (trawls), m = number of depth strata, and $a_{R,y,d,i}$ = swept area in sample i. By assuming independent sampling between depth strata we estimated the variances for $\bar{D}_{R,y}$ as:

$$V[\bar{D}_{R,y}] = \sum_{d}^{m} \frac{s_{R,y,d}^2}{n} = \sum_{d}^{m} \frac{\sum_{i=1}^{n} (D_{R,y,d,i} - \bar{D}_{R,y,d})^2}{n(n-1)} . \tag{10.2}$$

Here we ignored the finite population correction factor as the trawled area in the survey was much smaller than the total area in each region. The fishable biomass in year *y* was then estimated by:

$$B_y = \sum_{R} \frac{\bar{D}_{R,y}}{q} A_R , \tag{10.3}$$

where $\bar{D}_{R,y}$ is the mean weight per unit of swept area from Equation 10.1, *q*, referred as relative catch rate, is the survey gear (prawn trawl) efficiency for catching each byproduct group, A_R is total area where fishers have reported catch of a byproduct group during 1998 – 2007. We obtained *q* for bugs and scallops from a field study in the Great Barrier Reef: 0.47 for bugs and 0.73 for scallops (Pitcher et al. 2007). As no information on squid and cuttlefish is available, we assumed q = 0.4 for squid and q = 0.5 for cuttlefish. We considered sampling between regions to be independent and obtained the variance for biomass estimate as:

$$V[B_y] = \sum_{R} \left(\frac{A_R}{q} \right)^2 V[\bar{D}_{R,y}] \tag{10.4}$$

We estimated the acceptable biological catch for each byproduct group based on their life-history traits. We defined the potential acceptable biological catch (ABC) for each byproduct group as:

$$\mathrm{ABC}_y = U_{MSY} B_y, \tag{10.5}$$

where U_{MSY} is a proxy for exploitation rate at MSY:

$$U_{MSY} = \frac{F}{F+M} [1 - \exp(-F - M)] = \frac{1}{2} [1 - \exp(-2M)] . \tag{10.6}$$

Natural mortality *M* estimates for each group were obtained from the literature (Courtney 2002 for bugs, Hoenig 1983; Jensen 1996 for other groups): An estimate of *M* for the three other groups were obtained from calculations with the following two equations:

(1) $\ln(M) = 1.44 - 0.982 \ln(t_m)$;
(2) $M = 1.65/t_{mat}$.

In the above equations t_m = maximum reproductive age and t_{mat} = average age at maturity and were each obtained from the literature (bugs: Jones 1993, squids: Jackson and Choat 1992; Jackson and Yeatman 1996, scallops: Jebreen et al. 2003).

10.4 Results

10.4.1 Biomass estimated from NPF prawn monitoring surveys

Estimated fishable biomass varied from year to year for all byproduct groups (Figure 10.1 – Figure 10.3). One species of scallop and one species of bug dominated those two byproduct groups (Figure 10.1, Figure 10.2). Bugs had the highest biomass while the scallops the lowest.

10.4.2 Natural mortality estimated from life-history parameters

All these byproduct species are short-lived tropical invertebrates. Their estimated natural mortality varies from 1.3 yr^{-1} for bugs to 8.1 yr^{-1} for squid (Table 10.1). The proxy exploitation rate at MSY is about 50%.

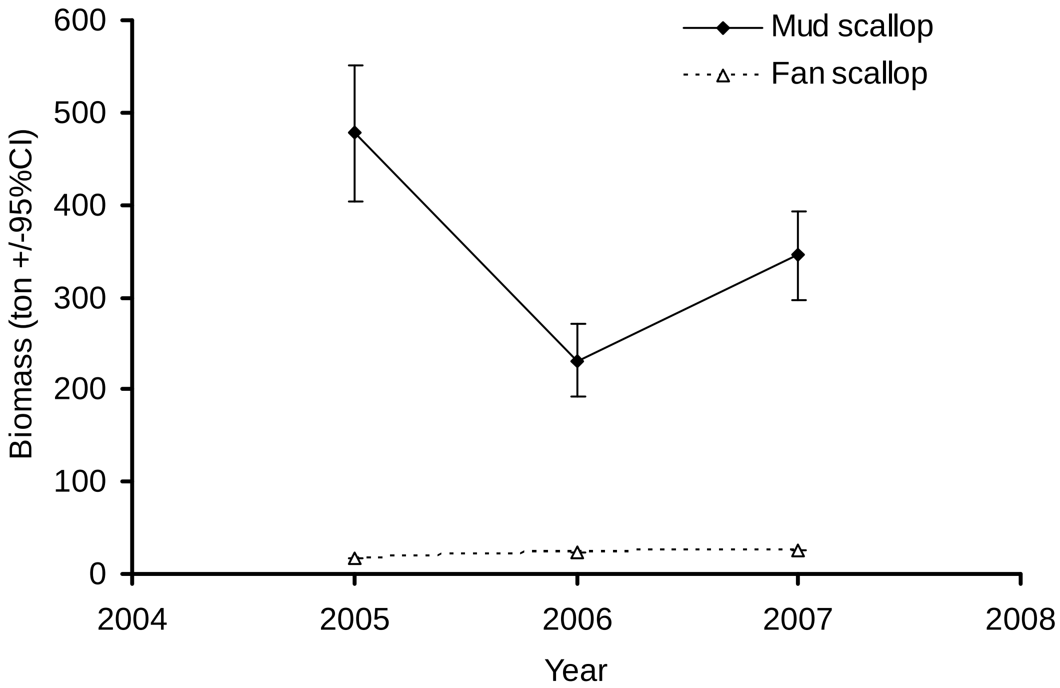


Figure 10.1. Estimated biomass for the two scallop species in the Gulf of Carpentaria based on NPF prawn monitoring survey data.

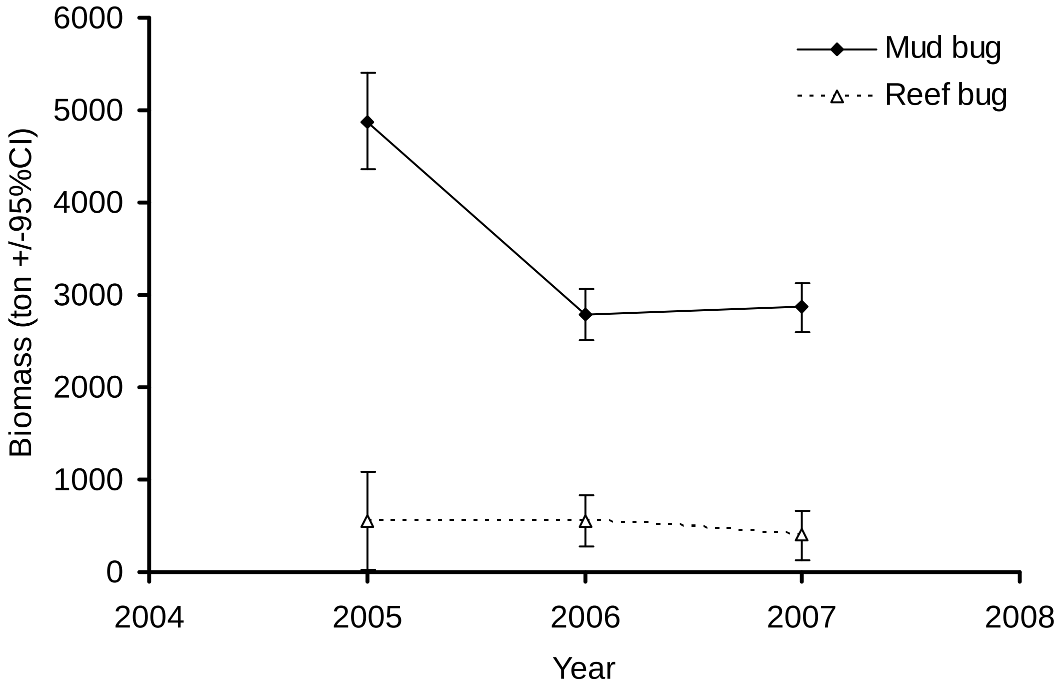


Figure 10.2. Estimated biomass for the two bug species in the Gulf of Carpentaria based on the NPF prawn monitoring survey data.

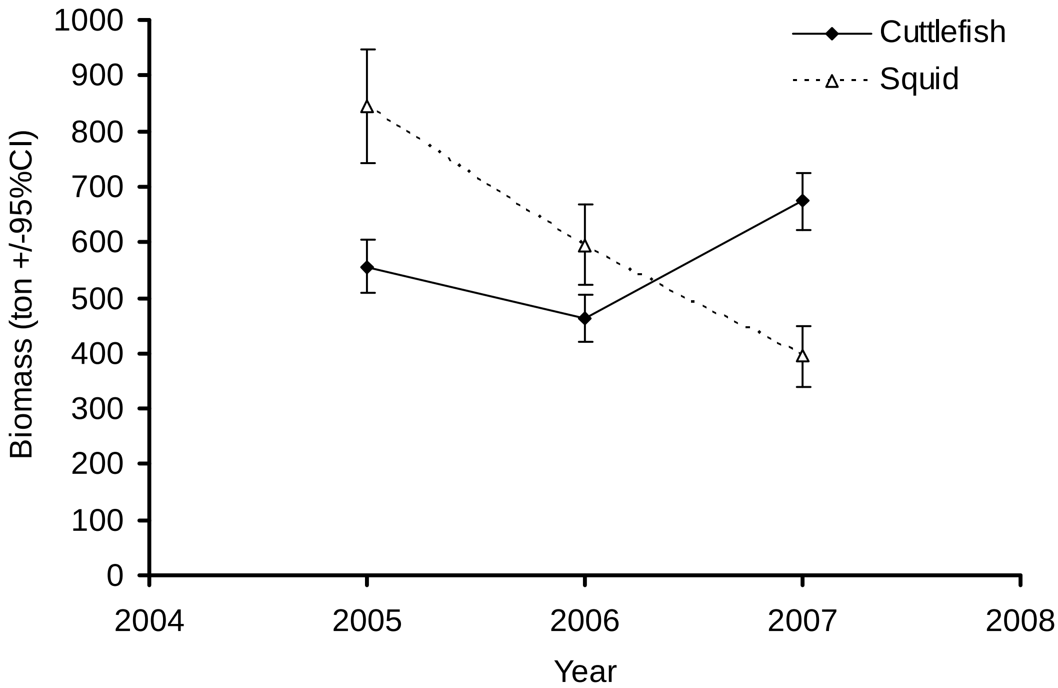


Figure 10.3. Estimated biomass of cuttlefish and squid species groups in the Gulf of Carpentaria based on NPF prawn monitoring survey data.

Table 10.1. Life-history parameters, estimated natural mortality *M*, and proxy MSY exploitation rate U_{msy} for different byproduct groups. Values for maximum age and age at maturity were obtained from the scientific literature. * *M* was estimated directly for reef bugs by Courtney (2002). Mean *M* is obtained by averaging from the equations shown above.

Species	*M*	Max age	Age at maturity	Mean *M*	U_{msy}
Bugs	0.92*	3.0	1.0	1.3	0.47
Squid		0.7	0.3	8.1	0.50
Cuttlefish		1.0	0.3	4.6	0.50
Scallop		2.0	0.5	2.7	0.50

10.4.3 Acceptable biological catch

The acceptable biological catch (ABC) for each byproduct group was estimated from biomass in 2005 to 2007 (Figure 10.4 – Figure 10.7). We included the NPF commercial logbook catch of these byproduct groups in the Gulf of Carpentaria from 1998 to 2007 as a comparison. The actual catch is much lower than the estimated ABC for bugs, cuttlefish and scallops. However, the catch of squid may have exceeded the ABC in some years, particularly 1998 and 2001 (Figure 10.7). The mean ABC for each group based on the three years' estimates is shown in Table 10.2.

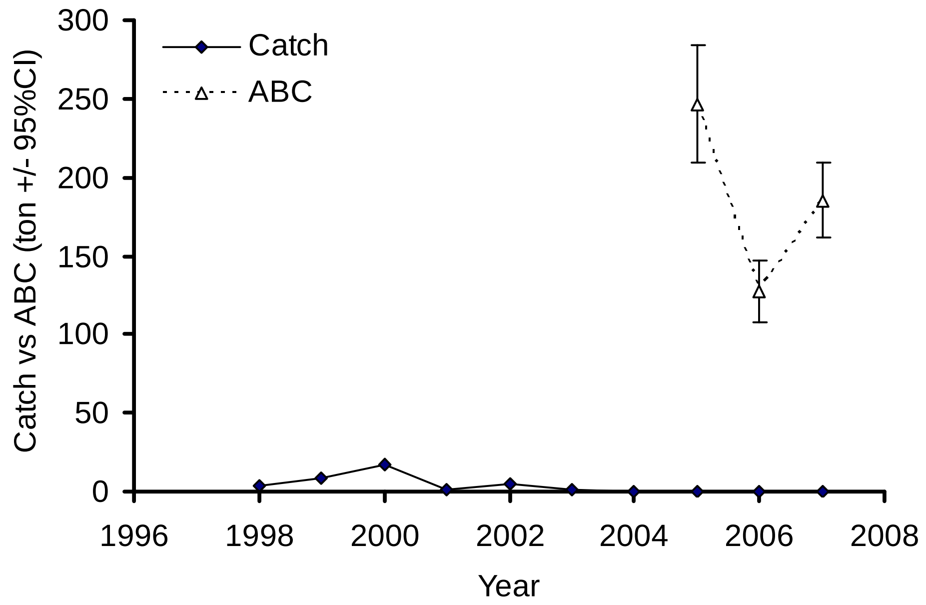


Figure 10.4. Comparison of NPF commercial logbook catch and the estimated potential acceptable biological catch for the scallop group in the Gulf of Carpentaria.

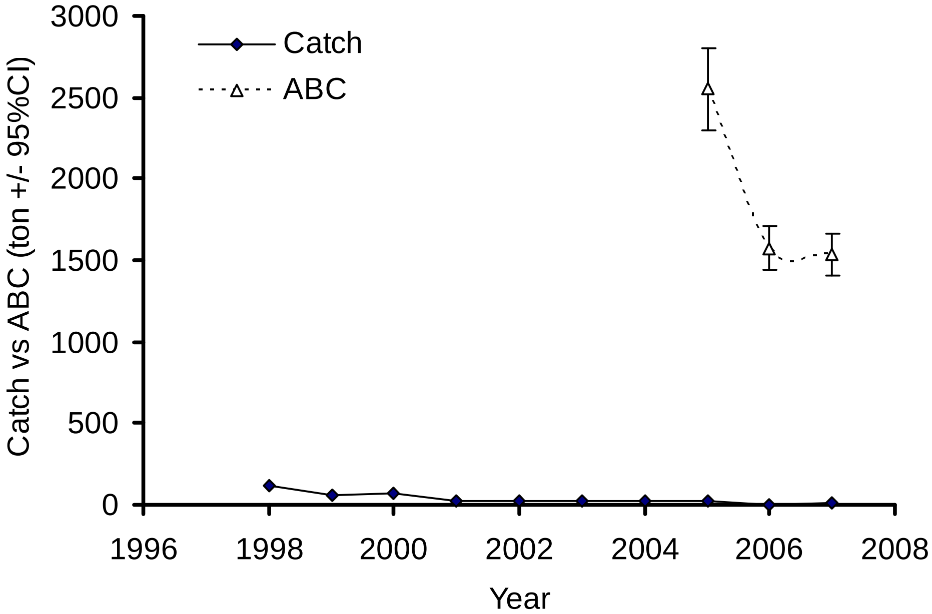


Figure 10.5. Comparison of NPF commercial catch and the estimated potential acceptable biological catch for the bug group in the Gulf of Carpentaria.

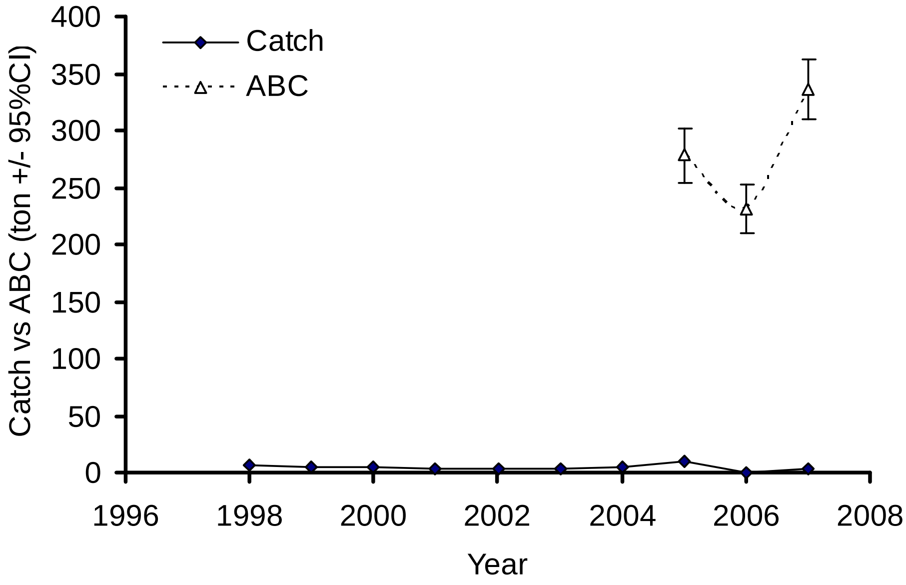


Figure 10.6. Comparison of NPF commercial catch and the estimated potential acceptable biological catch for the cuttlefish group in the Gulf of Carpentaria.

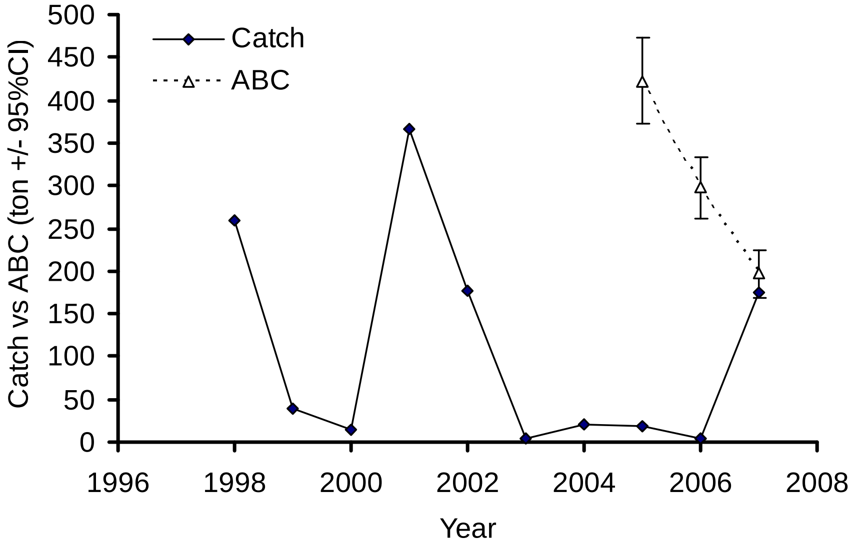


Figure 10.7. Comparison of NPF commercial catch and the estimated potential acceptable biological catch for the squid group in the Gulf of Carpentaria.

Table 10.2. Mean potentially acceptable biological catch (ABC, in tonnes) and its 95% confidence interval of each byproduct group in the Gulf of Carpentaria based on 2005 – 2007 NPF prawn monitoring survey data.

Group	Mean	L95%CI	U95%CI
Scallop	186	159	213
Bugs	1887	1716	2057
Cuttlefish	282	258	306
Squid	306	267	344

10.5 Evaluation of ABC as a management tool

This is the first attempt to undertake a quantitative assessment of byproduct species caught by the NPF in the Gulf of Carpentaria. This may also be the first quantitative assessment for data poor byproduct species in the world. However, this quantitative assessment was undertaken with new methods and there are several uncertainties in the assessment. Caution is needed in the interpretation of the results because of these uncertainties. Where possible, we have tried to estimate the uncertainty and to include multiple approaches to estimating parameters such as natural mortality.

The biomass estimates of each byproduct group may have larger uncertainty than our results suggest. To be conservative, we only included the fishing grids where particular byproduct groups have ever been recorded in the NPF commercial logbooks. Some groups, such as squid and cuttlefish have a much wider distribution than the prawn fishing grounds (Edwards 1982; Dunning et al. 1994). Edwards (1983) showed that significant squid catches from Taiwanese fishery vessels working in northern Australia in the 1970s were taken outside the commercial prawn fishing grounds. CSIRO scientific surveys across the Gulf of Carpentaria in the early 1990s also landed squid catches in deeper waters beyond the NPF prawn trawl grounds (Dunning et al. 1994). We have not considered the uncertainties in relative catch rate q but used a single number for each byproduct group. The relative catch rate for cuttlefish and squid may be too high, especially for the squid. Dunning et al. (1994) found higher catch rates in trawls during the day as squids and cuttlefish are known to undertake diel vertical migrations. The catchability estimate (q) for squid probably over-estimates the proportion of the population in the path of the nets. This suggests that we probably have underestimated the total biomass of squid in the Gulf of Carpentaria. Further work to refine the ABC method needs to include a sensitivity analysis of q.

Regardless of the limitations of this approach, the results are encouraging and consistent with other published data on the same species groups (Dunning et al. 1994; Pitcher et al. 2007). The results suggest that the Gulf of Carpentaria contains rich byproduct resources. In particular, the estimated ABC for one of the most valuable byproduct groups, bugs is over 1500 t. The current NPF commercial catch is much smaller than this reference point. This indicates that increased targeting of these species may well be profitable in areas where high abundances of bugs co-occur with the target prawn species.

For other groups such as squid and cuttlefish, there is also potential for a fishery that would have minimal interaction with the NPF. Squid can be harvested by methods such as by jigging or liftnetting. Spawning cuttlefish can be harvested with traps that would have limited interaction with the NPF. Using these methods for squid and cuttlefish would produce a much higher quality product than trawl capture and potentially higher export market price (Dunning et al. 2000).

Before any large increase in catch is encouraged, we need to know the proportion of byproduct discarded and its fate. The NPF commercial logbook records represent only a small proportion of the actual catch of each group. Data from numerous scientific observers onboard commercial vessels suggests that only large catches of squid and cuttlefish are retained. The proportion of small catches of most byproduct species in the logbooks is small. This suggests that fishers will only retain byproduct when there is sufficient quantity to market or when prawn catches are low. Bugs are probably the one byproduct group that the majority of the legal-sized catch is retained when catches are sufficient to be of economic interest (T. Courtney pers. comm.). Bugs are currently fetching a higher price per kilogram than prawns and they are easily processed. This means that it is relatively simple to retain all legal-sized bugs thus making them attractive to fishers. Discussion with the A. A. Raptis fleet manager indicated that the retention policy for some byproduct groups varies between vessels.

The NPF prawn monitoring surveys may provide a reliable index of bug abundance. This would enable our ABC estimates to be used as an upper limit for the NPF commercial catch of each byproduct group while the NPF prawn monitoring surveys continue. Annual catches approaching the ABC estimates or a measurable decline in the catch rates during the NPF prawn monitoring surveys should trigger further investigation of that byproduct group.

The harvest strategy for the NPF includes some catch limits for squid and size restrictions for bugs. Our ABC estimates could be incorporated as an additional harvest limit for both these groups and the cuttlefish and scallops. It would be precautionary to retain the current MLS and restriction on keeping berried bugs (see Chapter 11) as well as the ABC as an upper catch limit. The NPF prawn monitoring surveys provide the only reliable data by which to estimate the ABCs. It provides the means by which the ABC of each byproduct group can be updated and thus take account of changes in the biomass of any group.

11. MANAGEMENT SCENARIO EVALUATION FOR BUGS OF THE NORTHERN PRAWN FISHERY

11.1 Abstract

We undertook a management scenario evaluation of the MLS of bugs with a Bayesian Belief Network (BBN). This approach involved constructing a conceptual model of the bug catch in the NPF that took into account the influence of environmental, fishery and management factors. Four management scenarios were compared with the BBN on a range of management regulation options. These options included dropping the MLS, reducing it to 65 or 70 mm CW, retaining the MLS at 75 mm or increasing it to 80 mm. The four scenarios were: (1) the current fishery situation, (2) an increase in fishing effort on bugs of 20% with a 20% drop in CPUE and 50% compliance with the management regulation, (3) a 50% increase in effort, 50% decline in CPUE and no compliance and (4) actively decide to change the current fishing regulation under the status quo.

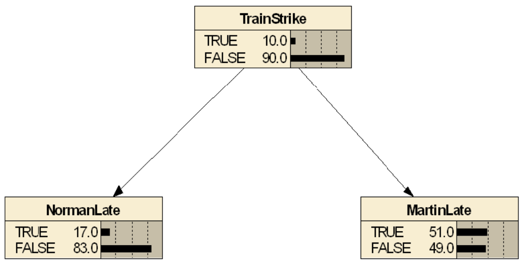
Under scenarios 1 and 2 (> 50% compliance and < 20% decline in biomass), the BBN showed that the current MLS regulation was the most optimal for the bug population, the fishery and management. Under scenario 3, the optimal MLS was increased to 80 mm. Under the last scenario (scenario 4), a change in the MLS to between 65 and 70 mm was best. The retention of the 75 mm MLS under the most realistic fishing situations contrasts with the results from the estimated acceptable biological catch (Chapter 10). The ABC analysis suggests that the MLS could be reduced to enable catches to increase. However, this analysis only estimates the maximum sustainable catch. It does not take into account the costs of implementing alternative management strategies. The current MLS was introduced in 2001 following declines in catch rates (Chapter 6) and to better protect the breeding adult bugs. The BBN takes these risks into account and also takes additional compliance costs in its optimisation. Thus, the solutions are more conservative than the ABC, which only considers maximizing catch.

11.2 Introduction

Management scenario evaluation (MSE) is usually undertaken for commercial fisheries in a population dynamics framework. To be reliable and effective, an MSE needs sufficient data on the temporal dynamics of the system, biological characteristics of the species and fishing effort (Wang and Die 1996). Understanding the population dynamics of a system is quite complex and there is a strong assumption that the parameters of models can be estimated with some degree of certainty. For byproduct species such as bugs, there are unlikely to ever be sufficient data to undertake an MSE based on species population dynamics.

The lack of data for byproduct species lends itself easily to a Bayesian Belief Network (BBN). Expert opinion can be incorporated into the network via priors and conditional probabilities that describe the causal links between nodes. The fundamental idea behind the BBN is the application of Bayes theorem (Gelman et al. 2000), which is used to construct posterior probabilities of events occurring based on likely prior scenarios that have a probability associated with each scenario. On the surface, a BBN provides a simple framework in which to estimate the most likely outcome from a number of plausible options. However, BBNs can become complicated when you try to make the network representative of the natural environment. This can lead to numerous causal links between factors that that are required to realistically describe the system under investigation.

As an example, we can construct a BBN of the relationship between a train strike and likelihood that two colleagues, Norman and Martin will arrive late to work (Figure 11.1). The BBN is defined through a set of nodes (represented by rectangles) that are linked together by arrows, where the direction of the arrow indicates the nature and direction of the causal relationship. In Figure 11.1 (a), a train strike will have an impact on either the arrival of Norman or Martin to work. Therefore the arrow is in the direction of the impact. We then populate the BBN with information about our beliefs on the impact the train strike has on their travel to work. We know from past train records that there is a 10% chance of a train strike occurring. This represents our prior that is assigned to the TrainStrike (TS) node (top line). While the probability that Norman makes it to the train on time is 0.9 (10% chance of being late), the probability of Martin being late to catch the train is 0.3. We also know that given that there is a train strike, the chance that Norman and Martin will be late to work is 80% and 60% respectively. These represent the conditional probabilities which are assigned to the NormanLate (NL) and MartinLate (ML) causal nodes. If we want to know the posterior probability of a train strike given that Norman and Martin were late into work, we can simply apply Bayes theorem as shown in Equation 11.1 (Figure 11.1 b).



$$p(TS|NL\&ML) = \frac{p(NL\&ML|TS)p(TS)}{p(NL\&ML|TS)p(TS) + p(NL\&ML|noTS)p(noTS)}$$
$$= \frac{0.048}{0.96} = 0.516$$

Figure 11.1. A BBN showing the causal relationship between a train strike and the chance of two colleagues, Norman and Martin arriving late for work. The figure shows the marginal probabilities and posterior probabilities given the model formulation.

Bayesian Belief Networks (BBNs) have become a popular tool for understanding system processes (Borsuk et al. 2004; Hamilton et al. 2007). Little has been done in the way of management scenario evaluation for non-target species such as byproduct. The construction of a BBN involves the interaction between stakeholders or experts who can provide knowledge or expertise about the problem. The structure of a BBN requires a number of workshops to ensure all aspects of the system are captured adequately by the BBN framework. Generally, the first workshop aims to elicit the conceptual model while subsequent workshops target specific components of the model for the purpose of eliciting relevant quantities, where no data exist. The idea here is for a general consensus to be formed on the model and elicited components. If management scenario evaluation is the primary objective then a subsequent workshop to investigate appropriate management actions may be beneficial.

The components of the BBN are constructed in such a way as to facilitate easy and straight forward elicitation. In the above example, a simple TRUE or FALSE was used to illustrate the different states each node can be in. This presents a very simple structure and therefore makes the elicitation of priors and conditional probabilities fairly straight forward. For other examples, it may be more beneficial to increase the number of states defining a node (e.g. low, moderate, high) or to an even much broader range of values (e.g. 0 – 10, 11 – 20, 21 – 30). The broader the definition, the more difficult it is to elicit the required conditional probabilities and there is a trade-off between providing a node that is informative as opposed to a node where the elicited components are accurate. Care must be taken in the definition of these nodes and the way in which the probabilities are elicited.

11.3 BBN Software

Although there are a range of packages available for constructing BBNs, we used Netica to facilitate BBN construction for this problem. This choice was based on our prior knowledge of the package and its availability. Although Netica provides a good framework for eliciting information and the model is easy to interpret and evaluate once the structure is well defined, the software does have a number of drawbacks. Netica cannot handle feedback loops easily in the model and therefore only incorporates acyclic structures. An example of a feedback loop is a predator-prey interaction or the temporal dynamics of the system. The former is not of real interest in this example, however the latter is. As temporal dynamics are not straight forward to implement in this framework, we chose to focus on modelling current condition but provide options for changes in effort and catch that may be expected over time.

A second issue with the software is that Netica defines each node in the network to be discrete, irrespective of whether a continuous distribution has been specified. In other words, any model developed is static. The discrete nature of each node implies that a continuous measure can be easily compartmentalised by the specification of appropriate bins. In our experience this specification is not straight forward. Furthermore, Netica uses Monte Carlo sampling (with and without uncertainty) to populate conditional probability tables when deterministic functions or continuous distributions have been defined at a node. We have found issues relating to the uncertainty component of this sampling regime when operating on the raw scale of the data. We have also found that the choice of bins for the purpose of compartmentalising the continuous nodes is sensitive to the Monte Carlo sampling. As a result, we have chosen to represent any abundance measures reported in the network on the log scale and we have had to reduce the number of bins in some instances to ensure that sampling could be undertaken. We also did not incorporate ’uncertainty’ through the Netica software. This approach provided greater computational stability in the network than if we chose to operate on the original scale of the data.

11.4 Workshop and Stakeholder Interaction

Due to the limited time available for the construction of a BBN for the management of bugs in the NPF, we could only hold one workshop and this was centred on the elicitation of the conceptual model. Subsequent interaction between the primary stakeholders in this exercise was conducted via email, phone and face-to-face interactions to populate the model and determine the inputs into various model components. We stress the importance of holding subsequent workshops to gain consensus on the model outlined in this chapter.

Prior to the workshop we structured a short questionnaire which focussed on: (1) the management of bugs, (2) measures of sustainability, (3) biological information and (4) factors that impact catch. These four areas were identified from previous work on the project (Chapters 7 – 10). The responses to this questionnaire varied and this seemed to depend on people's own experiences in the NPF and other fisheries. Using this information, we held a workshop on the 18th September 2008 to discuss the questionnaire responses and constructed a conceptual model for managing a bug fishery. Present at the workshop were the following people with key expertise: bugs population dynamics, Tony Courtney (QDPI&F); bug biology: David Milton, Gary Fry and Mark Tonks (CMAR); population dynamics modelling: Shijie Zhou (CMAR). The Northern Prawn Fishery Management Advisory Committee scientific representative and MSE expert, Cathy Dichmont (CMAR) was unable to attend but interacted at a later date. We began with an overview of the project, aims and objectives and then commenced the discussions with a preliminary model (Figure 11.2). The key features of this model were the impact factors on the biomass, determining what proportion of the population remains and a performance measure for determining how well the fishery is being managed and its ability to recover. We then used the whiteboard in conjunction with the questionnaire outputs to populate/change the components of the conceptual model.

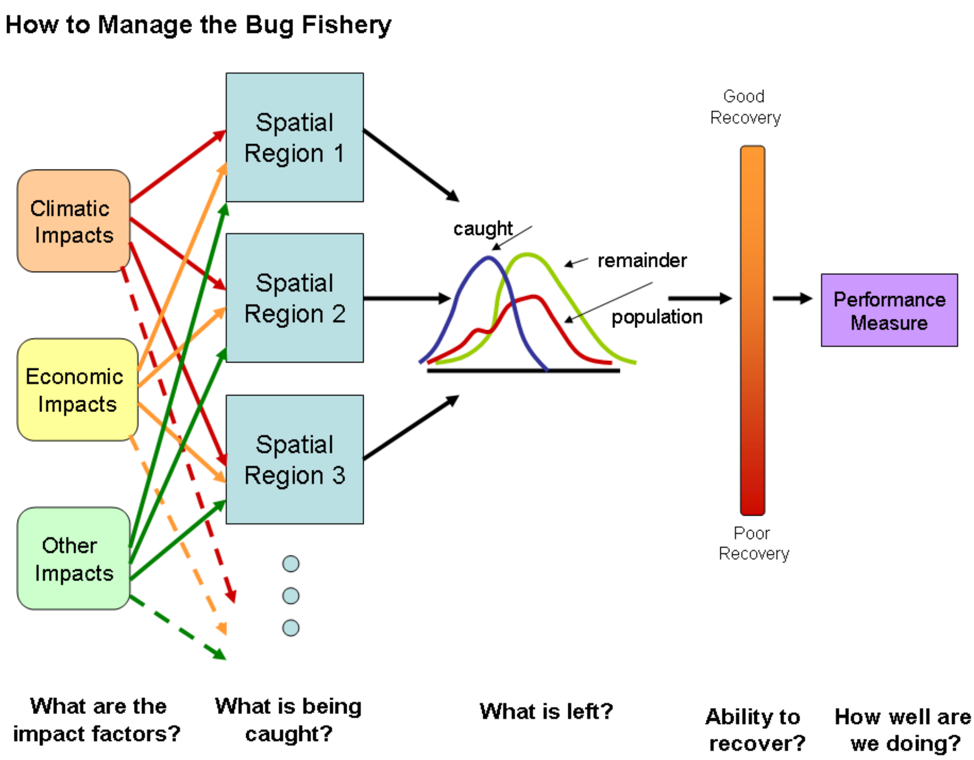


Figure 11.2. Initial conceptual model used at the workshop to engage workshop participants.

The outcomes from the workshop can be summarised below in terms of the topics that were discussed.

11.4.1 Overall Conceptual Model

- It was identified that the overall conceptual model proposed was a good starting point for thinking about how to manage bugs. However, there was much discussion regarding the performance measure of the fishery in the context of the BBN. Instead of using the word recovery it was decided that a better term to use is exploitation.
- It was identified that a useful performance measure would be the exploitation rate, $U = F/(M + F)$, where M is the natural mortality and F is the fishing mortality. An optimal value of U indicates the fishery is sustainable while a large value of U indicates that the fishery may be in decline and will need to be managed. The NPF is moving towards having the Maximum Economic Yield as the overall performance indicator for the total catch from the fishery. However, this measure would be difficult to implement in the BBN without substantial additional economic data.
- It was suggested that data from tagging studies conducted in the Queensland East Coast Otter Trawl Fishery (QECOTF), which allowed estimation of F and M could be used. It was also suggested that we could use NPF prawn monitoring survey and NPF commercial logbook data to obtain an estimate of F by examining the ratio of total logbook catch with the estimated abundance from the survey data.

11.4.2 Management Interventions

- A number of management interventions were discussed. Management interventions currently in place consist of a minimum legal size (MLS) of 75 mm and prohibition on berried females. However, investigations in the QECOTF have shown that the yield was maximized when harvest size for bugs is 80 mm. Courtney (1997) recommended increasing the MLS to 80 mm or even 91 mm. This has implications for a mixed species fishery because the reef bug *Thenus australiensis* grows to a much larger size than the mud bug *T. parindicus*. So increasing the MLS should be considered as one management option for the NPF.
- A total allowable catch (TAC) was discussed at the workshop. The regulator can define a TAC quite subjectively by specifying a number equal to some percentage of the highest catch for one species in the logbook history but it was agreed that this is difficult to define. One approach is to consider a cut-off for determining a TAC, where the cut-off represents 20% of the virgin stock. Stock sizes below this cut-off would instigate a closure. The workshop noted that an estimate of 'virgin' stock may be difficult to obtain.
- Spatial management was considered to be an important issue and it was determined at the workshop that the model should be developed and limited to four spatial regions: Groote, Mornington (including Karumba), Vanderlins and Weipa. It was decided that Mornington and Karumba should be considered together because of the varying definitions of the boundaries between the two regions in the NPF prawn monitoring survey and NPF commercial logbook data. It was also decided not to extend the spatial

region to other areas of the NPF outside of the Gulf of Carpentaria due to the lack of data from those areas.

- We discussed whether we should manage each species separately. Investigations by Courtney (1997) and others have shown that the two species of bugs grow to different sizes and therefore should be managed using different MLS cut-offs. However, it was decided that the implementation of any such management strategy would be difficult. Furthermore, since there is a higher proportion of mud bug in the NPF compared to the QECOTF, it would not make sense at this point to manage species or sexes separately.

- In terms of managing bugs, it was identified that an ideal method for managing, given that there are two management interventions already in place is to determine a trigger value, where the trigger is defined by the fishing mortality incurred from implementing a specific management action multiplied by the estimated biomass. If the total catch recorded in NPF commercial logbooks exceeds the chosen amount then this triggers a response for a more active management intervention.

11.4.3 Impact factors

Environmental

- Workshop participants were unsure what environmental factors impact bug abundance and it was suggested that we explore the impact (if any) of these environmental factors using a statistical model applied to the NPF prawn monitoring survey data.

- There was some debate on whether environmental factors impact more on mud bugs than the less common reef bug in the fishery. In the NPF, bugs are generally caught during the evening when fishers target tiger prawns. There was limited data available from the banana fishery. Therefore, any data we examine for the purpose of populating a BBN should factor in tiger prawn fishing season catches only.

Economic Issues and Compliance

- There was some debate about whether the price of bugs was impacting the bug catch and changing fishing behaviour. In the last 10 years the price of bugs has doubled compared to the price of prawns. The targeting and retention of illegal-sized or berried bugs was therefore seen as a major issue in the QECOTF. The workshop felt it was not a major issue in the NPF at present. There was no clear evidence to suggest bugs were being targeted in the NPF in the same way that they were being targeted in the QECOTF.

- Reef bugs comprise the majority of the bug catch in the QECOTF and it has been identified that the stripping of eggs is an issue. However, mud bugs comprise the majority of the catch in the Gulf and it was hypothesised that fishers may not be stripping eggs to the extent of that occurring in the QECOTF.

- The two bug species are marketed in the same way at the present time.

Stressors

- Scientific observations on commercial trawlers in the NPF and Qld east coast have found that bugs have a reasonably good trawl survival rate from trawling. However, studies in the QECOTF have shown that as the length of trawling increases, the survival rate decreases. It is anticipated that a 4 – 5 hour trawl in the Gulf of Carpentaria will reduce bug survival.

11.5 BBN Framework

11.5.1 Managing a single spatial region in a fishery

The outcomes described in Section 11.4 provided the impetus for structuring a BBN for the management of bugs in the NPF. We first considered the problem of managing a single spatial region. The framework for managing a single spatial region in a fishery was broken up into three components: (1) Sustainability, (2) Fishing Effort and (3) Management (Figure 11.3). Both the sustainability of the fishery and fishing effort provide a causal mechanism for determining whether management actions need to change.

The sustainability of the fishery is defined through various factors that impact on the biomass of the species. Environmental factors certainly play a role but these factors alone do not describe the variation in biomass experienced in fisheries such as the NPF. Fishing obviously plays a large role and incorporating fishing strategies and scenarios of compliance in relation to these strategies is important for setting trigger values for maintaining the sustainability of the fishery.

Fishing effort is captured in the model through the NPF commercial catch records. Provided that these records are accurate, we can use this data to compare against a defined trigger to determine whether a change in management is required. A change in effort due to socio-economic factors, or implemented management strategies can result in higher than usual catches. If fishing effort and fishing mortality (F) increase and the catch is above the trigger limit, this will lead to a change in management position and lead to a change in measures. Given this change (passive or active), we can then explore various management options by examining the benefit that the strategy has on the fishers and the resource and the negative benefit incurred from enforcing a particular management strategy (Figure 11.3).

A BBN was constructed initially for one spatial region in the Gulf of Carpentaria to form the framework for models developed for the three remaining regions. The BBN for Groote (Appendix C) incorporated the components of the conceptual model above in terms of creating a trigger limit value for maintaining sustainability, capturing effort through commercial catch records and scenarios of changes in effort that may lead to a change in management position. Although various components of the model will be outlined in detail in Section 11.6, we described the general framework here and how it links with the conceptual model described above.

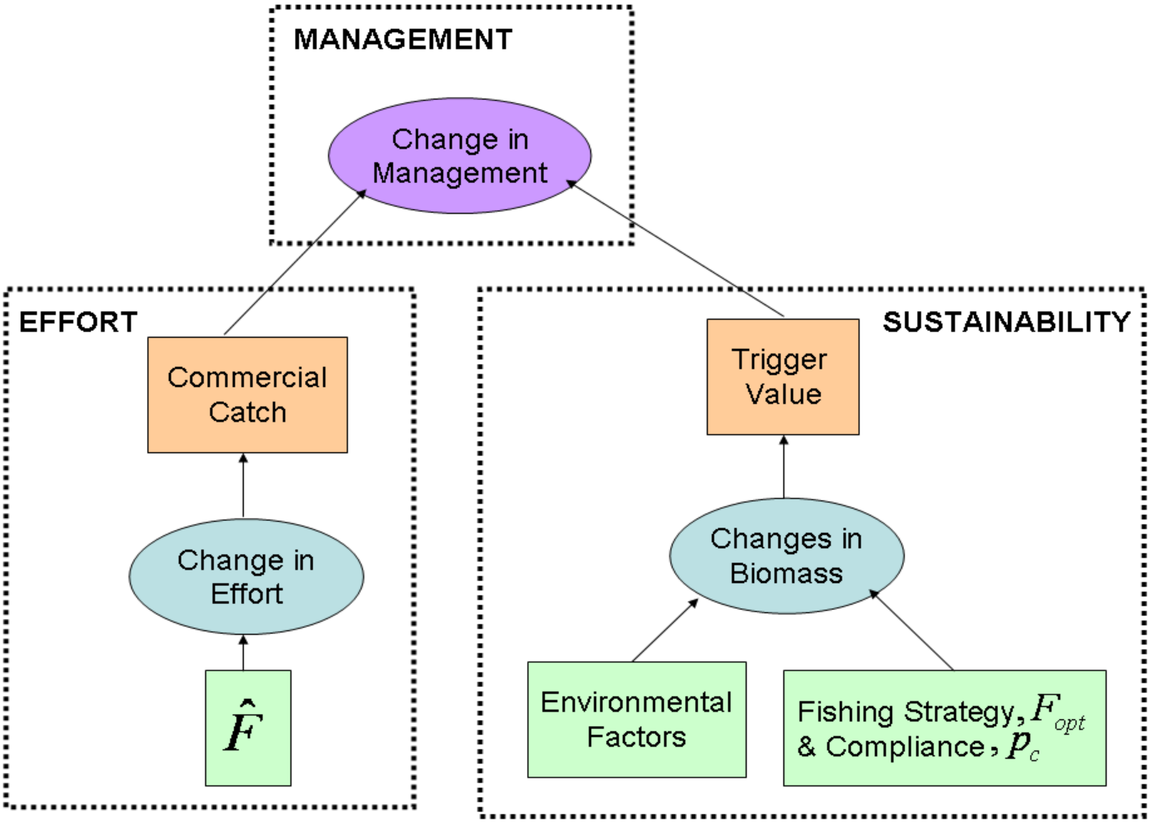


Figure 11.3. A conceptual model for managing a single spatial region in a fishery. The model compares a defined trigger value with the recorded commercial catch to determine if management needs to change.

Appearing at the base of the network are important factors, identified through a statistical model, that impact the density and hence the biomass of bugs. In this network, biomass is defined as a deterministic function incorporating the baseline density for the region, changes in density due to environmental factors, fished area and the state of the fishery (e.g. whether it is stable or in a state of increase/decline). Factors that impact biomass in this model consist of environmental variables which include sediment, nitrate, oxygen, wind speed and sea surface temperature. These variables impact biomass through a change in the estimated density. Prior probabilities based on empirical data from the NPF prawn monitoring surveys define the priors for the environmental variables, while conditional probabilities which define the causal relationship between the environmental variables and changes in density were obtained from a generalised additive model.

A fishing strategy also impacts on the fishery as it has the potential to cause changes to the bug population. Given a particular management strategy and level of fisher compliance, we can determine an optimal fishing mortality F_{opt} that leads to a sustainable population. F_{opt} can then be used to define a sustainability trigger in conjunction with the natural mortality of the bug population and the estimated biomass.

Further up the network, we have a distribution of commercial catch recorded for a given amount of effort. This catch together with the sustainability trigger and the state of the fishery can be used to determine the management action. This action may be to remain passive and continue to implement a 75 mm minimum legal size (MLS) or become active and change to a management strategy that is more restrictive. Each management strategy can be investigated by considering the benefits for each. The maximisation of benefits then leads to an optimal solution, given the management position on the fishery.

Although the network appears complex, only parts of the network incorporate subjective information. Table 11.1 outlines the components of the network, what data we used to define each node and outlines how this information was captured in the network (e.g. via a deterministic function, a constant or through a prior or conditional probability table, a cost/benefit or proposed as a scenario evaluation).

11.5.2 Managing the Gulf of Carpentaria

The management of an entire fishery that may comprise a number of spatial regions provides a complicating factor. Not only do we have to decide on whether management needs to change within each spatial region, but as a whole, we need to determine how to manage the fishery. Although it is in the interest of the managers to examine the sustainability of each region in the fishery separately, it is unreasonable to assume that the spatial regions in a byproduct fishery will be managed differently because byproduct including bugs is not the primary target of fishers. Thus, we assume that if at least one region needs to be actively managed, then the identified strategy would need to be implemented for all regions. Of course more complicated scenarios could be considered but these are outside the scope of this analysis.

To keep the model relatively simple, we construct a BBN for each region separately rather than incorporating all regions into the one BBN framework. These BBNs (Appendix C) are structured in the same framework as described above, ensuring that the priors and conditional probability tables relate to each region. As outlined earlier, the optimal management strategy is defined as the strategy yielding the maximum benefit of that action to the fishery. Where a change in management is identified for any particular region, we would suggest adopting that strategy across all regions.

11.6 Bayesian belief network components

The probabilities underlying the marginal nodes of the Bayesian Belief Networks (BBNs) (Appendix B) and the relationship between nodes were derived from a combination of empirical data (NPF prawn monitoring survey data and NPF commercial logbook catch records and environmental data), modelled data (via statistical models) and expert opinion (Table 11.1). We describe how each source of data was used in the construction of the BBN.

Table 11.1. Data defining the nodes of the BBN for bugs in the NPF.

Node	Type of Information	Captured information
Impacts on density		
Environmental predictors	empirical data	prior
Changes in density	statistical model (GAM)	conditional probabilities
Baseline density	statistical model (GAM)	prior
Calculation of biomass		
Biomass	function	deterministic
Fished area	empirical data	constant
State of fishery	subjective	scenario evaluation
Trigger value		
F_{opt}, F trigger, implemented strategy	Yield-per-recruit analysis	deterministic
Compliance	elicited	prior
Sustainability trigger	function	deterministic
Natural mortality	published study	constant
Catch		
Commercial catch	empirical data	prior
Effort	subjective	scenario evaluation
Management		
Management type	function/subjective	conditional probabilities
Benefit to fishers	Value-per-recruit analysis	benefit/costs
Benefit to resource	Egg-per-recruit analysis	benefit/costs
Compliance enforcement	subjective	benefit/costs

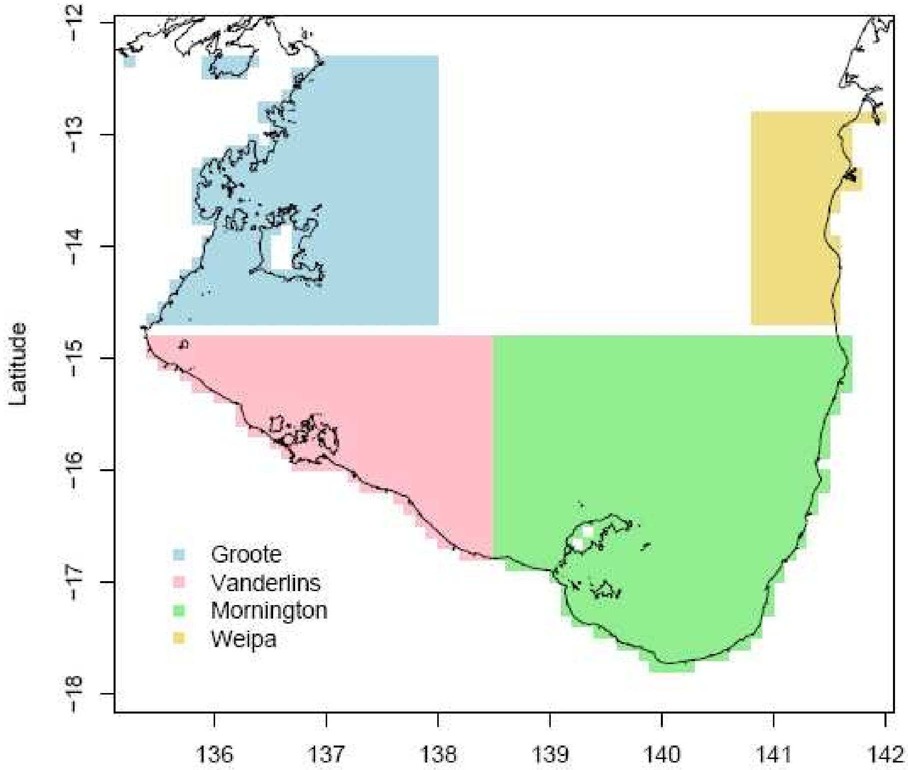


Figure 11.4. Map of the NPF prawn monitoring survey regions for bugs caught in the Gulf of Carpentaria.

11.6.1 Impacts on density

Data corresponding to four byproduct groups (bugs, cuttlefish, squid and scallops) of all sizes were collected from the NPF prawn monitoring surveys between 2002 and 2007. We focused on the commercially important bugs, which comprise two species: *T. parindicus* (mud bug) and *T. australiensis* (reef bug). Although the NPF covers a large body of water to the north of Australia, the region of interest in this report extended between Cape York in Queensland and Groote Eylandt in the north western parts of the Gulf of Carpentaria (Figure 11.4). Regions covered in the NPF prawn monitoring surveys include Weipa, Groote, Mornington and Karumba and Vanderlins. Coastal areas are predominantly fished with some more central regions of the Gulf also being surveyed during 2003. A higher proportion of mud bug was observed across most regions in the Gulf with higher proportion of reef bug occurring in parts of Weipa, Vanderlins and Mornington (Chapter 9).

Environmental data consisting of wind speed, two sea surface temperature measurements, salinity, oxygen, nitrate, two chlorophyll measures, turbidity and sediment were also available for analysis. These were extracted from an external database of model predictions corresponding to specific grid locations and dates recorded in the NPF prawn monitoring survey dataset. Most variables were derived from sensory satellites and climatology maps. In this analysis we used data obtained from the MODIS (Moderate Resolution Imaging Spectroradiometer), SeaWIFS (Sea-viewing Wide Field-of-view Sensor) and CARS (CSIRO Atlas of Regional Seas) programs. Details of how each variable was measured and/or created is described elsewhere (NASA 2008; CARS 2006).

11.6.2 Investigation of environmental variables

We merged the NPF prawn monitoring survey data and environmental variables by year and spatial location (six nautical mile grid position) and performed an analysis to investigate if any environmental factors were important in the estimation of bug density (in $g.ha^{-1}$). We began the investigation by fitting models to each species separately and included a region and depth variable in order to estimate a regional baseline that we could include in the BBN. We excluded any environmental variables that contained a large number of missing observations (chlorophyll and turbidity) and used a generalised additive model (GAM) using the `mgcv` package in R (Woods 2006). Although including a temporal term such as year is important for investigating changes in density through time, we found it difficult to incorporate a temporal term in the BBN with Netica. Instead, we provided a model for current condition with likely scenarios of change that might occur through time.

We fitted a GAM where the mean log of the bug weight, μ_i (in g), recorded for trawl *i* as a function of region, R_i, smoothed functions of the environmental predictors, $f(X_{ij})$ and adjusting for the swept area through an offset term, α_i as outlined in equation 11.2 below.

$$log(y_i) = \mu_i + \epsilon_i, \quad (i = 1, \ldots, n_{shot})$$
$$\mu_i = \alpha_i + \beta R_i + \sum_j f(X_{ij}) \qquad (11.2)$$

The smooth terms in the above model are represented by thin plate regression splines, with knots optimally positioned based on a generalised cross-validated score. We only considered main effect terms in the model and excluded interactions because they were difficult to interpret and translate into the BBN framework. We also only included environmental variables that made sense biologically.

The resultant model had significant smooth terms including depth, mud, sea surface temperature (SST), wind speed, oxygen and nitrate (Table 11.2). The curves for the smoothed relationships for the six environmental variables show the contribution to the mean density as each variable increases (Figure 11.5). A rug plot is also shown on the x-axis to indicate where data was collected or more importantly, where it was missing. In summary, we found the following:

- As depth increases from 10 to 40 m, we saw an increase in the bug density.
- As the percentage of mud increases we saw a general trend of lower bug densities. However, we notice that when mud dropped below 20% of the substrate composition, density also decreases.
- A slight increasing trend in density when sea surface temperature increases. This same trend is also noted for oxygen and nitrate.

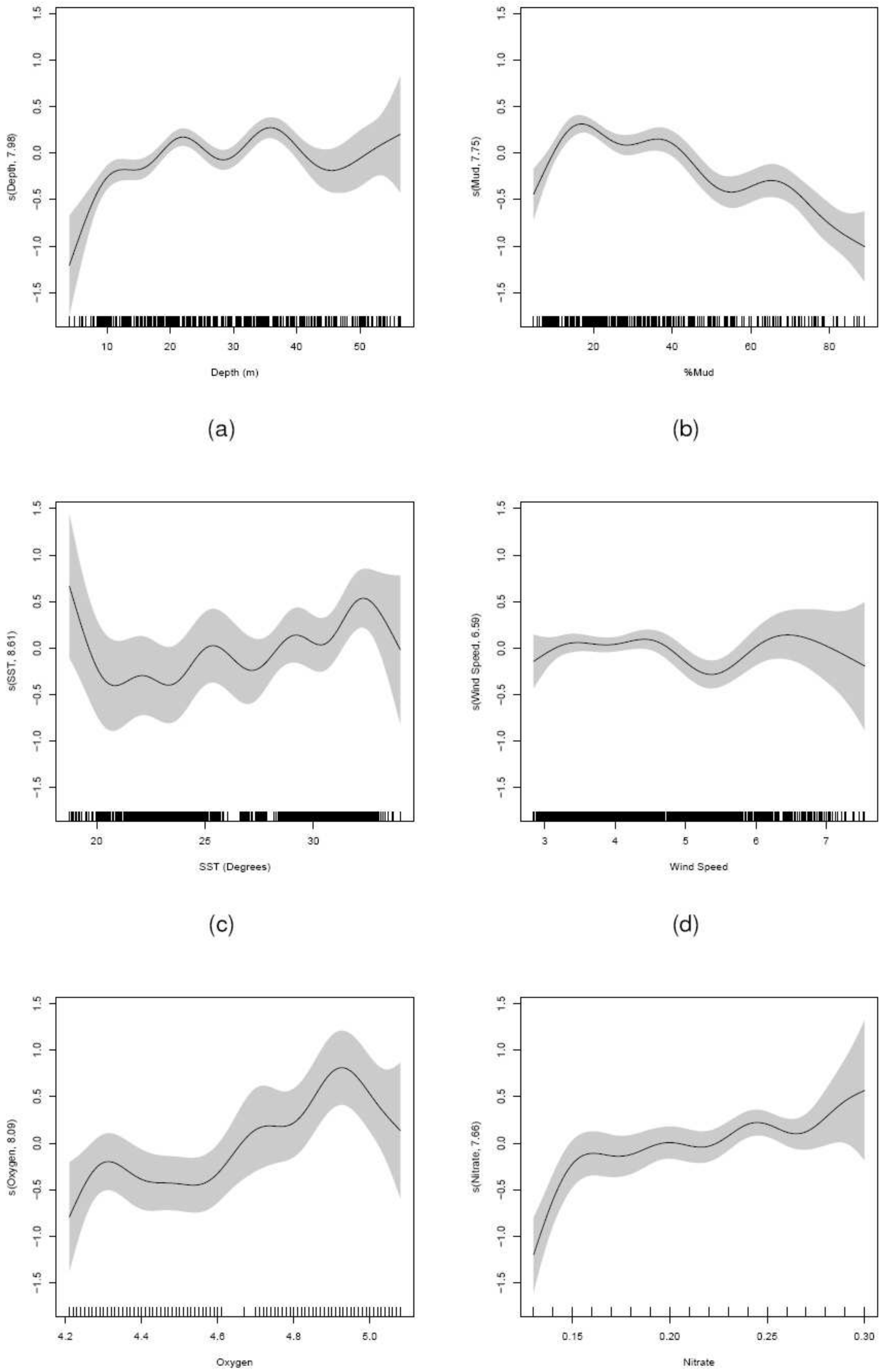


Figure 11.5. Plots of the component smooth functions for (a) depth, (b) mud, (c) SST, (d) wind speed, (e) oxygen and (f) nitrate.

- Wind speed appears to only impact density when it reaches about 5 $m.s^{-1}$ at which speed appears to slightly decrease bug density and then increase it once wind speed increases beyond 6 $m.s^{-1}$.

- In terms of regional baseline values, Mornington had the highest baseline estimates of density (162 $g.ha^{-1}$), followed by Weipa (140 $g.ha^{-1}$), Vanderlins and Groote (73 $g.ha^{-1}$).

- Only 27.7% of the deviance was explained by this model, suggesting that the density of bugs is only partly explained by these environmental factors.

Table 11.2. Parameter estimates and smoothed terms from the GAM fit to the NPF prawn monitoring survey data. The parameter estimate ± SE and *p*-value are shown for fixed effect regional coefficients. For smoothed terms, the effective degrees of freedom (Edf) and *p*-value are displayed.

Variable	Edf	Estimate	SE	*p*-value
Regional coefficients				
Mornington		5.085	0.053	< 0.0001
Groote		4.285	0.074	< 0.0001
Vanderlins		4.298	0.055	< 0.0001
Weipa		4.942	0.139	< 0.0001
Smoothed terms				
s(Depth)	7.981			< 0.0001
s(Mud)	7.752			< 0.0001
s(SST)	8.613			< 0.0001
s(Wind Speed)	6.593			0.01
s(Oxygen)	8.094			< 0.0001
s(Nitrate)	7.658			< 0.0001

11.6.3 Translation of environmental variables to the BBN

The BBN framework requires any information to be translated into marginal or conditional probabilities irrespective of how the information was derived. To facilitate this translation, we consider the causal relationship (Figure 11.6). From the GAM model we can determine the change in density and baseline density as indicated by the orange nodes in the diagram. The NPF prawn monitoring survey data provides the prior distribution as indicated by the green node (Figure 11.6). The blue node, which represents the bug density, is simply a deterministic relationship (as indicated by the dotted line). This deterministic relationship is the sum of the change in density and baseline density and represents the prediction we would obtain from the statistical model.

The prior distribution is easily obtained for each variable through inspection of histograms and contingency tables constructed for a specific range of values (e.g. Figure 11.7 a). However, the conditional probability distributions representing the change in density with respect to a specific value of an environmental variable were a little more challenging. To construct these conditional probability tables we used the predicted terms from the GAM and their corresponding term plots (Figure 11.5). At a particular slice (x-value) through the spline, we can determine the probability that the curve intersects this slice within a given y interval. For example, the spline for oxygen (Figure 11.7 b) represents the midpoints at which a conditional probability is determined for a specific change in density. In each conditional probability table we list the density cut-off which corresponds to the red dotted lines in Figure 11.7 (b). The density values, γ represent values used in the BBN to calculate the change in density. We selected the midpoint between two consecutive cut-offs to represent γ. The priors and conditional probabilities for each significant term in the GAM (Appendix C) show their relative contributions. We incorporated depth into the baseline density for each spatial region as we would expect depth across the regions investigated to remain fairly constant. Furthermore, it does not make sense to explore changes in depth in a BBN framework. We therefore assigned a Normal distribution to the baseline density node in the BBN that reflected changes in depths observed across each region (Table 11.3).

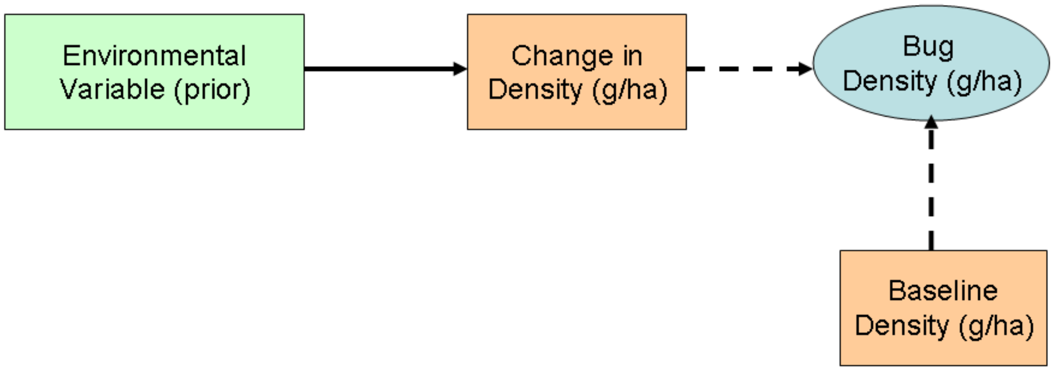
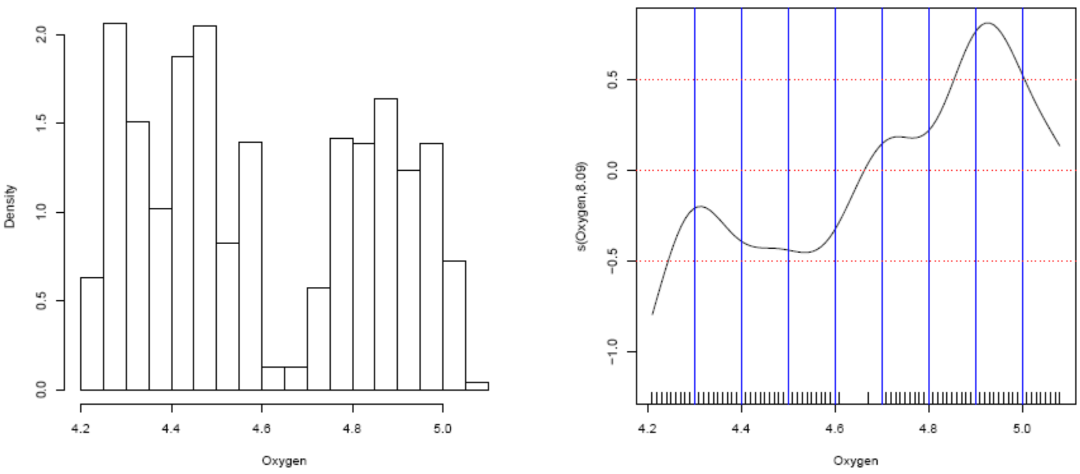


Figure 11.6. Causal relationship between important environmental factors and bug density. Solid lines indicate a causal link with conditional probability tables assigned. Dotted lines indicate a deterministic function that relates the respective nodes through some function relationship.



(a) (b)

Figure 11.7. Plots showing (a) a histogram of oxygen and (b) the component smooth function for oxygen resulting from the GAM.

11.6.4 Calculation of biomass

The biomass node in the BBN represents a deterministic function that incorporates the baseline density for the region investigated, changes in density due to environmental factors, fished area and a conversion factor to convert the biomass to tonnes. The deterministic relationship can be formally written as

$$\hat{B} = K\bar{y}' exp(\theta_b) \quad (11.3)$$

where $\hat{B}$ represents the calculated biomass, K represents the fished area in hectares, $\bar{y}'$ represents the average density of bugs in tonnes per hectare and θ_b represents the estimate of the average yearly decline in biomass of bugs. Table 11.3 shows the fishing area constants used for each region in the Gulf of Carpentaria.

Table 11.3. Priors chosen for the baseline density node and fished area for the BBN of each region. Depth is incorporated into the baseline estimate.

Region	Prior	Fishing area (K in ha)
Mornington	$N(\mu = 7.449, \sigma = 0.3297)$	3864815.8
Groote	$N(\mu = 6.1787, \sigma = 0.4453)$	2037363.0
Vanderlins	$N(\mu = 6.557, \sigma = 0.3974)$	2704136.3
Weipa	$N(\mu = 6.7328, \sigma = 0.5974)$	753206.9

The estimated average yearly decline θ_b is estimated from a statistical model that includes a yearly term for data that has been collected over a considerable length of time. Fitting a yearly term to the NPF prawn monitoring survey data revealed a negative estimate for theta (θ_b = -0.051 ± 0.019), suggesting that on average, the catch rate across all regions has been declining over years. This was also observed by examining the average weight of bugs recorded across each region from 2003 – 2007 in both the NPF prawn monitoring survey and NPF commercial logbook catch datasets. In the BBN, we specify a node that represents the status of the fishery in terms of a rate of decline, π. This rate can be defined in terms of θ by the following expression $\theta = \log(1 - \pi)$ which can be substituted into equation 11.3. We explored scenarios with rates of decline from zero to 80% (Table 11.4).

Table 11.4. Scenarios of decline examined in the BBN.

State of fishery	π_b	θ_b
Stable (no decline)	0	0
5% decline	0.05	-0.0513
10% decline	0.10	-0.1054
20% decline	0.20	-0.2231
50% decline	0.50	-0.6931
80% decline	0.80	-1.6094

11.6.5 Calculation of the trigger value

Optimal Fishing Mortality, F_{opt}

Yield-per-recruit is a standard steady-state model widely used for stock assessment to determine the optimal fishing mortality and maximum sustainable yield for a given MLS. In a steady-state fishery, yield-per-recruit can be estimated from the following equation (Ricker 1975).

$$Y/R = \exp(-M(t_c - t_r)) \sum_{i=t_c}^{t_m} \{F/Z \exp(-Z(i - t_c))(1 - \exp(-Z))W_i\} \quad (11.4)$$

where Y represents the steady state yield of the fishery, R is the number of recruits, Z is the total mortality which equals the instantaneous rate of natural mortality M plus the instantaneous rate of fishing mortality F, W_i is the mean weight of bugs at age i, t_r is the age at recruitment to fishable stock, t_c is the age of bugs at minimum legal size, and t_m represents the maximum age of bugs in the stock which is assumed to be 4.5 years. The calculation of yield-per-recruit is based on the age increment of 0.1 year, so bugs with the same age (rounded by 0.1 year) will be treated as the same cohort. Other rigorous assumptions underlie the equilibrium yield-per-recruit including:

- recruitment is constant, yet not specified (hence the expression 'yield-per-recruit');
- all bugs of a cohort are hatched on the same date;
- fishing and natural mortalities are constant over the post-recruitment phase;
- bugs older than t_m make no contribution to the stock.

Biological parameters required for the yield-per-recruit analysis are outlined below in Equations 11.5 – 11.8. These equations describe the growth curve of bugs (Equation 11.5), the relationship between carapace length (CL) and total weight (W) (Equation 11.6), conversion between carapace length (CL) and width (CW) (Equation 11.7), and fecundity (Equation 11.8). Although the two species of bugs have different biological characteristics, the parameters defined in the equations below are based on mud bugs (*T. parindicus*) as they comprise the majority of catch in the NPF (~ 90%).

Jones (1988) described the growth curve per day for mud bugs on the Queensland east coast as

$$L_t \text{ (mm CL)} = L_\infty(1 - \exp(k(t - T_0))) = 91(1- \exp(0.002(t + 79))) \qquad (11.5)$$

where L_t represents the carapace length at day t, k is the growth rate per day, L_∞ is the maximum size, and T_0 defines the starting carapace length at $t = 0$. More recently, the analysis of tag-recapture data by Courtney (1997) estimated $L_\infty = 72.4$. This was considerably lower than that of Jones (1988) and a slightly higher growth rate, $k = 0.0023$ per day.

There were 118958 mud bugs measured from the NPF prawn monitoring surveys carried out by CSIRO in the Gulf of Carpentaria from 2002 to 2008. A quantile regression shows that the 99% quantile of carapace lengths measured is 71.6 mm. Although Jones (1988) provides evidence of very large mud bugs (exceeding 100 mm CL) which would support his large L_∞ (91 mm) estimate, we believe those of Courtney (1997) better represent the bug populations in the Gulf of Carpentaria.

Based on the NPF prawn monitoring survey data, we estimated the relationship of the carapace length (CL in mm) and total weight (W in g) as

$$W = 0.00055CL^{3.0075} \qquad (11.6)$$

The conversion between carapace length (CL) and carapace width (CW) was estimated by

$$CW = 1.7623CL^{0.9429} \qquad (11.7)$$

The sex ratio of mud bugs is typically constant at 1:1 throughout the year, whereas reef bug populations, have a preponderance of males, with a sex ratio of 0.57 (Jones 1988). Fecundity (*Fe*) was related to carapace length (CL) by

$$Fe = 658.7CL - 26329 \qquad (11.8)$$

This estimate is based on 44 samples with carapace length range from 46.7 mm to 70.5 mm. Jones also estimated in the same study that the size at which 50% of the population is mature is 52 mm for mud bugs. This closely corresponds with the results from this study (Chapter 7).

There has not been any reliable estimate of the natural mortality *M* for mud bugs. A rough estimate of 1.2 can be calculated with the empirical formula of Pauly (1980). Courtney (1997) estimated the natural mortality of reef bugs is 0.92 yr^{-1} using the Ricker (1975) sequential tagging method. Courtney (1997) also commented that this estimate of *M* for reef bugs is likely to be high and includes a small (unquantified) component of fishing mortality. As mud bugs grow faster than reef bugs and they have a shorter life span, we would expect that *M* of mud bugs is no smaller than that of reef bugs. In yield-per-recruit analysis, a high *M* leads to a high optimal fishing mortality *F* in general. Considering the risk of allowing for high *F*, we opt for the more conservative estimate of 0.918 in this analysis in order to produce a conservative optimal fishing mortality.

Using a yield-per-recruit analysis, we were able to identify an optimal fishing mortality, F_{opt}. This represents the fishing mortality corresponding to the maximum yield-per-recruit for different minimum legal sizes (MLS). Currently, a 75 mm MLS is enforced along with a total ban on taking berried females. An $F > F_{opt}$ indicates overfishing and can lead to an unsustainable fishery, while an $F < F_{opt}$ indicates sustainability, given the biological parameters defining the yield-per-recruit are reliable. The optimal fishing mortality for different minimum legal sizes (Table 11.5, Figure 11.8) and the mean sustainable yield (MSY) corresponding to each MLS varied with MLS. As one would expect, we can see that as the MLS increases, the optimal fishing mortality increases and the mean sustainable yield decreases.

11.6.6 Compliance

Fisher compliance plays an important role in managing a fishery. Not only does it impact on the sustainability of the fishery but it impacts the ability to manage due to the costs involved in enforcing any management regulations. It is apparent that as the management regulations become stricter (e.g. increasing the MLS), compliance tends to decrease because of the increasing pressure faced to retain valuable catch that has to be released (T. Courtney pers. comm.).

We incorporated compliance in two components of the BBN. The first is in defining the optimal fishing mortality that will lead to a sustainability trigger. We call this F_{trig} in the model. The second is in the weighting of management strategies. We focus on the first component in this section as the weighting of management strategies will be outlined in a later section of this report.

Table 11.5. Results of the yield-per-recruit analysis for mud bugs in the NPF assuming an exploitation rate of F≈M.

Minimum legal size (mm)	Maximum sustainable yield (MSY in t)	F_{opt}
No restriction	144	0.80
65	146	0.95
70	137	0.95
75	129	1.00
80	125	1.15

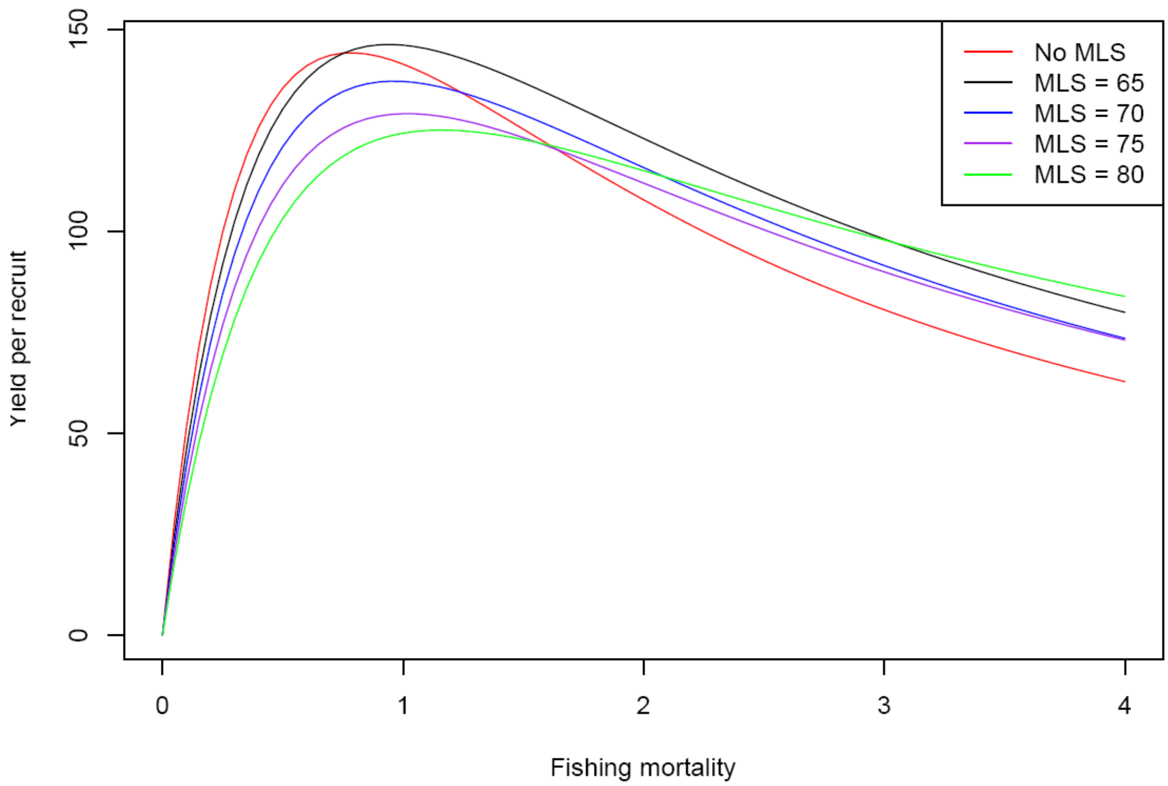


Figure 11.8. Yield-per-recruit curves for a range of minimum legal sizes (MLS). The optimal fishing mortality is indicated by the maximum peak for each curve.

Compliance can be thought of as a mechanism for altering the optimal fishing mortality, F_{opt} to some new measure which we refer to as F_{trig}. When fishers are 100% compliant, F_{trig} becomes F_{opt}. However, if fishers are always non-compliant, then the optimal fishing mortality for the management strategy under investigation drops to the worst case for the fishery, no restriction or F_{nr}. (See Table 11.5 for corresponding F_{opt} under this scenario). If compliance is represented as a proportion, p_c between 0 and 1 then F_{trig} represents a mixture of the optimal fishing scenario and the worst case as outlined in Equation 11.9.

$$F_{trig} = p_c * F_{opt} + (1 - p_c) * F_{nr} \tag{11.9}$$

Elicited information from fishers in the NPF suggested that the rate of compliance to current catch restrictions in this fishery is approximately 95% (M. Tonks pers. comm.). Based on this information, we formed a prior probability distribution for compliance in the BBN with prior probabilities as outlined in Table 11.6.

Sustainability triggers

The sustainability trigger in the BBN represents a deterministic equation that incorporates the optimal fishing mortality given compliance, natural mortality and the calculated biomass which was based on density estimates and fished area. The sustainability trigger or S_t may be expressed through the following deterministic relationship;

$$S_t = \hat{B}\frac{F_{trig}}{F_{trig} + M}(1 - e^{-(F_{trig}+M)}) \tag{11.10}$$

where $\hat{B}$ represents the calculated biomass, F_{trig} represents the optimal fishing mortality given compliance and M represents the natural mortality of the species. This equation is based on the Baranov catch equation (Quinn and Deriso 1999).

Table 11.6. Prior probabilities assigned to compliance proportions, which results in an estimate of p_c = 0.954 (SE = 0.14).

p_c	$p(p_c)$
0	0.0005
0.2	0.0095
0.4	0.02
0.6	0.03
0.8	0.07
1	0.87

11.6.7 Calculation of total catch and investigating effort

Commercial catch data was used to determine the amount of bugs caught (in tonnes) averaged over the last four years of fishing. Ideally it would be useful to incorporate a yearly term to investigate changes through time but as this is a static model, we represented catch records from 2003 – 2007 as a probability distribution defined by the Commercial Catch node in the BBN (Table 11.7).

We then created an effort node that represented changes in effort compared to the current condition to facilitate management scenario investigation. We defined effort as a multiplier of current effort ranging between 1 (representing current effort) to 20 (representing 20 times what is observed currently). Given the prescribed effort and commercial catch we can then determine the catch that is based on a functional relationship between the two. The comparison of the catch *given* effort, the sustainability trigger and the state of the fishery will determine how best to manage the fishery. If the calculated catch is less than the trigger value the probability of managing the fishery passively will decrease with increasing decline in the state of the fishery. A passive management position (current situation) results in no change to the management and a ’business as usual’ strategy. If the calculated catch is greater than the trigger value we would move to a more active management position by implementing a higher minimum legal size. The probability of managing the fishery passively or actively given the sustainability trigger, catch and state of the fishery is shown in Figure 11.9. We can see that as the state of the fishery gets worse the probability of actively managing the fishery increases irrespective of the ratio of the trigger to the commercial catch.

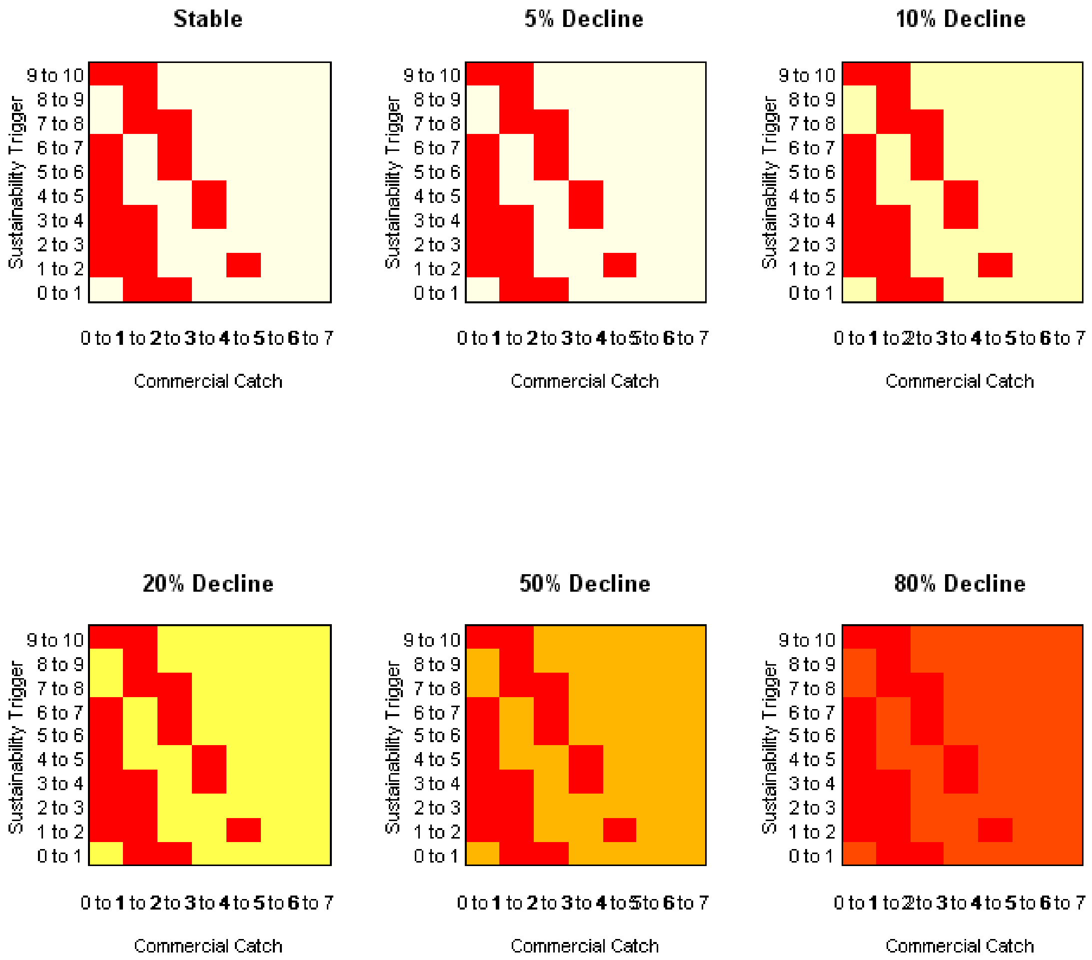


Figure 11.9. Probability of actively managing given the management position. Red indicates a probability close to 1 while yellow indicates a probability close to 0.

11.6.8 Evaluating management strategies

At the initial workshop, we discussed a number of different management strategies ranging from increasing the minimum legal size to restrictions on the sex and individual species and very strict measures such as a total allowable catch (TAC) and closures. Although some of these measures will have major effects on catch, some are clearly not feasible. Closures in particular can not be enforced as byproduct does not represent the target species for fishers in this fishery. For the same reason, it is also difficult to enforce a TAC. Furthermore, defining a TAC, catch limit or closure is difficult to do. Therefore, the only management scenarios we considered were changes in the minimum legal size of bugs. Using the NPF prawn monitoring survey catches, we limited the investigation of minimum legal sizes to none, 65 mm, 70 mm, 75 mm (current), and 80 mm carapace width. As the Gulf of Carpentaria is dominated by mud bug, a MLS greater than 80 mm was not considered.

Table 11.7. Priors chosen for the commercial catch node in the BBN defined for each region.

Region	Prior
Mornington	$N(\mu = 1.27846, \sigma = 0.6235)$
Groote	$N(\mu = 1.75395, \sigma = 0.4761)$
Vanderlins	$N(\mu = 2.0241, \sigma = 0.5934)$
Weipa	$N(\mu = -1.13791, \sigma = 0.6412)$

We considered three mechanisms for weighting each management strategy and ensured that each was scaled to represent a value between 0 and 1, with 1 providing the most benefit and 0 providing the least benefit. The first weighting mechanism represents the benefit of a particular implemented strategy to a fisher. The second is the benefit of implementing a strategy to the resource while the third is the cost (or negative benefit) received from enforcing compliance. Each of these utility functions will be described in more detail in the following sections.

11.6.9 Benefits to the fisher

We adopted a value-per-recruit analysis to weight each management strategy according to the benefit to the fisher. As bugs caught in the NPF are sold wholesale at $29 per kg, irrespective of their size, we can determine the benefit or weighting from a yield-per-recruit analysis which was discussed earlier in this report. Given the management position (passive or active) and a management strategy we can define a maximum sustainable yield (MSY) from this analysis. This can be re-scaled by the maximum yield to obtain a weighting between 0 and 1. Table 11.8 illustrates how the weighting was constructed. Note, a N/A indicates a management strategy that cannot be considered for the management position adopted.

11.6.10 Benefits to the resource

We used an egg-per-recruit model similar to the one outlined in Courtney (1997) to determine the percentage of virgin stock available after a given management scenario evaluation. This model requires knowledge of the relationship between the carapace length and the carapace width corresponding to the strategy under investigation (Equation 11.7). A corresponding age for a given carapace length can be determined via the relationship shown in Equation 11.11;

$$T_{opt} = -log(1 - (CL/L_{\infty}))/k \qquad (11.11)$$

where T_{opt} represents the optimal age for a given minimum legal size, CL represents the carapace length, L_{∞} represents the maximum size and is based on Courtney's estimate of 72.4 mm and k represents the annual growth rate (0.84 yr^{-1}). The egg-per-recruit can then be evaluated for a given age, T_{opt}, exploitation rate, $U = F/(F + M)$ and age at the minimum legal size. The egg-per-recruit relationship with age corresponding to a minimum legal size of 75 mm retains 76% of the virgin biomass (Figure 11.10). The age corresponding to this MLS is approximately 1.55 yrs. We see that as age increases, the number of eggs per recruit increases and plateaus. This analysis results in a percentage of virgin biomass retained for each MLS investigated (Table 11.9). Note, a negative benefit is assigned to the strategy where no minimum legal size is enforced, representing a negative benefit to the fishery.

11.6.11 Compliance enforcement

The third weighting used in this model is the cost (or negative benefit) from enforcing a particular management intervention. Although we do not know the absolute cost of implementing and enforcing a particular management strategy, we can determine a weighting between 0 and 1 which represents the relationship between the cost of compliance versus the proportion who comply for a given minimum legal size. We considered a model of the form;

$$C = e^{-wpc} \qquad (11.12)$$

where pc represents the compliance proportion, w represents the management weighting and C is the cost of compliance. The management weighting assigned to each management action was subjective (Table 11.10) and for the purpose of this report it was set such that the relationship between the cost and compliance resembles something like that shown in Figure 11.11. Table 11.10 outlines the weighting used to produce the relationships shown in Figure 11.11. If compliance is 0, indicating that no-one complies, irrespective of the management strategy, the cost is large (C = 1). If compliance is 1 then the cost of enforcing a management strategy decreases and it becomes 0 for no management intervention but increases as the MLS increases.

Table 11.8. Benefit to the fisher. Strategies not applicable under a given management position are indicated by an N/A in the table. These correspond to a 0 benefit.

Management position	Management strategy	MSY	Benefit
Passive	No MLS	144.13	0.9858
Passive	MLS 65 mm	N/A	0
Passive	MLS 70 mm	N/A	0
Passive	MLS 75 mm	129.08	0.8828
Passive	MLS 80 mm	N/A	0
Active	No MLS	144.13	0.9858
Active	MLS 65 mm	146.21	1
Active	MLS 70 mm	137.12	0.9373
Active	MLS 75 mm	N/A	0
Active	MLS 80 mm	125.03	0.8551

Table 11.9. Percent virgin biomass retained and corresponding benefit to the resource for a given minimum legal size and management position.

Management position	Management strategy	Virgin biomass retained (%)	Benefit
Passive	No MLS	N/A	-1
Passive	MLS 65 mm	N/A	0
Passive	MLS 70 mm	N/A	0
Passive	MLS 75 mm	76.17	0.7617
Passive	MLS 80 mm	N/A	0
Active	No MLS	N/A	-1
Active	MLS 65 mm	42.32	0.4232
Active	MLS 70 mm	62.17	0.6217
Active	MLS 75 mm	N/A	0
Active	MLS 80 mm	88.61	0.8861

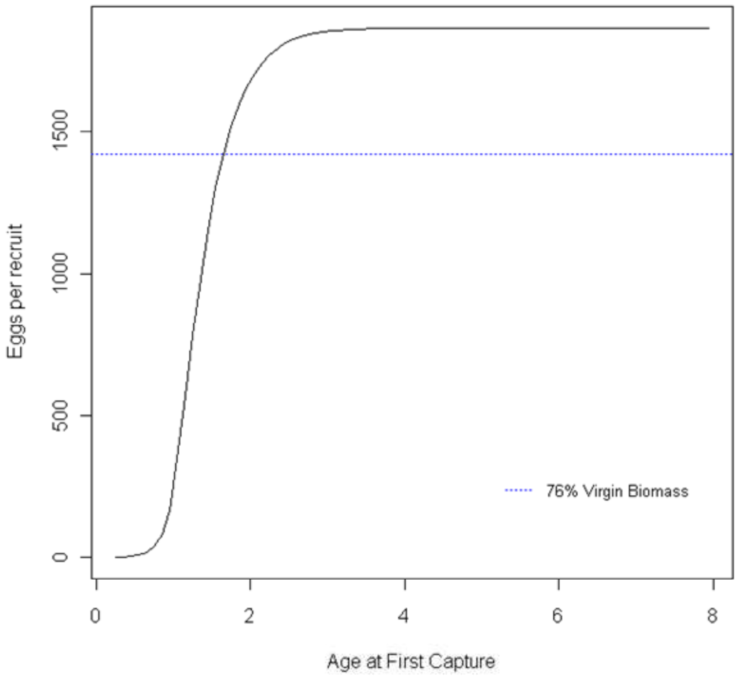


Figure 11.10. Egg-per-recruit analysis showing the eggs-per-recruit for different ages.

Table 11.10. The relative management cost weightings (ω) under different MLS options.

Minimum legal size	Weight (ω)
No restriction	5.0
MLS 65 mm	2.5
MLS 70 mm	1.67
MLS 75 mm	1.43
MLS 80 mm	1.0

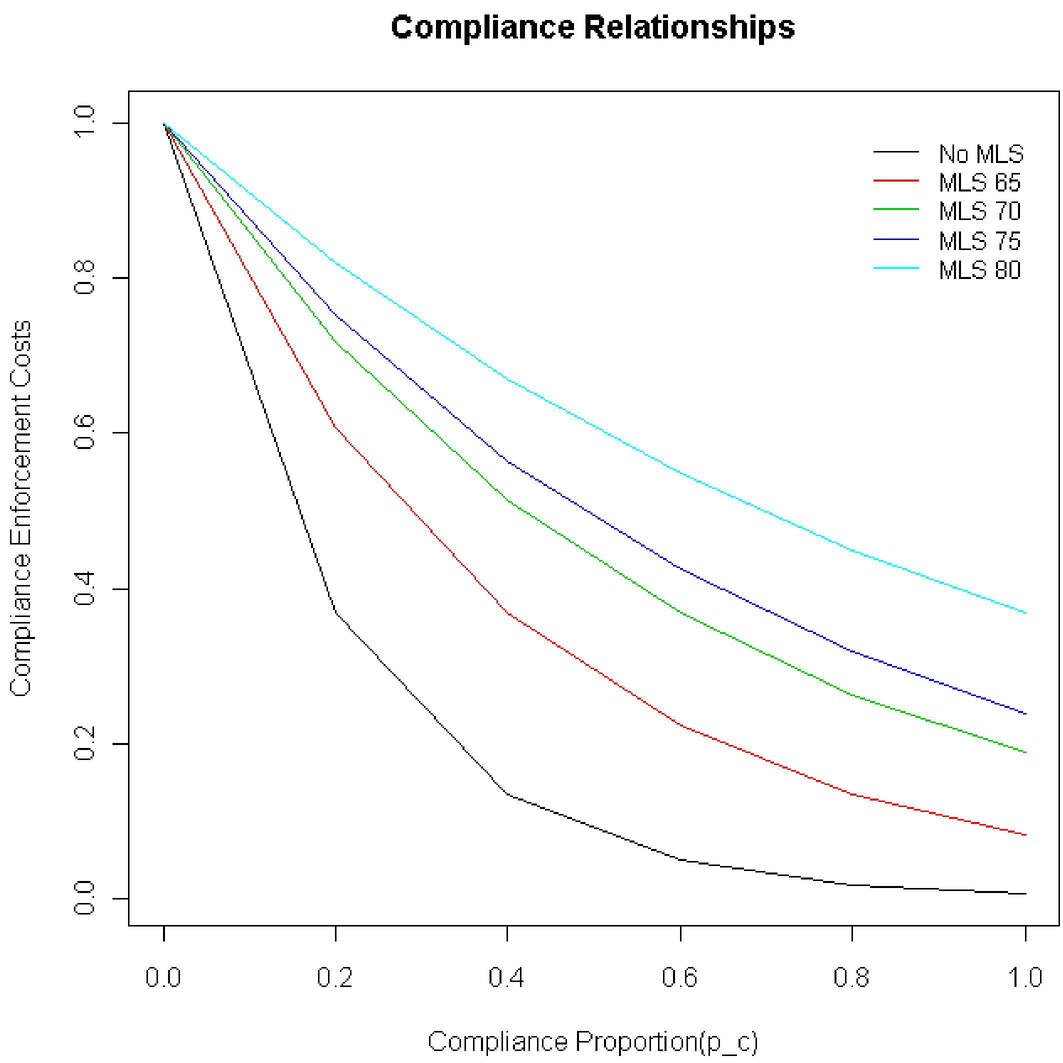


Figure 11.11. Plot showing the cost of enforcing compliance for given proportions of compliance and minimum legal sizes (MLS).

11.7 Investigation of scenarios

11.7.1 Impact of environmental variables

Environmental factors may have a significant impact on the distribution and abundance of bugs. From our study, we found that sediment characteristics and spatial terms such as depth and location are major factors that explain fluctuations of bug biomass. Whereas nutrients and other environmental variables such as sea surface temperature have limited impact (~ 30% of the deviance explained by the statistical model). This suggests that either other variables not explored in these models may be important in predicting the density of bugs (e.g. migration characteristics, predator-prey relationships) or that bug densities are predominantly determined by their spatial location.

11.7.2 Impact of compliance

Compliance has an indirect impact on the trigger value through the optimal fishing mortality for a given minimum legal size. It also impacts on the management decision through the compliance enforcement costs. We found that in a scenario where fishers are non-compliant, this has the impact of substantially reducing the trigger value by up to 20% compared to a fully compliant fleet. We also found that a fleet that was non-compliant would opt for a more stringent management intervention.

11.7.3 Changes in effort and decline in biomass

The comparison of the commercial catch with the calculated trigger value is crucial in determining the optimal management intervention. The effort node in the BBN is used to investigate changes in NPF commercial catch and how it impacts the management position (i.e. remain passive or revert to an active management intervention). We found through scenario evaluation that as we increased the effort, a shift in management position from passive to active to be more likely.

The state of the fishery also represents an important factor in managing the fishery. A declining trend in biomass would trigger a strict management action in the scenarios we investigated and this was irrespective of the fishing mortality (Figure 11.9).

11.7.4 Scenario evaluation

As an example of scenario evaluation using the BBNs created for each fishing region in the Gulf of Carpentaria, we investigated three scenarios:

- Scenario 1: 0% compliant, 50% increase in effort, 50% decline in the fishery, passive management
- Scenario 2: 50% compliant, 20% increase in effort, 20% decline in the fishery, passive management
- Scenario 3: 95% compliant, 5% decline in the fishery, passive management – current condition
- Scenario 4: 95% compliant, 5% decline in the fishery, active management

The results of each investigation are presented in Table 11.11. Active management strategies are highlighted in bold.

11.8 Discussion

We conducted an initial investigation of management strategies for bugs in the Gulf of Carpentaria using BBNs in the Netica software. We chose the BBN framework after careful consideration of the problem, the species and the nature of the data collected (or available) for that species. Our analyses resulted in four BBNs, one constructed for each spatial region in the Gulf of Carpentaria to facilitate management scenario evaluation.

Provided that the BBN is constructed properly and reflects the problem accurately, we found the BBN model to be an intuitive tool that incorporates a range of information from different sources to quantify feasible management options. This type of model offers great flexibility when it comes to incorporating new knowledge through marginal probabilities (or priors) and conditional probability tables.

Table 11.11. Evaluation of scenarios to identify the optimal management strategy for bugs in each region of the Northern Prawn Fishery.

Region	Scenario	Cost of managing					Optimal
		No MLS	65 mm	70 mm	75 mm	80 mm	action
Groote	1	-1.01	-0.71	-0.68	0.31	-0.64	**MLS 75 mm**
	2	-0.06	0.08	-0.05	0.88	-0.28	MLS 75 mm
	3	-0.02	0.01	-0.11	1.32	-0.39	MLS 75 mm
	4	-0.03	1.32	1.33	-0.25	1.23	MLS 70 mm
Vanderlins	1	-1.01	-0.27	-0.20	-0.20	-0.11	**MLS 80 mm**
	2	-0.06	-0.10	-0.03	0.86	-0.26	MLS 75 mm
	3	-0.03	-0.03	-0.15	1.31	-0.43	MLS 75 mm
	4	-0.03	1.32	1.33	-0.25	1.23	MLS 70 mm
Mornington	1	-1.01	-0.29	-0.22	-0.18	-0.13	**MLS 80 mm**
	2	-0.06	0.06	-0.07	0.91	-0.31	MLS 75 mm
	3	-0.03	-0.03	-0.15	1.31	-0.43	MLS 75 mm
	4	-0.03	1.32	1.33	-0.25	1.23	MLS 70 mm
Weipa	1	-1.01	-0.22	-0.15	-0.26	-0.04	**MLS 80 mm**
	2	-0.06	0.14	0.02	0.82	-0.21	MLS 75 mm
	3	-0.03	0.06	-0.05	1.21	-0.32	MLS 75 mm
	4	-0.03	1.32	1.33	-0.25	1.23	MLS 70 mm

The results of the scenario modelling (Table 11.11) showed that the current management regulation of a MLS of 75 mm CW is the optimal management action for both the current situation and when the bug populations decline by 20%, catch increases by 20% and there is only 50% compliance. These results provide a clear signal to AFMA that no additional management actions are required. This is probably because the population of bugs is large and current catches are well below the optimal yield estimates from all the analyses so far (Table 11.5; Chapter 10). These analyses suggest that the current (2007) landings of 15 t is well below both the steady-state MSY (129 t) or the acceptable biological catch (1887 ± 171 t: Chapter 10). Although these two estimates of sustainable yield vary widely, and have different assumptions, both are substantially larger than current total catch reported in NPF commercial logbooks.

The optimality of the current MLS regulation is somewhat surprising, given the yield is maximised when the MLS is around 65 mm CW. The optimal solution is influenced by a number of factors, including the relative weighting of the benefits to the fisher and the resource and the empirical relationships used to develop the priors. In the absence of additional information, we assumed fairly simple relationships among the factors we considered. Changes in the relative weighting of the benefits to the resource or the costs of compliance or management are likely to shift the optimal solution. Under the current passive management, the benefits to the resource of changing the MLS are nil (Table 11.9). This lack of benefit from changing the MLS plus the increased compliance costs of changing from the current regulations mean that the optimal solution is to retain the current MLS regulation.

The results of scenario 4 suggest that if AFMA decided to change the MLS and ignore the compliance costs then the optimal solution would be to reduce the MLS to between 65 and 70 mm CW. This suggests that the compliance costs and the benefits to the resource as very influential in the optimisation of overall benefit. Further work to better define the actual compliance costs may improve the confidence of all stakeholders in the outcome of the BBN. The BBN also predicts that by shifting to an active management position, the probability of a large decline in the state of the fishery will increase substantially. This is the tradeoff between relative benefits to the resource and the fishers. Studies of related bug species have also suggested that their populations are vulnerable to over-fishing (Spanier and Lavalli 2007; Duarte et al. 2010). They recommend a MLS that protects female spawners like that implemented in the NPF (Stewart et al. 1997; Oliveira et al. 2008; Duarte et al. 2010).

We found that the current catch data is also not as sensitive to changes in bug biomass as would be expected in a targeted fishery. This is due in part to bugs being a non-target species and the current MLS. These appear to have resulted in commercial CPUE not being a reliable index of abundance. The recent commercial logbook catches appear to be relatively stable and independent of the CPUE from the NPF prawn monitoring surveys. Fishers at the NPF Resource Assessment Group indicated that only a small proportion of the bug catch is retained (< 10%, I. Booth and M. O'Brien pers. comm.).

In order to explore the sensitivity of the model to the influences of these factors, an additional workshop with all stakeholders would be necessary. At such a workshop, the stakeholders would have the opportunity to discuss and comment on the relationships developed to link factors with management actions. They can also assess the relative weighting of different factors in the model and highlight any unrealistic values.

While we have confidence in the outcomes of the MSE developed with the BBN, we do acknowledge that the relationships and priors developed from expert knowledge in the analyses may not represent all views. This may lead to some biases in the outcomes presented. Additional weaknesses of the model relate to the inability of the software to handle feedback loops, the need to categorise continuous nodes and the Monte Carlo sampling approach used to incorporate ”uncertainty” into the model. These issues have been recognised as potential problems with BBNs elsewhere (Heckerman 1997; Barton et al. 2008).

We feel it is also necessary to outline some issues relating specifically to the BBN model for bugs in the Gulf of Carpentaria that warrant further consideration before this BBN could be used operationally in helping set management reference points for the fishery. Ideally, these issues could be resolved at a secondary workshop that was attended by a broader range of experts, including AFMA managers and fishers.

- Biomass estimate

  Fish stock assessment is challenging. Estimating biomass of a not well understood species may turn out to be a misleading exercise. There are a number of issues that have arisen from estimating bug biomass in this report. Firstly, we needed to define the area where the stock exists. In this study, the stock area is approximated by the fished area which includes any grid (6 nm x 6 nm) where bug catch was recorded in logbooks over the past ten years. Secondly, we assumed the area covered by the NPF prawn monitoring surveys is representative of bugs although the surveys are designed to estimate prawn abundance. Finally, we assumed a uniform distribution of bugs in each region. In the case of bugs, which tend to aggregate (Jones 1988), this assumption could potentially lead to a very inaccurate estimate. A more reliable assessment would have to use additional information, including the historical logbook catch and effort. More intensive survey data in areas of high bug catch will certainly improve the regional biomass estimates.

- Yield-per-recruit analysis

  The yield-per-recruit analysis is conducted for steady-state fisheries. However, the NPF prawn monitoring survey data indicates that there has been some decline in bug CPUE over the past five years. These declines do not appear to be related to the available biomass, but to the introduction of the 75 mm MLS in 2001 (Figure 6.3) (I. Boot and M. O’Brien NPF Industry Reps. pers. comm.). Therefore, the calculated optimal fishing mortality might be questionable. As mentioned in the yield-per-recruit analysis, there are four rigorous assumptions. Amongst these four, the assumption of constant fishing mortality is the most questionable. A simple and feasible improvement to this assumption is to assume that fishing mortality is proportional to fishing effort across a year.

- Environmental factors – causality or phenomenon?

  Without much knowledge of the factors most affecting the bug populations, the environmental factors we considered in the study might not actually be linked to their abundance. Any inference on status of the biomass based on changes in these factors could possibly turn out to be unreliable. Further investigation into these possible drivers is therefore recommended.

We noticed that there are significant interactions amongst the environmental factors themselves and the environmental factors with time. However it is a real challenge to incorporate interactions in Netica, not to mention that interaction terms are difficult to interpret. As a result, we did not explore interactions in the current model.

- Incorporation of reef bugs

As mud bug is the predominant species in the Gulf of Carpentaria, we used biological parameters based on this species for defining the optimal fishing mortality and the trigger value. Reef bugs have different biological characteristics and sediment preference compared to mud bugs. Although reef bugs only comprised a small proportion of the catch in the Gulf of Carpentaria (< 10%), reef bugs are important for measuring the health of the resource. It would be desirable therefore to incorporate reef bugs into the model in the future.

- Management actions and weightings

The management actions investigated and the weightings assigned need further scrutiny. We used a value-per-recruit and egg-per-recruit analysis to define weightings that describe the benefit to the fisher and resource respectively. With regards to compliance we developed a relationship between compliance enforcement costs and the compliance proportion and this was determined subjectively. Input into these approaches is required as the relationships may be more complex than we have assumed. The weightings of the different attributes and their contribution to the overall optimal outcome will vary with the context of the experts involved in the elucidations. Additional input from a broader range of stakeholders including fishers, AFMA managers and scientists may result in different optimal solutions.

For proper implementation of this model, we suggest further investigation, refinement and testing of the model components. Furthermore, we suggest the need for a further workshop to capture expert opinion of the models that have been derived and whether they make sense in the context of management of the NPF. We also support the ongoing implementation of the fishery-independent NPF prawn monitoring surveys. These surveys are important in populating the nodes in the BBN and being able to determine when a more active strategy for management is required. The model presented in this report cannot operate and be updated unless such information is collected.

12. BENEFITS AND ADOPTION

This project has made major advances in the assessment of fishing impacts on byproduct species in the Northern Prawn Fishery (NPF). We have identified the four main economically-important groups of byproduct species. These byproduct groups, squid, cuttlefish, bugs and scallops make up most of the byproduct retained by the NPF. We have identified the species caught within each group by examining samples taken by the Australian Fisheries Management Authority (AFMA) - funded fishery-independent NPF prawn monitoring surveys. Studies of these samples have provided insight into the ecology and life history of each species within the four main byproduct groups. We have been able to use the species composition of these samples in combination with spatial, temporal and environmental variables to develop statistical models to predict the byproduct species composition of NPF commercial logbook records. This has enabled us to identify the byproduct species caught by the NPF and examine trends in catch rates. We have been able to identify the key factors most influencing the trends in distribution and abundance of each byproduct species. The data has also been used to estimate the acceptable biological catch (ABC) of each species group and define reference catch limits for each group.

In order to estimate the proportions of each species within the grouped NPF commercial logbook records, new, novel statistical approaches needed to be developed that took the sparse data available into account. The lack of adequate indices of abundance over an extended time period made a stock assessment impossible with traditional fisheries models. We have developed a new method to estimate the sustainable catch limit (Acceptable Biological Catch) for each byproduct group. This method combines catch rates of byproduct species from the NPF prawn monitoring surveys and life-history characteristics to calculate an allowable catch.

For the most economically-valuable byproduct group, bugs, a management scenario evaluation (MSE) of the current fishery regulations was undertaken. For this, we had to develop a novel Bayesian approach that utilised both quantitative data and expert opinion. This MSE showed that the current fishery regulation of a 75 mm carapace width minimum legal size was effective at optimising benefits to both the fishers and the bug populations in the NPF.

The study has shown that populations of most byproduct species the NPF are lightly impacted by prawn trawling at current levels of fishing effort. The exception may be squid in 2007 when the catch was similar to the estimated ABC. We estimated reference catch limits for each byproduct group that can be used by AFMA to set allowable catch limits. Further, our MSE for bugs has shown that the current 75 mm (CW) minimum legal size is optimal for these species. The current additional regulation restricting the take of berried female bugs should be retained as an additional precautionary measure.

The new approaches to estimating species composition of multi-species group records in logbooks developed in this project are widely applicable to similar situations in other fisheries worldwide. Furthermore, the approach of estimating an acceptable biological catch has wide applicability in many data-limited fisheries. Management scenario evaluation usually requires large amounts of quantitative data in order to adequately compare options. Our Bayesian approach will be applicable to MSEs and other decision-making situations in many fisheries throughout the world. It is particularly useful in situations where a lack of suitable data is hampering objective decision-making. It provides a mechanism to incorporate the large amount of collective knowledge that is available in most fisheries. By developing suitable priors from these expert opinions, this information can be incorporated into the MSE model.

Adoption of the outcomes of the project would be expected to be rapid as the current status of the results has shown that most byproduct species are underexploited by the NPF. Current regulations on MLS for bugs should remain. The reference annual catch limit for squid of 500 t appears to be higher than our estimates of an acceptable biological catch for this group. The practice of targeting large aggregations of spawning squid should be monitored. AFMA scientific observers on board commercial vessels that make large catches of squid or cuttlefish (> 100 kg) should collect subsamples for analysis of species composition. New ABC reference catch limits can be calculated and updated annually if the NPF prawn monitoring surveys currently funded by AFMA continue.

13. FURTHER DEVELOPMENT

This study has applied two new approaches to develop a management strategy for byproduct in the Northern Prawn Fishery (NPF). Both approaches are novel ways to address the challenges of assessing the effects of fishing on non-targeted catch. Both methods rely on the availability of fishery-independent data to estimate the biomass of each byproduct species group. We found the recent catches of bugs, cuttlefish and scallops are below their recommended acceptable biological catch (Table 10.2). The catch of squid can approach the recommended acceptable biological catch in some years.

These methods could benefit from further development by improving the precision and accuracy of the underlying parameters. They also show that the current management regulations in the NPF are adequate to minimise the risk of overfishing. More data will need to be collected in order to improve the precision and accuracy of each method. However, the costs of collecting these data may not be justifiable for species that are an incidental catch of the fishery.

Our assessment of the ABC of each byproduct group is only for the Gulf of Carpentaria as this is the region where we had fishery-independent catch data available. It is also the region with the majority of prawn and byproduct catch. Thus, the byproduct catches from elsewhere in the NPF, including the Top End and Joseph Bonaparte Gulf have been ignored. Although there were few data in the NPF logbooks from these regions, a change in the distribution of byproduct catches may require additional studies in order to take these catches into account in assessments of the fishery impact.

The Bayesian Belief Network (BBN) model developed for bugs in the NPF is a new approach that may be applicable to many other data poor fisheries. The models can be quite complex and their utility is dependent on the quality of the data available. The software used in the BBN (Netica) has the disadvantage that it only allows static models. Thus the model is just a snapshot of the fishery, economics, compliance and management at that time. In order to update the model to keep it relevant, additional data needs to be collected. The AFMA-funded NPF prawn monitoring surveys are critical to the updating and refinement of the model.

One of the outcomes of the BBN and the estimates of Acceptable Biological Catch (ABC) is the indication that the bug population in the Gulf of Carpentaria is underexploited. If the management of the fishery changes and the MLS for bugs is reduced from the current 75 mm carapace width, the BBN will need to be updated once the new regulations have been implemented.

14. PLANNED OUTCOMES

1. *Advice to management of actions required to manage fishing effort on each byproduct species group.*

The most commonly retained byproduct groups in the Northern Prawn Fishery are all relatively short-lived (< 5 yrs) and have life-history strategies adapted to unpredictable and often high natural mortality. The Northern Prawn Fishery fleet has reduced from about 100 vessels to 52 vessels in 2007. This has led to a reduction and contraction in the fishing grounds trawled. Thus, it is not surprising that the project has found that the current catches are below the estimated sustainable catch for all groups except possibly squid. For cuttlefish, scallops and bugs, the results show that the current NPF commercial catch is a small proportion of the estimated sustainable harvest. Thus, it appears that no active management intervention should be required for these groups at current levels of fishing effort. Yield-per-recruit analyses for bugs showed that yield would be maximised if the MLS was reduced to 65 mm CW. Other analyses undertaken also showed that the sustainable yield for bugs was much higher than current catches. However, management scenario modelling found that the optimal MLS was the current 75 mm CW. There are a number of possible reasons why these different methods produced apparently contradictory results. The ABC approach only examined the byproduct populations from the fisher perspective. Whereas, the BBN scenario modelling attempted to optimise the management action across potential benefits to the fisher and resource while accounting for compliance costs. Thus, the optimal solution from the BBN will be conservative compared with the ABC estimates of sustainable catch. Should AFMA decide to relax the MLS regulation on bugs, the BBN indicated that it would be better to reduce it to 70 mm CW. However, this reduction would be associated with an increased risk of population decline.

For squid, the estimated annual sustainable catch (ABC) from our analyses (between 200 – 400 t) is probably an underestimate. We know from historical studies that large populations of squid occur outside the current prawn fishing grounds. Our estimate of catchability for squid by the NPF prawn monitoring survey vessels is also probably an overestimate. These suggest that the 2007 commercial catch of 200 t is sustainable. The current management reference catch limit of 500 t for squid may be an overestimate in the absence of other data. We recommend that AFMA continue to monitor the catch of squid and that the reference catch limit when catches be reviewed be reduced from 500 t to 400 t.

2. *Compilation of existing knowledge about the distribution, abundance and biology of species in the four main byproduct groups.*

The project has examined a large volume of byproduct samples collected from the AFMA-funded NPF prawn monitoring surveys. This has enabled models of the species composition of each byproduct group in the NPF commercial logbooks to be estimated. The results show that there are clear differences in the distribution and relative abundance of the two bug species and the dominant species in the squid and cuttlefish groups. Location, depth and sediment type appear to be good surrogates for the prediction of abundance in these groups.

The spatial and temporal distribution of spawning by each group has been identified. For the two bug species, most spawning occurs in the spring and a single recruitment occurs each year.

Young bugs recruit to the fishery early in the fishing season (April – May). Berried (spawning) female bugs are caught in the tiger prawn fishing season (July – November) but the impact of their capture on the populations appear to be sustainable at recent levels of fishing effort.

Squid and cuttlefish species are short-lived animals (probably < 1 yr) that spawn frequently throughout the year in relatively predictable locations in the southern Gulf of Carpentaria. Squids appear to aggregate strongly for spawning and the timing and locations of these aggregations are relatively predictable. Some fishers return to these spawning areas each year and target these aggregations. Up to 200 t of squids (mostly *Uroteuthis* sp 4) can be caught during a short period, suggesting that most of the animals in the aggregation are caught. Many of these squid have already spawned and were probably going to die, so their harvest will have less impact on populations. However, the impact of trawling on the large clusters of squid eggs laid on the substrate is unknown and may require further investigation.

The project has also greatly increased our understanding of the distribution, relative abundance and life history of the main byproduct species. We can now estimate the proportion of the commercial catch made by each species based on a range of proxy variables. This will allow future monitoring of species-specific fishing impacts. Predictions of potential fishing impacts can also be made if the distribution or intensity of fishing changes dramatically.

3. *Demonstration of the extent that stock assessments can be conducted on NPF byproduct species and demonstration of options for dealing with data poor situations.*

Catch of byproduct is by definition non-targeted and thus, commercial catch rates are unlikely to represent an index of the abundance of the population. This makes the application of traditional fisheries stock assessment based on commercial catches almost impossible. Our analyses of the commercial logbook catches of byproduct in the NPF show that traditional stock assessment approaches are not appropriate for these species. The results suggest that current catches are not having a detectable effect on the populations of most species. We have developed novel alternate approaches to estimating byproduct biomass and the sustainable catch of each group. These methods require an index of abundance before they can be applied. At present, AFMA supports fishery-independent NPF prawn monitoring surveys. Catches of byproduct from these surveys have allowed us to estimate the acceptable biological catch (ABC) for each byproduct species group. These surveys need to continue to allow the ABC estimates to be updated with the new annual biomass estimates of each group. If these surveys continue, annual updated estimates of the ABC of each byproduct group could be obtained and an assessment made about the need for management intervention.

We have also developed a new approach to management scenario evaluation for data poor resources. This approach can incorporate expert knowledge in situations where data are lacking. The method involves construction a Bayesian Belief Network (BBN) model of the fishery and potential factors that influence catch. We showed that BBNs can be developed to incorporate economic, biological and management objectives. The approach enables management scenarios to be compared and optimal solutions obtained. Continuation of the AFMA-funded NPF prawn monitoring surveys is critical for the improvement and refinement of the BBN model developed for bugs in the NPF. This survey has been funded until 2010 and is anticipated to continue. Further development of the BBN is needed before it can be used operationally to evaluate alternative management options for bugs in the NPF. These developments include holding a follow-up expert workshop to discuss and possibly refine the relationships and weightings of factors included in the model. The BBN model is sensitive to the weighting applied to the three main objectives and each is similarly influential on the optimal solution.

4. *Identification of critical knowledge gaps limiting the ability to undertake such assessments and recommendations on the most appropriate way to obtain these data to ensure these assessments can be conducted in the future.*

The project has undertaken extensive biological studies with samples collected from the NPF prawn monitoring surveys. The results of these studies have provided the relevant life-history parameters of most byproduct species for management. The project has developed a new novel approach to estimating the biomass and sustainable catch of each byproduct group. This method relies on catch-rate data from the fishery-independent NPF prawn monitoring surveys. These surveys provide a reliable index of abundance for prawns (Milton et al. 2008) and other species that are highly susceptible to trawling such as bugs, scallops and possibly cuttlefish. While the surveys were not designed to sample byproduct species, our analyses show the surveys provide a similar estimate of abundance to other trawl survey designs (Chapter 9).

Our assessment of the acceptable biological catch (ABC) was less reliable for squid as they are mostly nocturnal and feed in the water column at night. At this time, they would be much less vulnerable to the demersal prawn trawls. In order to obtain a more accurate estimate of squid abundance, methods such as day-time trawling, jigging or small-mesh purse-seining may provide a more accurate index of abundance. If the commercial catch of squid increases dramatically (> 50%), then a more accurate estimate of squid biomass may be required. The most cost-effective approach would be to make day-time trawls during the existing NPF prawn monitoring surveys. These could also be used to calibrate night-time trawls and possibly improve the accuracy of the current estimate of catchability applied to the catches from the NPF prawn monitoring survey night-time trawls.

15. CONCLUSIONS

The total landings of byproduct have declined as the fishery has restructured and the size of the fleet reduced. The byproduct of the Northern Prawn Fishery (NPF) comprises a wide variety of fish and invertebrates. Byproduct has been recorded in logbooks since 1998 in up to 30 broad categories. The most important components of the byproduct are squid and bugs, followed by cuttlefish and scallops. These four groups comprise over 90% of the byproduct landed by the NPF in 2007. In recent years, squid has become more important, accounting for almost 80% of the byproduct by weight.

We collected samples of the four main byproduct groups (squid, bugs, cuttlefish and scallops) during the NPF prawn monitoring surveys in the Gulf of Carpentaria undertaken since 2002. These samples were used to identify the species composition of each of the four byproduct groups. Aspects of the life history of squid, bugs and cuttlefish were examined to provide relevant parameters for population models and assess the temporal and spatial patterns in reproduction and abundance.

The squid catch comprised six species (*Uroteuthis* sp 1, *Uroteuthis* sp 2, *Uroteuthis* sp 3, *Uroteuthis* sp 4, *Sepioteuthis lessoniana* and *Aestuariolus noctiluca*) but was dominated by *Uroteuthis* sp 3 and *Uroteuthis* sp 4. Samples from a large squid aggregation NW of Mornington Island targeted by fishers in May 2007 comprised only *Uroteuthis* sp 4. Female *Uroteuthis* sp 4 in this sample were either in spawning condition or recently spent. This, along with squid egg clusters in the trawl nets, indicated that this was a spawning aggregation. NPF commercial logbook records showed that squid aggregations were fished in this area at the same time of year in multiple years. Other similar large catches of squid were made near Groote Eylandt in several years. This suggests that these are also probably spawning aggregations of *Uroteuthis* sp 4 or possibly *Uroteuthis* sp 3. Spawning by both of these species occurred throughout the year, but with greater intensity during the dry season (May – November). The occurrence of spawning aggregations in the same region each year suggests that intensive fishing of these aggregations does not appear to have measurably affected their populations to date. The squids were more abundant in shallower waters, especially the smaller species (*A. noctiluca*, *Uroteuthis* sp 1 and *Uroteuthis* sp 2). These species were also more abundant in areas with muddier substrates, whereas *Uroteuthis* sp 4 was more abundant on sandier sediments.

The bug catch in the NPF comprised two species, mud bugs *Thenus parindicus* and reef bugs *T. australiensis*. Over 90% of the commercial catch is of mud bugs, *T. parindicus*. This species occurred throughout the prawn fishing grounds in the Gulf of Carpentaria. It was most abundant in the 15 – 35 m depth zone, around the Mornington and Karumba regions and on muddier substrates. There is currently a minimum legal size (MLS) for bugs of 75 mm carapace width (CW) in the NPF. This MLS allows bugs to reach sexual maturity before being retained. The mean size at maturity of *T. parindicus* was 52.0 ± 0.5 mm CL (corresponding to 75 mm CW). This size was similar to the current MLS regulation in the fishery. The reef bug *T. australiensis* did not mature until 58.9 ± 0.5 mm CL, a size significantly larger than the MLS. Increasing the MLS to 80 mm CW will ensure reef bugs reach maturity before entering the fishable population. However, reef bugs represent a small proportion of the total bug catch and showed a distinct preference for deeper offshore waters (> 35 – 40 m), around Vanderlins and Weipa. Therefore, most of their population probably occurs beyond the main prawn fishing grounds. We found no evidence of overfishing on these species and the yield-per-recruit analyses undertaken as part of the management scenario modelling suggests that the yield would be maximised if the MLS was reduced to 65 mm. We recommend the current MLS regulation be retained, but that consideration could be made to reduce the MLS to 65 mm as the bug population is currently underexploited.

Spawning by bugs (*Thenus*) occurred throughout the year, with berried female mud and reef bugs present in samples taken in both the wet and dry seasons. A greater proportion of females of both species were berried during spring. Juveniles were only caught in the January – February surveys. This suggests that the spring spawning period contribute most of the recruitment to the adult bug population in the Gulf of Carpentaria.

The cuttlefish catch from the NPF prawn monitoring surveys comprised five species (*Metasepia pfefferi*, *Sepia elliptica*, *S. papuensis*, *S. pharaonis* and *S. smithi*), with *S. elliptica* being the most abundant and widespread. Most species occurred throughout the prawn fishing grounds. While their abundances varied spatially, most species were more abundant in deeper waters. Spawning occurred throughout the year, with a greater proportion spawning during the dry season. Most species spawned throughout the deeper parts of the Gulf of Carpentaria (25 – 40 m). Only *S. elliptica* and *S. smithi* spawned in inshore areas around Karumba. Fecundity of all species of cuttlefish was much lower than in the squids, varying between 170 and 350 eggs per spawning compared to 3000 to 5000 eggs for squids. Cuttlefish appear to compensate for this lower productivity by having larger eggs that are better protected in an egg case. They are also much longer-lived than squid and presumably spawn in successive years.

Two species of scallops were caught during the NPF prawn monitoring surveys (*Annachlamys flabellata* and *Amusium pleuronectes*). The fan scallop *Annachlamys flabellata* were rare, comprising < 5% of the total scallop catch. Anecdotal evidence from fishers indicated that only larger scallops (> 65 mm) were retained. This meant that only *Amusium pleuronectes* would be retained by fishers. *Amusium pleuronectes* were more abundant in muddier regions and in waters > 20 m deep. There was no temporal trend in catch rates from either the NPF prawn monitoring survey or NPF commercial logbook records. No studies were made of reproduction, but small *A. pleuronectes* were only caught in the January – February surveys. This suggests that most spawning occurs in spring, similar to that found for the other byproduct groups.

In order to estimate the species composition of the byproduct in the NPF, we developed statistical models to predict the proportion of each species within each byproduct group. A range of spatial, temporal and environmental variables were used as predictors. Generalised additive models were used to estimate the proportions of the two bug species. The separation of multiple species of squid and cuttlefish required a different approach. We used a bagged classification tree approach to estimate the proportions of each species in each trawl catch. The models explained over 60% of the variation in the proportion of each species, with spatial terms being the most useful. The proportions of each species were then used to estimate the species composition of NPF commercial logbook records. Catch rates of each species from NPF commercial logbooks, CSIRO scientific and observer surveys and NPF prawn monitoring surveys were then examined to assess the main factors influencing abundances. Depth and sediment type were both influential in explaining patterns of distribution and abundance of each species.

The Australian government introduced a Harvest Strategy Policy in 2007 that included harvest control rules or decision rules that control the fishery according to the biological and economic condition of the fishery (Dowling et al. 2008). We developed a harvest control rule for each byproduct group that consisted of an acceptable biological catch (ABC). The ABC is based on biomass estimates from the NPF prawn monitoring surveys and published life-history traits of each byproduct group. The ABCs of each byproduct group were compared with the recent (2005 – 2007) NPF commercial catch. For all groups except squid, the recent catch is only a small proportion of the estimated ABC. For squid, the ABC and recent commercial catch were similar, suggesting that squid catches need to be monitored. There are large populations of squid outside the prawn fishing grounds, suggesting that the ABC may be underestimating the potential sustainable catch.

We also undertook an alternative approach to examine management scenarios for bugs. For this byproduct group, we undertook a management scenario evaluation (MSE) by constructing a Bayesian Belief Network (BBN) of the fishery. The BBN consists of a conceptual model of the fishery and the environmental, economic and management factors influencing catch. The current MLS regulation was examined and compared with alternative scenarios such as reducing the regulation or increasing the size limit. In most cases, the best scenario was to maintain the current 75 mm CW minimum legal size. This limit optimised the benefits to both the fishers and the resource as well as kept management costs to a minimum. Operationalising the model for routine use in assessing the fishery for bugs in the NPF will require additional expert interaction to validate the relationships and weightings of different factors in the model. However, all analyses indicate that the bug population in the Gulf of Carpentaria are underexploited. Thus, if the management objective was to maximise the yield, then the MLS for bugs could be reduced to 65 mm CW.

16. REFERENCES

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APPENDIX A — INTELLECTUAL PROPERTY

All components of this research are in the public domain.

APPENDIX B – PROJECT STAFF

The following staff contributed to the project:

CSIRO Marine and Atmospheric Research

- Dr David Milton (Principal investigator, Chapters 2 – 6, 12 – 15)
- Mr Gary Fry (Co-investigator, Chapter 8)
- Dr Shijie Zhou (Population dynamics modeller, Chapter 10)
- Mr Mark Tonks (Project scientist, Chapter 7)

CSIRO Mathematics, Informatics and Statistics

- Dr Petra Kuhnert (Research statistician, Chapters 9 and 11)
- Ms Min Zhu (statistician, Chapter 11)

APPENDIX C – BBN PRIOR AND CONDITIONAL PROBABILITY CONSTRUCTION (CHAPTER 11)

A.1 Oxygen

Table 13: Prior probability distribution for oxygen.

Midpoints	Range	Probability
4.3	4.00-4.35	0.210
4.4	4.35-4.45	0.145
4.5	4.45-4.55	0.144
4.6	4.55-4.65	0.074
4.7	4.65-4.75	0.035
4.8	4.75-4.85	0.140
4.9	4.85-4.95	0.144
5	4.95-5.50	0.108

Table 14: Conditional probability table for bug density given oxygen.

Density	Density	$e^{-\gamma}$	Oxygen							
Cut-off	Values (γ)		4.3	4.4	4.5	4.6	4.7	4.8	4.9	5
-0.5	-0.5	0.607	0.0269	0.2441	0.3332	0.1306	0.0019	0	0	0
0	-0.25	0.779	0.8867	0.7483	0.6655	0.8506	0.2546	0.1167	0 0.0043	
0.5	0.25	1.284	0.0864	0.0076	0.0013	0.0188	0.6875	0.8201	0.0916	0.4638
1	0.75	2.117	0	0	0	0	0.0560	0.0632	0.7925	0.5491
1.5	1.25	3.490	0	0	0	0	0	0	0.1159	0.0098

A.2 SST (5 Day)

Table 15: Prior probability distribution for SST.

Midpoints	Range	Probability
20	18-21	0.041
22	21-23	0.149
24	23-25	0.213
26	25-27	0.041
28	27-29	0.046
30	29-31	0.306
32	31-34	0.204

Table 16: Conditional probability table for bug density given SST.

Density	Density	$e^{-\gamma}$	SST (Degrees)						
Cut-off	Values (γ)		20	22	24	26	28	30	32
-0.5	-0.5	0.607	0	0	0.0002	0	0	0	0
0	-0.25	0.779	0.1279	0.1699	0.1554	0.0118	0.0009	0	0
0.5	0.25	1.284	0.6625	0.7478	0.7732	0.5895	0.7901	0.3523	0
1	0.75	2.117	0.2066	0.0823	0.0712	0.3959	0.2090	0.6464	0.4752
1.5	1.25	3.490	0.0030	0	0	0.0028	0	0.0013	0.5248

A.3 Wind Speed

Table 17: Prior probability distribution for Wind Speed.

Midpoints	Range	Probability
3	2-3.5	0.209
4	3.5-4.5	0.481
5	4.5-5.5	0.175
6	5.5-6.5	0.099
7	6.5-8	0.036

Table 18: Conditional probability table for bug density given Wind Speed.

Density	Density	$e^{-\gamma}$	Wind Speed				
Cut-off	Values (γ)		3	4	5	6	7
-0.5	-0.5	0.607	0	0	0	0	0.0032
0	-0.25	0.779	0.7577	0.1419	0.9798	0.4426	0.4508
0.5	0.25	1.284	0.2423	0.8581	0.0202	0.5574	0.5397
1	0.75	2.117	0	0	0	0	0.0063

A.4 Nitrate

Table 19: Prior probability distribution for Nitrate.

Midpoints	Range	Probability
0.15	0.1-0.175	0.268
0.20	0.175-0.225	0.258
0.25	0.225-0.275	0.428
0.30	0.275-0.350	0.045

Table 20: Conditional probability table for bug density given Nitrate.

Density	Density	$e^{-\gamma}$	Wind Speed			
Cut-off	Values (γ)		0.15	0.20	0.25	0.30
-0.5	-0.5	0.607	0.0135	0	0	0
-0.25	-0.275	0.760	0.3949	0.0015	0 0.0148	
0	-0.125	0.882	0.5513	0.4658	0.0012	0.0510
0.25	0.125	1.133	0.0403	0.5303	0.7503	0.1339
0.5	0.275	1.317	0 0.0024	0.2485	0.2297	
1	0.75	2.117	0	0	0	0.4458
1.5	1.25	3.490	0	0	0	0.1182
2	1.75	5.755	0	0	0	0.0066

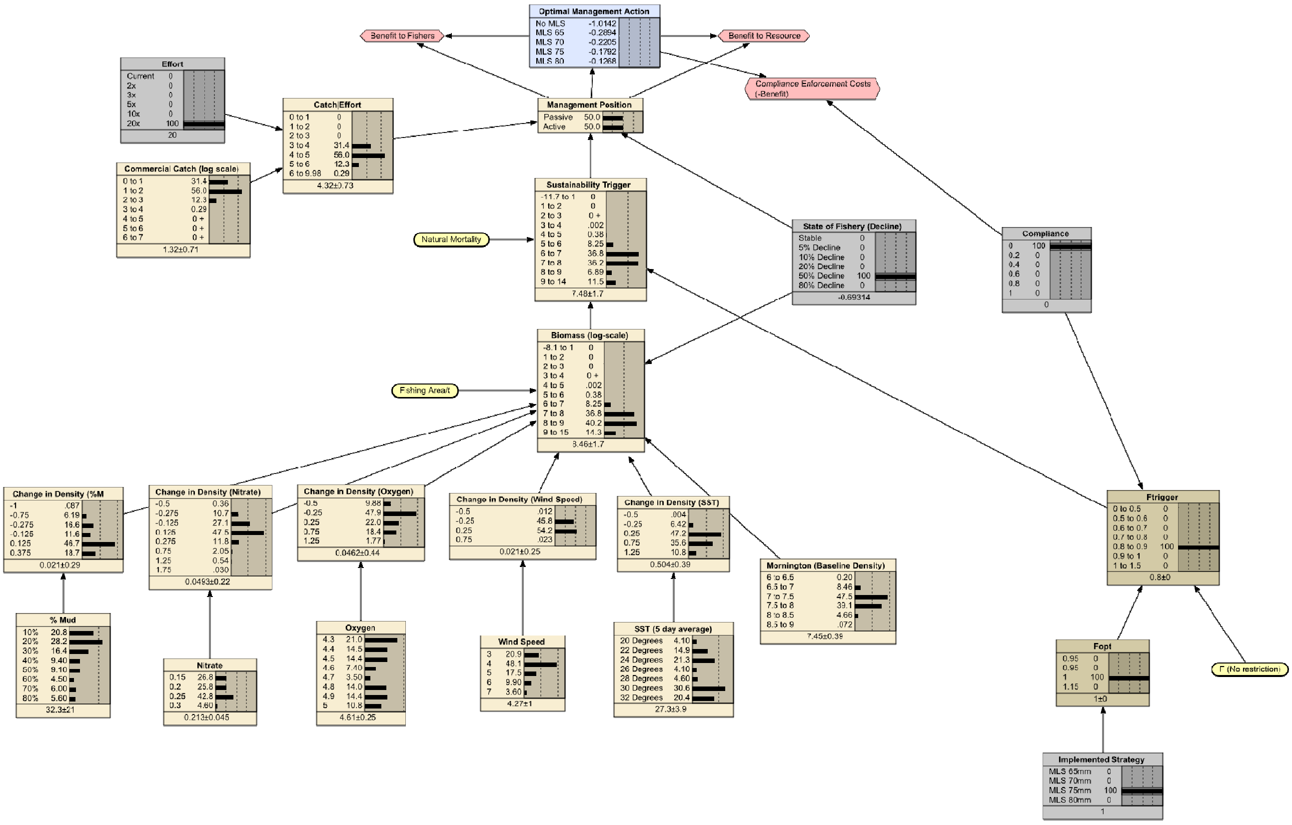
A.5 Mud

Table 21: Prior probability distribution for mud.

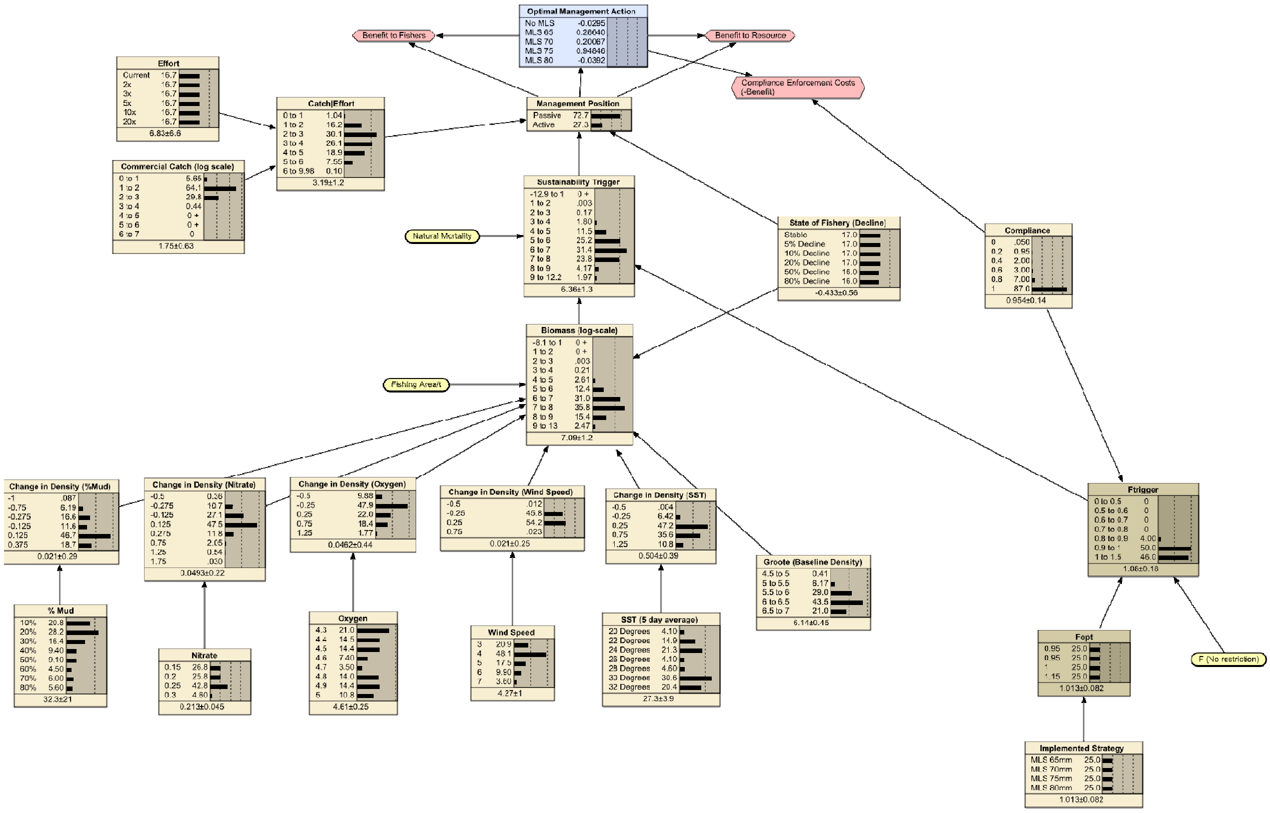
Midpoints	Range	Probability
10	0-15	0.208
20	15-25	0.282
30	25-35	0.164
40	35-45	0.094
50	45-55	0.091
60	55-65	0.045
70	65-75	0.060
80	75-100	0.055

Table 22: Conditional probability table for bug density given mud.

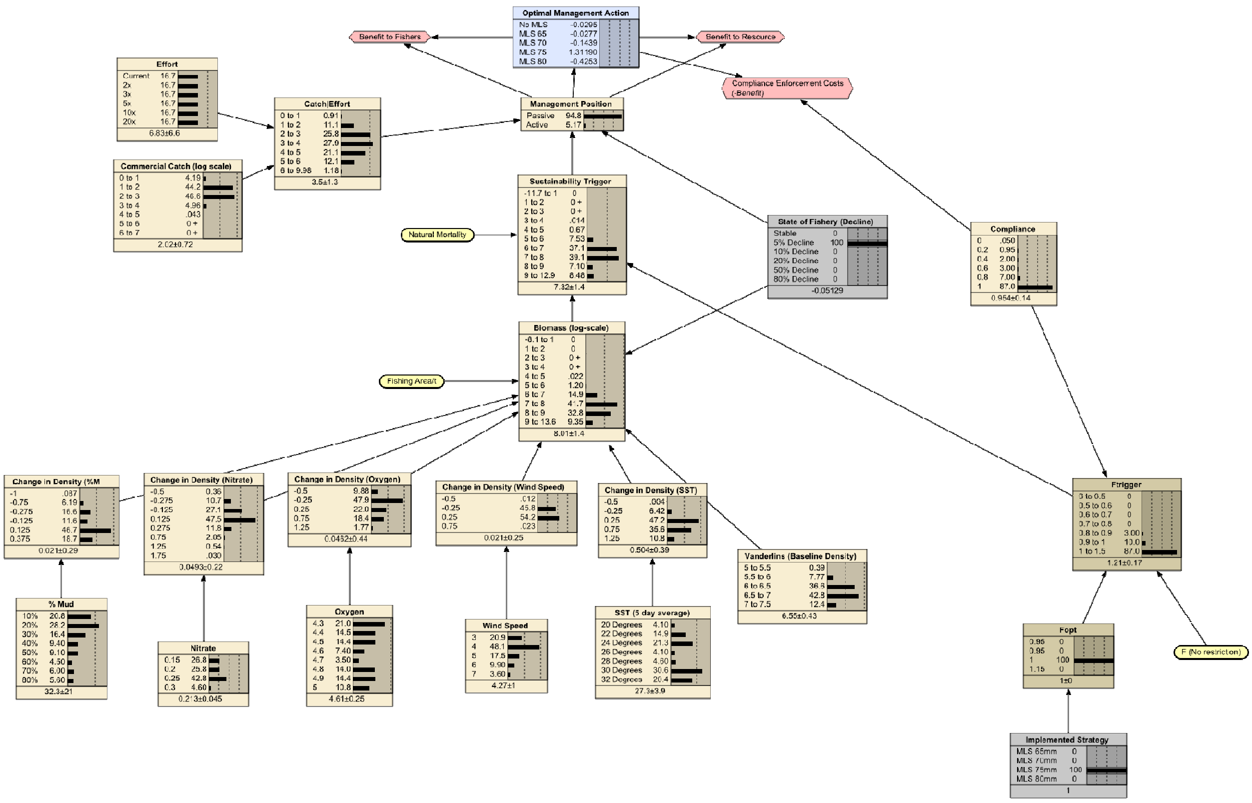
Density	Density	$e^{-\gamma}$	Mud							
Cut-off	Values (γ)		10	20	30	40	50	60	70	80
-1	-1	0.368	0	0	0	0	0	0	0	0.0156
-0.5	-0.75	0.472	0	0	0	0 0.0132	0.0493	0.0645	0.9760	
-0.25	-0.275	0.760	0	0	0	0	0.8387	0.8532	0.8495	0.0084
0	-0.125	0.882	0.3825	0 0.0475	0.0650	0.1481	0.0975	0.0860	0	
0.25	0.125	1.133	0.6175	0.3426	0.9507	0.9205	0	0	0	0
0.5	0.375	1.455	0	0.6574	0.0018	0.0145	0	0	0	0



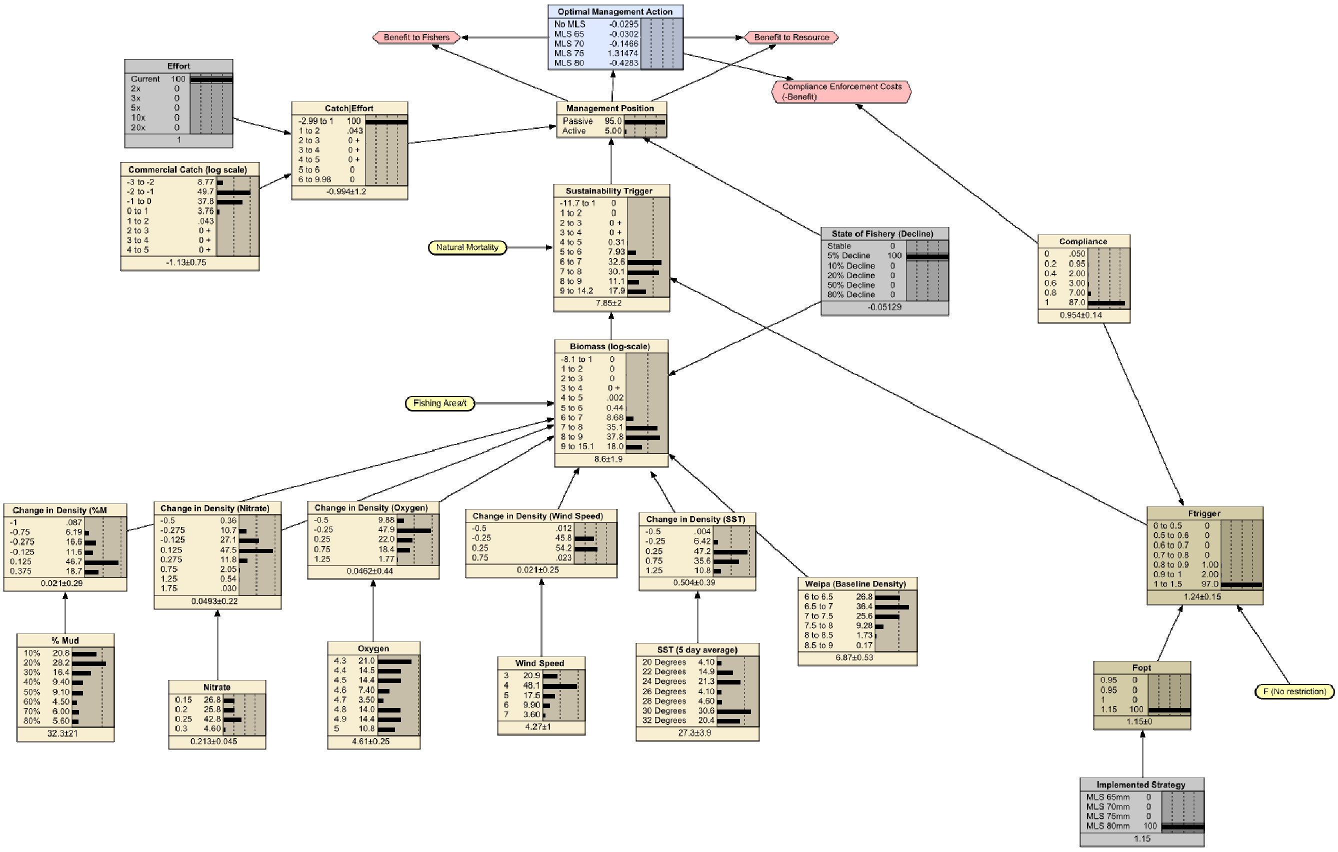
Mornington region BBN model



Groote region BBN model



Vanderlins region BBN model



Weipa region BBN model

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