Spatial and Seasonal stock dynamics of Northern Tiger Prawns using fine-scale commercial catch-effort data

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December 2000

FRDC Project No. 1999/100

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1. Non-Technical Summary

99/100 Spatial and Seasonal stock dynamics of Northern Tiger Prawns using fine-scale commercial catch-effort data.

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1.1 Objectives:

Determine whether the spatial and temporal scales of fleet behaviour bias the interpretation of the tiger prawn stock dynamics when analyzed by a non-equilibrium stock-production model.

Prepare NPFAG Working Papers, which will include full descriptions of the model structure, data analyses, and potential management implications.

Communicate to the Northern Prawn Fleet and Industry the results of the analyses in a format such that the implications become clear to everyone and that permits comments and criticisms by Industry members.

1.2 Non-Technical Summary:

The northern tiger prawn fishery, primarily based in the Gulf of Carpentaria, is a vital part of the Northern Prawn Fishery. This is an input managed fishery that, in August 2000, moved to using a limited number of gear units to manage effort applied to the stock. This change in management has been brought about at least partly because of perceived problems with the health of the stock and the need to reduce the applied effort. The present assessment, based on the Wang & Die (1996) model, indicates that the fishery is presently close to the management target of E_{MSY}. Nevertheless, despite recent cuts in effort, aimed at allowing the rebuilding of the spawning stock, the catch rates experienced in the fishery have not recovered as expected. The model developed

in this present work suggests that the stock is in fact severely depleted, possibly down to only approximately 13% of the average unfished biomass, and that there is an urgent need to control effort or reduce fishing mortality. The geographical range over which the fishery is prosecuted has also reduced in recent years. Neither of these indications bode well for the fishery.

In this present work, the Northern Prawn Fishery database was checked for potential internal inconsistencies and records fully on land and duplicate records were identified so that analyses, based upon the information in the database, could avoid using these erroneous records. A list of the erroneous records has been given to the data managers responsible for the maintenance of the database so that they can be corrected, marked as problematical, or deleted.

The catch rate data from the commercial logbook data has been standardized relative to year, month, week, 30-minute geographical area, and the amount of banana prawn caught. All of these factors had highly significant effects upon catch rates. The data standardization had more effect upon the apparent trend in catch rates in the 1970s and 1980s than it did in the 1990s. This may be a reflection of the fleet becoming more similar in its equipment and methods of fishing. Whatever the case may be, with the approach to standardization used and documented in this work we have enhanced the ability of producing repeatable summary information regarding the fishery performance. The changes in the seasonal nature of the fishery were emphasized and had to be included in the assessment. Likewise, the spatial distribution of the fishery was demonstrated to be of vital importance to understanding the dynamics of the fishery. It was shown that the areas of greatest fishing pressure had reduced in the Groote and Melville statistical areas, especially the latter, which was dominant early in the fishery, to more effort being applied in the Mornington and Vanderlins statistical areas. This change reflects the long-term average catch rates being slightly higher in these areas.

The new model developed during this work has provided an alternative stock assessment for the Northern tiger prawn fishery and enabled a clearer view of the levels of uncertainty associated with the assessment. To move from a deterministic, apparently precise assessment, to one that admits to uncertainty in the parameter estimates may appear to be a step backwards. However, it is better (meaning safer for the prawn stocks) to be aware of the limitations of an assessment than to mistakenly believe that an assessment is precise when it is not. The new model also lends itself more easily to permitting risk assessments of different management options than the older assessment. Such risk assessments are important to obtain the full benefits possible from the new gear unit management regime. Having more than one assessment model is beneficial in permitting the results from each to be compared leading to a greater understanding of the implications of the available information for the status of the prawn stocks.

The new model is based upon a yearly time scale and has been developed as far as perhaps it should. If more years of data accrue in which no recovery is seen, the model will begin to be unstable so there is a need to develop a model with an explicit time-step of two or four weeks. This future model could be either a surplus-production model or a delay-difference model.

The objectives of the study were achieved by the investigations into the spatial distribution and seasonality of the fishery using the raw commercial logbook data and the model developed during this project. Three papers summarizing the work in progress were presented to the Northern Prawn Fishery Assessment Group, and less formal presentations were made (both written and verbal) to a large Fishing Industry gathering during the Northern Prawn Fishery Strategic Planning Meeting in June.

The new model has been adopted as part of the tiger prawn assessment process and the Principle Investigator is now a member of the Northern Prawn Fishery Assessment Group and the NORMAC Research and Environment Committee.

Keywords:

Surplus-production, Northern-Prawn-Fishery, NPF, tiger-prawns, standardization, risk-assessment, performance indicators, management targets, catch-rates, spatial changes.

2. Introduction

2.1 History and Nature of the Fishery

The Northern tiger prawn fishery is an important component of the Northern Prawn Fishery (NPF). The fishery began at the end of the 1960s and is based mainly in the Gulf of Carpentaria and parts of the coastline immediately westward on the northern coast of Australia (Fig. 2.1).

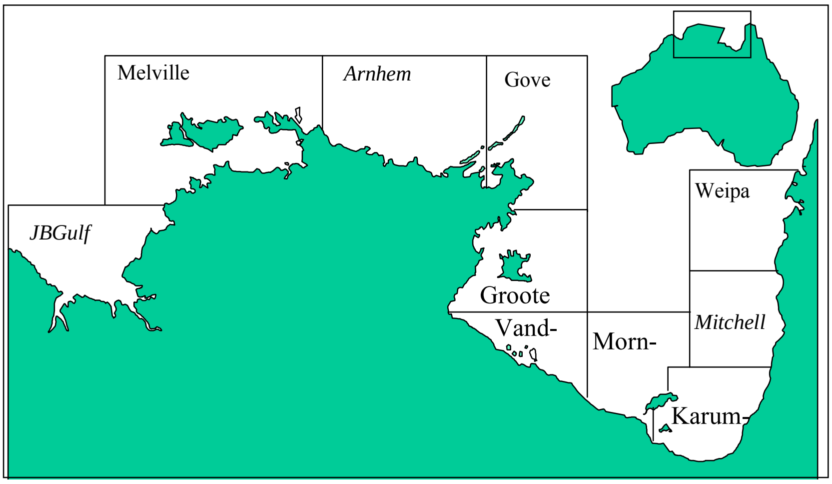

Fig. 2.1 The Gulf of Carpentaria and the westward coastline with the statistical reporting regions of the Northern Prawn Fishery. Summed over the entire fishery, tiger prawns are primarily taken in Groote (33% of total catch), Vanderlins (Vand- 17%), Mornington (Morn- 15%), and Karumba (Karum- 11%), with about 9% in Melville, and about 6% each in Gove, and Weipa, with relatively trivial amounts in other areas (Table 2.1). After Robins & Somers (1994).

The fishery is managed using a complex set of input controls designed to limit total effort (gear limitations, limited numbers of vessels in the fishery, seasonal and area closures). At the start of the 2000 season the only fishing method used for catching prawns in the Northern Prawn Fishery (NPF) is twin rigged otter trawls (Pownall, 1994; Die & Taylor, 1997). In August 2000, the management of the fishery moved away from controls based upon vessel units to controls based upon a maximum amount of gear (headline length) in the fleet. The impact of this change is yet to be felt but it will alter the quality of the catch effort information and will have future significant impacts upon the assessment.

The commercial catch statistics relate only to species groups (eg. banana prawns, tiger prawns, endeavour prawns). There are a variety of species caught in the tiger prawn fishery with identifiable tiger prawns making up about 76% of the catch and most of the rest being endeavour prawns (Robins & Somers, 1994). The three species identified as tiger prawns are *Penaeus semisulcatus* (grooved or green tiger), *P. esculentus* (brown tiger), and *P. monodon* (black tiger), but only insignificant amounts of *P. monodon* are ever caught (Robins & Somers, 1994).

Trawl tows targeted at tiger prawns can last up to three hours long and are made mainly at night, when catch rates are highest. The fishing season has two parts. The first relates to the opening in April or May, corresponding to the banana prawn fishery (*Penaeus merguiensis*). This fishery now lasts less than four to six weeks and the fleet then switches to concentrating on attempting to catch tiger prawns. Fishing in the first part of the season can occur at any time of day. There is a break in the fishing until the start of August, after which fishing can only occur after 6:00pm and before 6:00am.

Areas of high prawn density are discovered by use of a smaller otter or beam trawl known as the 'try' net now towed astern between the two main nets and hauled in more often. The use of Global Positioning System (GPS) receivers and plotters now enable skippers to be more effective at focussing effort on the more productive areas and visit previously un-fishable areas that have high proportions of foul ground. This and many other gear and fishing practice changes has led to a continuous increase in catching efficiency of a single boat-day of effort. Managing any fishery through effort controls entails determining a sustainable effort level but with effective effort continuously rising, there is the added problem of finding equitable ways by which to reduce the actual effort in order to keep effective effort stable.

Table 2.1 The relative amounts of effort (boat days) and catch (tonnes) summed for tiger prawns over 1970 to 1998. The areas Arnhem, Joseph Bonaparte Gulf, and Mitchell all experienced very low levels of effort early in the development of the fishery and they still only contribute small amounts to the tiger prawn fishery. In total they account for 2.15% of the total effort information and 1.89 % of the total catch throughout the fishery. Data from Robins & Somers (1994), Sachse & Robins (1996), and AFMA (1999). Effort is in boat days and catch is in tonnes.

Area	Total Effort	% Effort	Total Catch	% Catch
Grootte	191374	34.80	39660	32.58
Vanderlins	88482	16.09	20989	17.24
Mornington	79449	14.45	18838	15.47
Karumba	53653	9.76	13221	10.86
Melville	45523	8.28	11504	9.45
Wiepa	45359	8.25	7973	6.55
Gove	33339	6.06	6720	5.52
Arn	7661	1.39	1358	1.12
Bon'p	4485	0.82	1354	1.11
Mitchell	575	0.10	117	0.10

As commercial catch statistics only record the catch of commercial groups (eg. tiger prawns) instead of species, the outcome of any stock assessment analysis that uses the amalgamated data is thus related to the averaged behaviour of both species. Because the two main tiger prawn species have slightly different life cycles (Crocos, 1987) variation, and associated uncertainty, may be increased and trends obscured by using combined data. This implies that the fisheries data has inherent uncertainty that should be acknowledged when attempting to interpret model outputs.

2.2 The Issue of Effort Creep

The NPF fishery developed slowly in the early 1970s followed by a rapid increase in catches that then declined precipitously from 1984 until about 1986 (Fig. 2.2). Since then catches have remained at a lower level with an average annual catch of tiger prawns over the last 10 years of 3,078 tonnes (Fig. 2.2). Fishing effort, in terms of boat-days spent fishing, followed a similar pattern although the decline since the early 1980s was more gradual and continuous (Fig. 2.2).

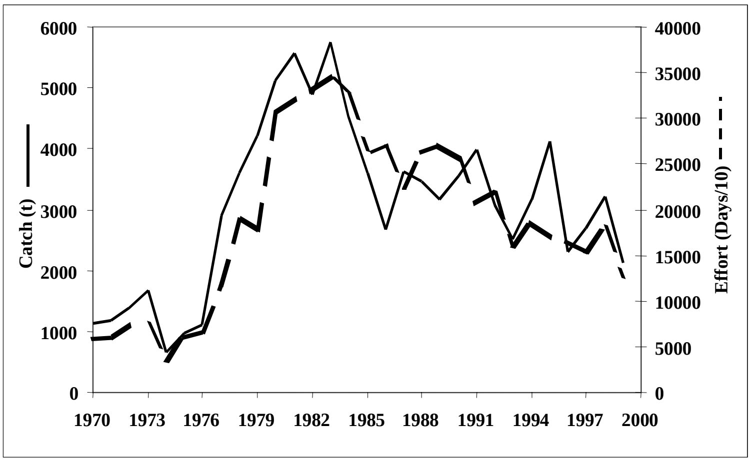

Fig. 2.2 Annual catch of Tiger prawns and the related effort. Data from Robins & Somers (1994), Sachse & Robins (1999), and AFMA (2000). Mean catch over the last ten years, 1990 - 1999 was 3,078t.

Through the 1970s, catch-per-unit-effort (CPUE), in terms of tonnes caught per boat-day, when averaged over all areas, was relatively high and varied by up to 20% with a peak at the end of the 1970s. During the latter part of the 1970s, effort in the tiger prawn fishery rose rapidly. CPUE stayed high during the rapid rise in effort because catches also increased greatly.

After 1979 there followed a major decline in the CPUE which continued through to the late 1980s and only started a subsequent apparent rise in the 1990s after a large reduction in the number of vessels fishing plus increased closed seasons led to a decline in the total number of days fished (Fig. 2.3; Table 2.2).

A major management problem with the NPF fishery is that technological advances and other improvements to fishing practices have led to a continuing increase in the effectiveness of each unit of effort since 1970 to the present day. This was recognized early on and the Industry and Management combined to accept a value of 5% increase in the effectiveness of fishing effort per annum. Thus, despite the catch rate data appearing to improve through time, when the agreed upon 5% per annum increase in the effectiveness of a day’s effort is taken into account then the CPUE provides a rather different view (Fig. 2.3). When this effect is included, the late 1970s peak in CPUE was more like a relatively stable period which was followed by a decline which has not recovered at all but rather, since 1985, has stayed relatively low and stable (Fig. 2.3), with more recent years suggesting a slow decline. Of course, this is only with the effective effort so the actual CPUE in tonnes per day gives the impression that all might be well with the fishery. By considering the effective effort, however, it becomes clear that the Northern Prawn fishing fleet is having to work a great deal harder simply to retain the same levels of catch.

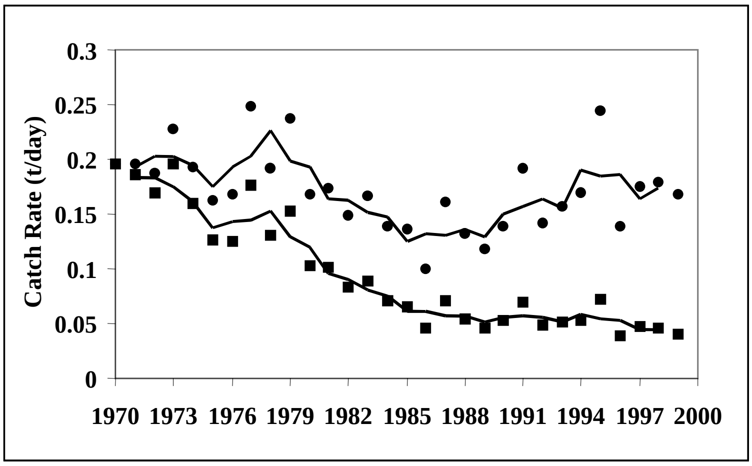

Fig. 2.3 Catch-per-unit-effort (CPUE) from 1970 to 1999, where catch is in tonnes of tiger prawns and effort is in boat days spent fishing. The top line (circles), illustrates the sequence of observed CPUE observations with the line being a three-year moving average to illustrate general trends. The bottom line (squares), is the same except that the influence of a 5% per annum increase in the efficiency of the effort has been included.

The agreed management response to the failure of catches to recover in the 1980s was a 50% reduction in the size of the prawn trawl fleet and this finally appeared to halt the decline, however, the hoped for recovery in effective catch-effort has not occurred. With such evidence that the tiger prawn fishery is stressed, the outcome of stock assessment procedures are of especial concern.

Management strategies to avoid overfishing included the introduction of limited entry, plus gear restrictions, bans on daylight trawling from August to December, permanently closed areas, and closed seasons from January through March, and June through July (Robins & Somers, 1994). Despite these attempts at managing increases in effective effort, it was clear that fishing effort continued and continues at too high a level (Fig. 2.3). The vessel buy-back scheme was implemented to remove vessels permanently from the fishery, and this was aimed both at reducing effort and reducing over-capitalization. The buy-back scheme was voluntary through to 1993 but final compulsory reductions in boat numbers were made in April 1993 (Taylor, 1994). In 1995 there were 125 vessels left in the fishery (Sachse & Robins, 1996). This number has reduced slightly in 2000 as a result of rationalization of the fleet in response to the introduction of gear units.

The value agreed upon (5%) for the annual increment in the effectiveness of the fishing effort has a major impact upon the outcome of any stock assessment. An estimate was made of the average increase in fishing power per year based upon changes in swept area trawled during the period 1979 to 1986 (Buckworth, 1987; Die & Taylor, 1997). It was this estimate that led to the agreement being reached with the fishing industry that the average annual increase in effective fishing effort has been 5% since 1970 and this value has been included in all subsequent formal assessments of the state of the stock.

Other estimates of effort creep have been made since Buckworth's study. These include an estimate that the introduction of GPS and associated Plotters would have increased fishing power by approximately 14% over a five-year period (Robins *et al*. (1998). In a similar study, Die and Bishop (1998) estimated an average increase of 2.5% per annum over the period of 1988 to 1992 brought about by increases in headrope length, increases in hull size, and the installation of GPS. This was not the total increase during those years but merely the contribution by those factors. Haddon (1997), using a non-equilibrium surplus-production model, estimated that there had been approximately a 5% per annum increase in fishing power over the period 1970 to 1995. Using standardized catch rate data for the period 1970 to 1999, Haddon and Hodgson (2000) generated a more recent estimate of approximately 7%, using similar methods. The estimates by Haddon (1997) and Haddon and Hodgson (2000) attempt to determine the increase in effectiveness of effort implied by the available data. They do not attempt to measure the increase directly.

Table 2.2 Catch statistics for the northern tiger prawn fishery, extracted from Robins & Somers (1994), Sachse & Robins (1996), and AFMA(2000) data update. Total catch is simply the sum of all landed catches. Total Catch Rate appears to be the geometric mean of the raw catch rate data in the database, at least for the records from 1990 onwards. Effort is merely the Catch divided by the reported Catch Rate.

Year	Total Catch (t)	Total Catch Rate	Effort
1970	1138	0.1956	5818
1971	1183	0.19531	6057
1972	1380	0.18699	7380
1973	1672	0.22711	7362
1974	666	0.19366	3439
1975	973	0.1619	6010
1976	1118	0.16787	6660
1977	2900	0.24844	11673
1978	3599	0.19196	18749
1979	4218	0.23709	17791
1980	5124	0.16748	30594
1981	5559	0.17429	31895
1982	4891	0.14841	32956
1983	5751	0.16645	34551
1984	4525	0.13946	32447
1985	3592	0.13547	26516
1986	2682	0.10057	26669
1987	3617	0.16091	22478
1988	3458	0.13166	26264
1989	3173	0.11736	27036
1990	3550	0.13908	25525
1991	3987	0.1922	20744
1992	3084	0.14154	21789
1993	2515	0.157	16019
1994	3162	0.17007	18592
1995	4125	0.24504	16834
1996	2311	0.13892	16635
1997	2694	0.17511	15385
1998	3218	0.17875	18003
1999	2136	0.16852	12675

A more recent study by Stirling (2000) attempted to characterize directly the influence of a variety of factors along with the dates when the various changes would have occurred. This, seemingly more empirical estimate provides alternative estimates of changes that have occurred in the fishery.

2.3 Tiger Prawn Stock Assessments

The potential long-term sustainable yield has been assessed a number of times for the stocks of grooved and brown tiger prawns. Somers (1990) used an equilibrium surplus-production model on 'standardized' catch-effort data from the whole tiger prawn fishery. The summary annual catch-effort data were standardized by assuming a 5% per annum increase in effective effort in each year of the fishery to allow for improvements in fishing gear and methods. Provided that fishing effort could be controlled, Somers concluded that the maximum sustainable catch of all species in the tiger fishery would be 6,000 t. With 76% of the fishery actually being tiger prawns this would imply a catch of about 4,560 t of grooved and brown tiger prawns. No estimates of uncertainty were included but Somers (1994) repeated the analysis when more years of data were available and obtained effectively the same result. However, with reference to the expectation of 6,000 t, he added "…this may be overly optimistic given the experience of the past few years, when catches have ranged between 4,000 and 5,000 tonnes." In fact, such equilibrium analyses should no longer be used as, when catch rates are declining, they are invariably over-optimistic in terms of predicted maximum sustainable catches (Hilborn & Walters, 1992).

A more recent attempt at producing long-term yield predictions (Wang & Die, 1996) used a combination of analyzing the relation between spawning stock and subsequent recruitment plus the relation between recruitment and subsequent commercial catch. Long-term yields were derived by constraining these relationships to equilibrium and searching for the fishing effort that would generate the maximum sustainable yield. Importantly, this analysis also differed from the earlier assessments by attempting to assess each of the two main tiger prawn species separately (Wang & Die, 1996). By separating the two species, Wang & Die attempted to avoid the uncertainty inherent in lumping the two species together and assuming both species would respond to fishing pressure in similar ways. Separating the commercial catch statistics into the two species was made possible by using and extending an earlier analysis of the relative distribution of the two *Penaeus* species (Somers, 1994). Somers' work derived the relative proportions of the two tiger prawn species that are likely to be caught within any of the 6 x 6 nautical mile grids that the commercial fishers in the Gulf of Carpentaria use to report their catches (this separation is being reworked using more sophisticated methods by the CSIRO). Wang & Die (1996) concluded that a maximum sustainable yield for *P. esculentus* would be 1,900 t and 2,200 t for *P. semisulcatus* (a total of 4,100 t combined).

2.4 Problems with the Current Stock Assessment

As Wang & Die (1996, p 94) state: "The effects on yield predictions of model uncertainty (eg. Ricker *v.* Beverton and Holt stock-recruitment model), of uncertainty in population parameters (estimation error), and of errors in landing and effort estimates, are unknown and should be quantified in further analyses." One of the main assumptions underlying the current assessment is that the method of apportioning the commercial catch records into the two separate species is precise and constant through time. Unfortunately, there appear to be important sources of uncertainty in the strategy of separation used which call the analysis into question. Somers (1994) produced a remarkable synthesis of information to derive the relative proportions of the two tiger prawn species in the different sampling sites throughout the Gulf of Carpentaria. But aspects of the analysis suggest that the distributions deduced using the current methodology are possibly too imprecise to form the basis of a formal stock assessment. The more recent attempts to improve on the methodology used to separate the two species are to be welcomed and should have beneficial impacts on the quality of the formal assessment.

Somers (1994) found that 72% of all 6 x 6 nautical mile grids had on average more than 90% *P. esculentus* or more than 90% *P. semisulcatus*. Of course this implies that about 30% have ratios rather less skewed towards a single species. Of obvious importance is the variability of these proportions through time. From an ANOVA of variation in species ratios, Somers concluded that about 90% of all variation was due to the grid square where fishing occurred and only 10% due to month and year of sample. However, ratios are notorious for behaving badly in parametric statistical tests (Sokal & Rohlf, 1995) and without attempts to normalize the data the application of ANOVA to ratios is invalid and likely to produce misleading results. We are left with the results that the standard deviation of the ratios was greater than 10% in about 40% of grid squares. It is unknown whether the standard deviations of the species proportions were calculated from the binomial expansion (the optimum situation) or from the normal equations (an approximation only).

Because it was derived from synthesizing information from various regions around the Gulf obtained at different times over a 14-year period, the analysis of the geographic distribution of the two species depends upon their distribution patterns remaining constant through time. The variability Somers (1994) reported is therefore important to the interpretation of the concluded patterns. By only using the average ratio of the relative proportion of each species within each grid square, variation through time is being ignored. This procedure reduces the heterogeneity of the data used in subsequent analyses.

Even if the analysis of the relative geographical distribution of the two species were precise there is another major problem with the data used. The commercial catches reported for each grid square are divided into the two species in the proportions determined for the 6 x 6 grid square. However, as Somers (1994, p 320) states: "Logbook records give daily information on catches by species group, fishing ground and, sometimes, a more precise position (6-n-mile grid square) *denoting the central location of the catch for the day*." [my italics for emphasis]. Tows tend to be two to three hours long but many separate tows may be made each day. If the fishers do not stay in the same grid in any one day but they only report one grid square then obvious and possibly large errors may enter the data used in the translations of commercial catches to catches of particular species. Also, the proportion of the fleet reporting the more precise 6 x 6 nm. grid square is now close to 100 % but earlier in the fishery this proportion is considered to have been far less. Thus, data from earlier periods will be even less precise. Without more details concerning how fishers operate when towing commercially, the analysis of the relative distribution of the two species appears to be a doubtful foundation upon which to base an assessment. A more detailed analysis of fisher behaviour is required.

2.5 An Alternative Assessment Strategy

By adopting the strategy of splitting the commercial catch statistics into separate species Wang & Die (1996) avoided the uncertainty introduced when analyzing the two species together. However, severe problems with how catches are separated into the two species imply that unknown levels of uncertainty are again introduced into the data used. Wang & Die's (1996) analysis is currently the best available and continues to be the basis of the annual assessment, although this is evolving in 2000. However, because of the doubts introduced by the unavoidable problems in their analysis, alternatives should be produced to compare with their results. One of the alternatives, considered in this work, is to return to assessing both species together while not forgetting that this is likely to increase the uncertainty in the conclusions drawn from any model.

2.6 The Present Study

The present study describes a non-equilibrium stock-production model, which includes non-linear density-dependence of production against total stock size, plus an independent estimation of the annual increment in effective effort brought about by improvements in technology and methods. This aims to provide an alternative stock assessment for the two tiger prawn species combined. In order to characterize the known uncertainty of the analysis after a maximum likelihood fit to available data was found, the residuals from this fit were bootstrapped to produce percentile confidence intervals around the model parameters and outputs.

Stock-production models are not normally applied to short-lived species so an alternative interpretation of the model structure is described. This altered interpretation leads to the production curve taking on the form of a classic stock-recruitment curve. Various theoretical developments made in the course of this study are described in detail in various appendices and these include derivations of closed form equations for three alternative views of increasing fishing power, and suggestions for algorithms to implement risk assessments using the surplus-production model described in this work.

Alternative model structures and data inputs were possible and each is presented. Having obtained access to the day by day commercial catch effort data an attempt was made to standardize the available catch rate data to account for spatial differences in the distribution of fishing effort through time. This standardized data was compared with the published data. Also, instead of directly estimating the average increase in fishing power through the history of the fishery, the empirically available estimates from Stirling (2000) were used for comparison.

2.7 The Objectives

The objectives of this study, as stated in the original FRDC proposal were to:

Determine whether the spatial and temporal scales of fleet behaviour bias the interpretation of the tiger prawn stock dynamics when analyzed by a non-equilibrium stock-production model.

Prepare NPFAG Working Papers, which will include full descriptions of the model structure, data analyses, and potential management implications.

Communicate to the Northern Prawn Fleet and Industry the results of the analyses in a format such that the implications become clear to everyone and that permits comments and criticisms by Industry members.

3. The Catch Effort Database

3.1 Introduction

The analytical work required to address the objectives entailed obtaining access to the record by record raw data from the commercial catch log-books. Earlier analyses (Haddon, 1997) had been on published summary data and hence were only preliminary. Given access to the commercial log-book data the objectives of this project could be realized by suitable manipulation of the original data. Prior to their use in the various models, the catch rate needed to be standardized (see Chapter on Standardization) to reduce the spurious influence of seasonality, location and other factors. However, prior to standardization the integrity of the data within the database was examined. The analyses desired involved a detailed consideration of spatial variation in effort and catch so there was a need for the spatial information to be internally consistent and realistic.

As with all fisheries data systems it was expected that some errors would have crept into the database either through fishers mistakenly putting incorrect or invalid data into the various fields (e.g. reporting fishing positions that are on land) or possibly through transcription errors on transfer from the log-books to the database (e.g. duplicate records). Only database fields relating to location were investigated in detail. A report was presented to the Northern Prawn Fishery Assessment Group (Hodgson and Haddon, 2000) and this chapter represents the contents of that report.

3.2 Background

The first logbooks for recording catch information were introduced to the Northern Prawn fishery in late 1969. The format of the logbooks and the information requested has changed several times during the history of the fishery (Sachse, 1994). Included among these changes is the scale at which spatial information concerning the catch is requested, as well as the structure and naming conventions concerning each spatial level as recorded within the database.

The current database of commercial logbook data includes a number of hierarchical fields recording location of catch. The area covered by the fishery is divided into Provinces, Regions, Areas and Grids. Grids are the 6 x 6 minute recording squares. Grids are nested within Areas, Areas are nested within Regions, and Regions are nested within Provinces. Despite there being four nested categories there are only two fields, named Area and Grid, recorded in the database. Region and Province are implied by the Area code; the 3-digit code for Area indicates Province, Region and Area respectively. Zeroes in any position (Region or Area) indicate the limit of precision of the spatial information. For example, an Area of 300 indicates location was recorded only at the Province level of precision, an Area of 320 indicates location was recorded at the Region level of precision (i.e. Region 32), whereas 321 was recorded at least at the Area level of precision (or better if a Grid is given too).

Pre-1980, the Northern Prawn Fishery name referred to a collection of fisheries around the northern coastline between Bowen in Queensland and Broome in Western Australia (Robins & Somers, 1994). In 1980, the western boundary of the NPF moved east and was fixed at 126 degrees, and the coding scheme for Areas changed. Some Area codes changed their meanings (i.e. covered a different area of the fishery), some codes were no longer used, some new ones began and some remained unchanged. Hence, in the database there are two coding conventions in the one Area field; records in the 1970s use one system of coding, records from 1980 onwards use another. The Grid square reference retains its meaning throughout, thus each Grid code can be associated with a 1970s Area as well as a post 1980 Area.

Area codes and hence the associated Region and Province were never recorded by the fishermen themselves. In the early days of the fishery, fishermen were required to give the name of the general fishing ground and/or the 6 nautical mile Grid reference for the location of the days greatest catch. Where Grid information was provided, Area, Region and Province were generated from the recorded Grid, and Latitude/longitude were recorded as the midpoint of the declared Grid. If the Grid square was not given then Grid was recorded as 0 and the Latitude/longitude refer to the midpoint of the Area, Region or Province depending on the precision of the fishing ground information.

In 1988 space was provided for fishermen to record Latitude/longitude to 1-minute precision as well as the Grid square code. This wasn't fully utilized until 1999 when the Grid field was no longer included in logbooks and fishermen were required instead to record the actual Latitude/longitude of their greatest catch. The database contains the Latitude/longitude of the midpoint of the appropriate Grid, generated from the given actual Latitude/longitude. This has made the Grid codes redundant so full Grid codes are no longer allocated. Days with position indicated by latitude and longitude have Grid as 9999, and the latitude and longitude indicate the midpoint of the 6nm Grid as for previous years.

3.3 Methods

Obtaining the data was delayed due to the introduction of new confidentiality agreements by AFMA. However, the data files were supplied by the CSIRO Laboratory and imported into an MS-Access database. Several inconsistencies were encountered during general use and led to a more thorough investigation.

Errors in spatial coding were checked at each scale (Area and Grid). Checks were made for records with codes that did not exist or were not within the bounds of the fishery, as well as for combinations of codes at different scales that do not match according to the nested structure. Records were checked against a reference table of all possible Area and Grid code combinations supplied by Janet Bishop (CSIRO). It should be noted that this reference table was not under scrutiny and only a small subset of problems found in the database using this table were checked further in order to confirm whether they are due to problems in the database or the reference table. In all cases where checked they were inconsistencies in the data, not the reference table.

Records that had Latitude and Longitude coordinates on land were also checked for using MapInfo. Since the Latitude/longitude of catches is the midpoint of the 6 minute grid square the catch was taken in, not the *actual* Latitude/longitude, only those catches in 6 minute Grids which are *entirely* on land were considered onerous. It should also be emphasized that the accuracy of the Australia map used will affect whether records are considered on land or in water.

Duplicate records were also searched for. All fisher-days for which there were more than one record were recorded.

3.4 Results

3.4.1 Area Level

1970s records: There are 19 records from the 1970's with Area codes that did not exist at this time.

1980s records: There were 3 records from the 1980s in the database with Area codes that did not exist in the 1980s.

3.4.2 Grid Level

1970s records: Eight records in the 1970's have Grid references that do not exist in the reference table.

1980s records: No Grid references in the 1980s appeared problematic.

3.4.3 Area/Grid Combination Level

1970s records: In the 70s there were 949 records with a total of 297 Area-Grid combinations that are not present in the reference table. This includes the 27 records noted above.

1980s records: In the 80s there were 1,203 records with a total of 217 Area-Grid combinations that are not present in the reference table. This is includes the 2 records noted previously.

There are 89,405 records, from 1981 to 1997, which have a specific Grid reference (i.e. not 0 or 9999) yet give a ‘Region’ (i.e. ##0) rather than an Area. These records occur in all regions. Either, the Grid reference is correct and the Region should be changed to the more specific Area, or alternatively the Grid reference may not have been given and the one in the database (as well as the Latitude/longitude) correspond to the centre of the Region. The latter does not seem likely, as there are 14 Regions to which specific Grids have been assigned, and 1915 Region-Grid combinations. Records were randomly chosen and checked and in all cases the Grid did not correspond with the centre of the Region. This is excluding Area 540, for which there is no breakdown into smaller Areas. Whatever the reason for this form of anomaly it was clearly a major problem in 1988, 1989, and 1990 (Table 3.1).

3.4.4 Records of Fishing on Land

Using MapInfo, 91 records were found to have latitude and longitude coordinates that are on land (Figure 3.1). The majority of these records were very close to the land-water border and the accuracy of the Australia map used will affect whether they are considered on land or in water. Since the Latitude/longitude of catches is the midpoint of the 6 minute grid square the catch was taken in, not the *actual* Latitude/longitude, only those catches in 6 minute Grids which are *entirely* on land were considered onerous (e.g. Figure 3.2).

Table 3.1 Numbers of records per year that have a specific Grid reference (i.e. not 0 or 9999) yet don't give a specific Area (i.e. ##0).

Year	#Records	Total Records	% Records
1981	3	23389	0.01
1983	3	31961	0.01
1986	5	30421	0.02
1987	3	27716	0.01
1988	28307	31101	91.02
1989	31859	33636	94.72
1990	29160	29890	97.56
1991	81	24739	0.33
1992	4	26332	0.02
1993	1	22157	0.00
1994	3	23255	0.01
1996	1	22160	0.00
1997	1	20861	0.00

3.4.5 Duplicate Records

There are 1,379 duplicate records in the database, i.e. with the same date and vessel number combination. This problem only occurs for records between 1971 and 1989, with the majority occurring from 1971-3 and 1982-3 (Table 3.2).

In 153 of these cases, one of the duplicate records had zero catch for all prawn groups. These records would have little effect on estimate of catch rates unless zero records were included in calculations.

In 577 cases the record is an exact duplicate for every field, while in 649 other cases, not all fields are exactly duplicated e.g. catches of Tiger prawns and/or Area of catch may differ while all other fields match. It is suggested that in these cases, assuming the original data sheets are not available, the records containing the smaller prawn catches be deleted.

Table 3.2 Numbers of boat-day records per year that have one or more duplicates.

Year	#Records	Total Records	% records
1971	188	7130	2.64
1972	243	6830	3.56
1973	189	6094	3.10
1978	7	12350	0.06
1979	51	13477	0.38
1980	119	25079	0.47
1981	65	23389	0.28
1982	218	24482	0.89
1983	214	31961	0.67
1984	1	35059	0.00
1985	54	32383	0.17
1989	30	33636	0.09

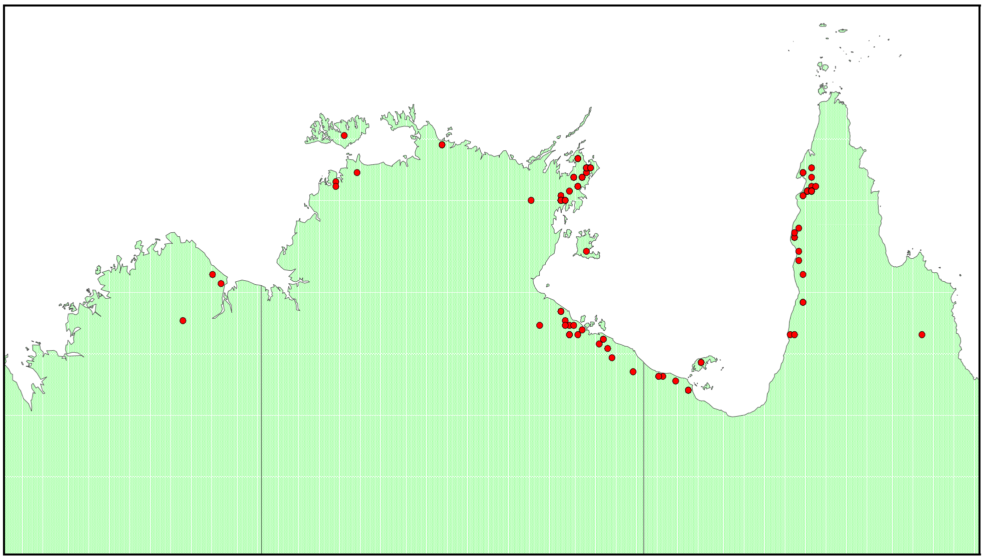

Fig. 3.1 Location of purely 'land' records in the database.

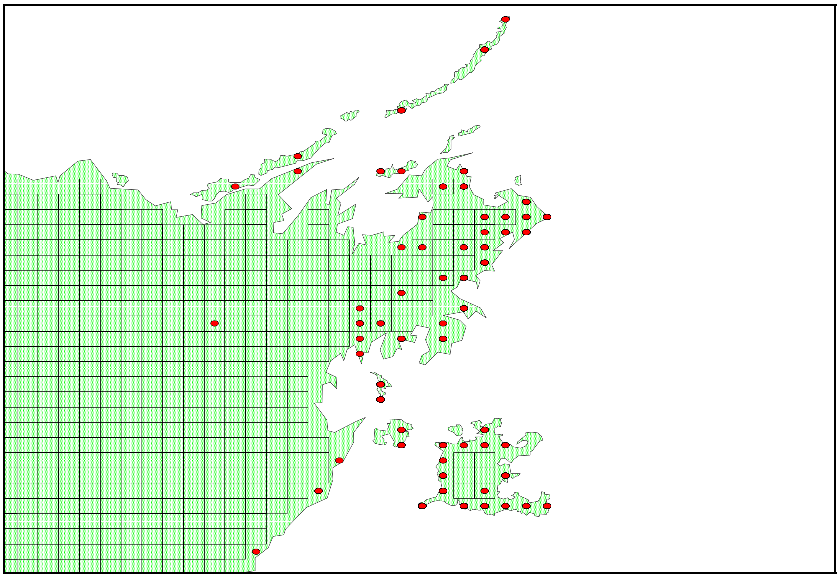

Fig. 3.2 Portion of land adjacent to fishing ground showing catches considered 'on land' (i.e. within a Grid square that is entirely over land) and those that weren't (i.e. water present in the 6' grid, but no grid square illustrated). Clearly, around Groote Eyland there were a number of records that were questionable.

3.5 Conclusion

This treatment can by no means be considered an exhaustive search. The investigations illustrated, only serve to highlight some problems with the database relating to spatial distribution of catch and effort, and bring awareness to potential discrepancies in the data being used for stock assessment. Records highlighted in this paper need to be further examined and corrected or flagged if required.

For purposes of the analyses used here, which data records were included and which excluded are described in the following section.

4. Other Data Issues

4.1 Data Availability

Commercial logbooks were only introduced into what became the NPF, in 1969. The proportion of the fleet that completed the logbooks did not reach 100% until the 1990s. This is especially the case in the 1970s (Fig. 4.1). The organization charged with the responsibility for the logbook data has changed three times since the data began to be collected. It was only with the introduction of more formal reporting requirements in the 1980s that improved fleet coverage occurred.

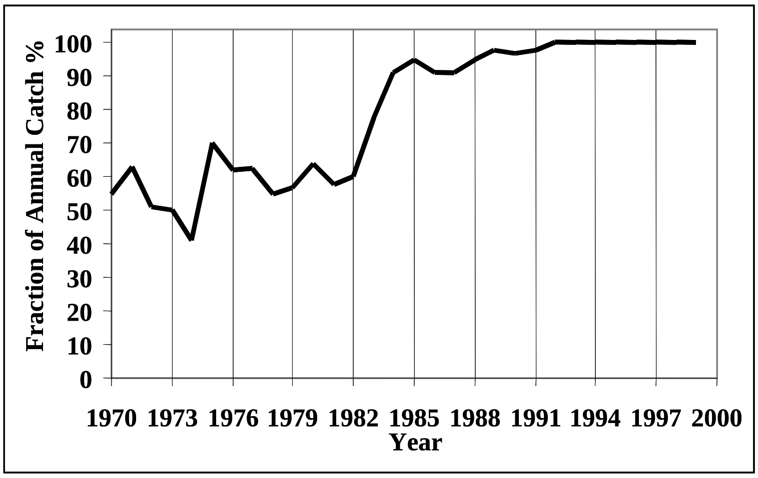

Fig. 4.1 Fraction of the annual catch (reported landings) recorded in the logbooks between 1970 and 1999. The data from 1970 to 1992 are after Sachse (1994) and the logbooks are only assumed to capture the full activity after that date. Recent unpublished work by CSIRO, Brisbane, is re-investigating the extent of reporting and related errors.

The assumption being made through all the following analyses is that the proportion of the fleet that completed the logbooks provided a representative sample of the fishery. For example, in the early years, vessels were either 'wet' boats (that just used ice and could only stay out fishing for relatively short periods) or freezer boats. If it were the case that the proportion of wet-boats that reported their fishing activities was less than the proportion of freezer boats reporting, or if these proportions varied significantly, then a significant bias could be introduced into the catch, effort and distribution data. There is, however, no evidence, to date, that such biases occurred.

4.2 Units of Effort

Effort is recorded in two ways in the database, as days fished and as hours fished per day. Unfortunately, hours-per-day was not recorded during 1975 – 1979 because, apparently, the field was omitted from the logbook or the instructions suggested that it was optional (Fig. 4.2). The argument used against the use of hours fished was that all operators did not record it in a consistent fashion. However, especially in the early years of the fishery, there is a significant amount of variation associated with the number of hours fished per day (Fig. 4.3). When the data were standardized, one of the factors considered was hours fished (see later chapter).

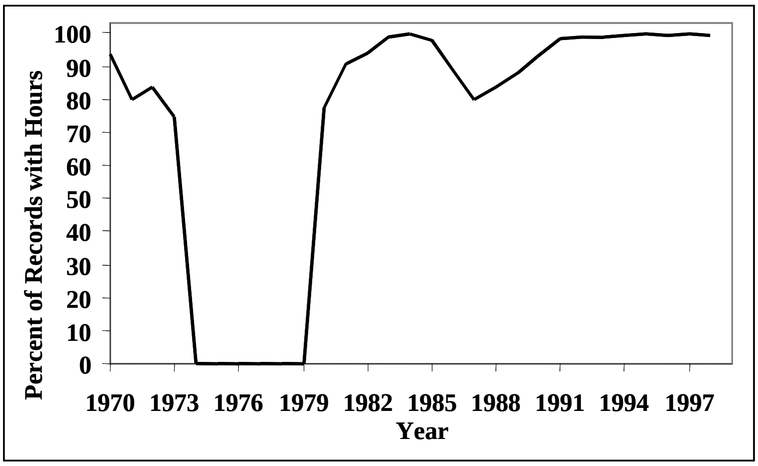

Fig. 4.2 The proportion of records reporting the number of hours trawled per day. The obvious drop during 1974 to 1979 was a period when reporting the number of hours was not required.

4.3 Tracking Individual Vessels Through the Fishery

A major source of variability in catch rates in any fishery relates to which vessels are fishing. If it is possible to follow the performance of individual vessels through time then the investigative fishing involved in the spatial development of the fishery can be mapped accurately. Also, in the data standardization, if vessel can be included as a factor, this invariably accounts for a great deal of variation that has little to do with stock size. Unfortunately, the vessel codes used in the 1970s appear to have many duplicates and the list of vessels to which they refer is incomplete (Janet Bishop, CSIRO, Brisbane, pers. comm.). As there were over 1,000 vessels involved in the fishery at one time or another during the 1970s this problem will take time and effort to resolve (if it is even possible). This means that attempts to track the efforts of individual vessels in the early years of the fishery are not presently possible.

4.4 Changing Location of Catches and Effort in the NPF

The full geographical range of the NPF was exploited relatively quickly in the 1970s but the distribution of effort has always been variable and has altered gradually (Fig. 4.4).

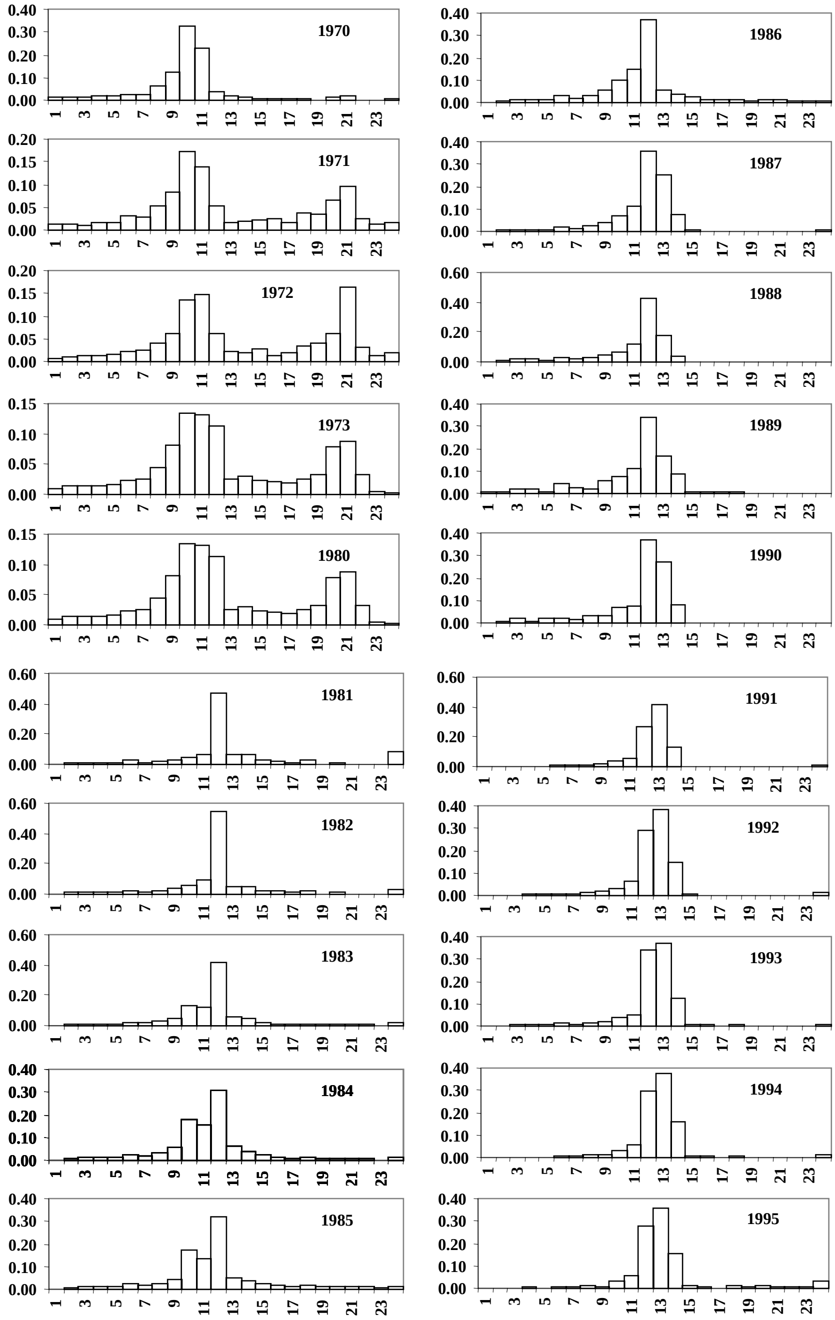

Fig. 4.3 Hours per day recorded on the NPF logbooks for the years 1970 to 1995. In each case the X-axis relates to the number of hours per day spend trawling, while the Y-axis relates to the proportion of records reporting each hour category. Note the Y-Axis is not a constant. The distributions of hours fished reported in the years 1996 to 1999 are very similar to those reported for the years 1991 – 1995. The years 1974 to 1999 had no hours-per-day information.

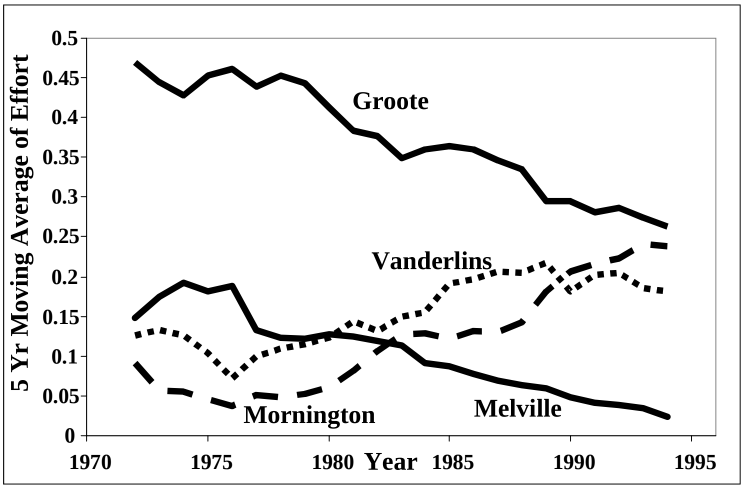

Fig. 4.4 Gross changes in the distribution of fishing effort (days fishing) in the NPF through time. Each line is a five-year moving average illustrating the long-term changes in the distribution of effort. The major areas receiving most emphasis has changed through time.

While the short-term distribution of effort around the NPF has been variable, the long-term distribution has followed a range of trends (Fig. 4.4). Early in the fishery much of the effort was focussed in the Groote region. However, the proportion of effort expressed there, and in Melville, has been steadily declining since the 1980s, dropping in Groote from an average of about 45% down to less than 30% in recent years. In the Karumba region the proportion of the total effort has remained approximately the same through time. However, the average effort through time in Mornington and Vanderlins has increased steadily from an average of about 10% up to about 20% in each. Catch statistics show similar trends (Fig. 4.5). With the average proportion of the catch from the Groote region dropping from about 55% to only 30%. Karumba, again, staying relatively unchanged, and Mornington and Vanderlins steadily increasing.

In fact, the gradual shift in general location through time reflects the long-term average catch rates experienced in the different areas (Fig. 4.6). The actual catch rates experienced at any one time are far more variable than this but the long-term average makes the long-term shifts in the distribution of effort understandable. This implies that in any standardization of effort it will be necessary to account for where the fishery was prosecuted during each year.

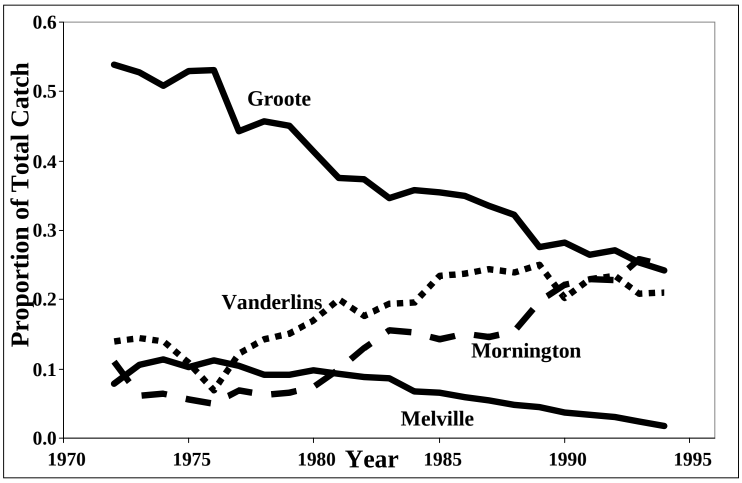

Fig. 4.5 Proportion of total tiger prawn catch taken from the major fishing regions in the NPF. The lines are the five-year moving average, introduced to reduce the variation around the trends observed.

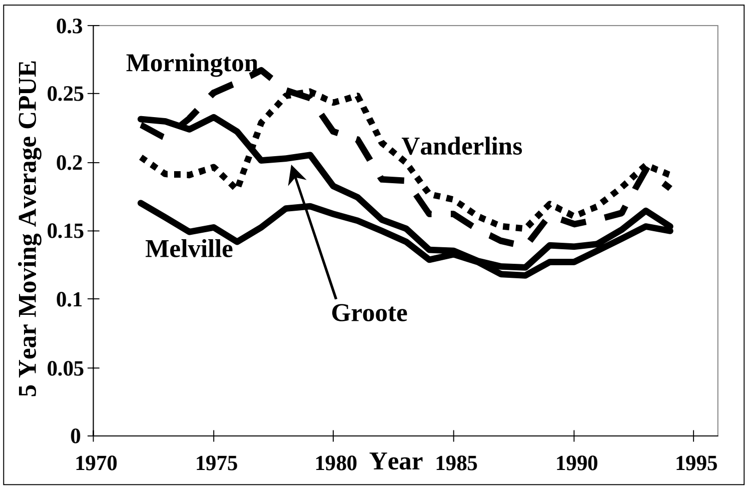

Fig. 4.6 Long-term average catch rates by area (expressed as five-year moving averages). Note that Groote started as high as Mornington but then declined until it was just above Melville. Mornington and Vanderlins have maintained catch rates approximately 20% higher than elsewhere, to shift effort into these regions constitutes a rational decision on the part of the fishing industry.

4.5 Changing Season of Fishing

When the fishery first began there were little or no restrictions of when fishing could occur or where it could occur. A useful summary of regulations up to and including 1992 is provided by Taylor (1994). Clearly the seasonality of the fishery is important.

There are now many small areas permanently closed to fishing and these, primarily are designed to protect juvenile tiger prawns and their nursery habitats (banana prawns originate in the estuaries and there is no prawn trawling in estuaries in NPF). When the catch of tiger prawns by month is summarized from the database the introduction of generalized closed periods is clearly seen, however, there have always been periods of relatively low catches of tiger prawns (Fig. 4.7; Table 4.1.).

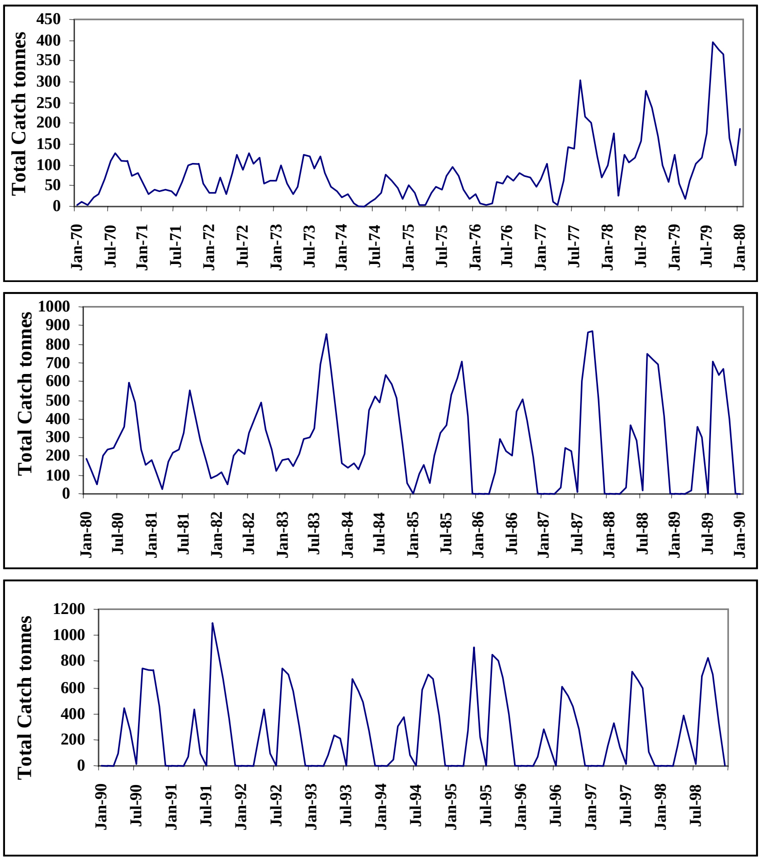

Fig. 4.7 Catch of tiger prawns by month illustrating when the fishery has been closed (Table 4.1). Formal, fishery wide closures only occurred from Jan 1985 onwards.

Table 4.1 History of closed periods during which the complete month was closed. Although April is often an open month it is often open from on April 15th. In years subsequent to 1990 the December through to March, and the July months have been closed to fishing.

First Closed Season	Mid-Season Closure
Jan-85	
Jan 86 - Feb 86	
Dec 86 - Mar 87	
Dec 87 - Mar 88	
Dec 88 - Mar 89	Jul-89
All subsequent years have closures identical to 88/89	

5. Catch Rate Standardization

5.1 Introduction

Once suspect records had been identified within the database an attempt was made to standardize the yearly catch rates for use with the surplus-production models. This standardization used standard General Linear Modelling (GLM) techniques (Klaer, 1994) on the raw logbook data (minus suspect records) in an attempt to account for variation in the data that was due to factors other than changes in the available stock biomass. A report was prepared for and presented to the Northern Prawn Fishery Assessment Group in August 2000 (Haddon and Hodgson, 2000) and this chapter represents the contents of that report.

5.2 Background

As the biomass of a fish stock is very rarely measured directly, some index of relative abundance must be used when attempting to model the stock. Without this index of relative abundance it becomes impossible to validly track changes in the stock biomass. In very many cases commercial catch effort data (CPUE) constitute the only index of stock biomass available. CPUE is usually assumed to be related to biomass by the classic equation $C/E = qB$, where q is the catchability coefficient (assumed constant) and B is biomass (Schaefer 1954). If CPUE falls through time this is taken to reflect a decline in the biomass available to the fishery and, conversely, an increase in biomass if catch effort increases.

Changes in stock biomass however, may not be the only source of variation in observed CPUE. If the areas that are fished, or the seasonality of fishing varies from year to year, we may observe changes in CPUE that have nothing to do with changes in the stock biomass. Such changes would instead be related to fleet dynamics and the distribution of fishing effort, and both have been observed in the NPF (see Section 4). If we wish to remove variation in CPUE due to the effects of factors such as fishing area, we need to standardize CPUE in relation to these factors. Standardization goes some way to identifying the relative contribution towards the observed trends in CPUE made by the factors being included in the analysis. Generating the GLM, constitutes a statistical decomposition of the catchability coefficient (q) into contributing components. Once the variation due to factors other than ‘year’ is described, the variation associated with a 'year' factor should provide an improved representation of the relative status of the stock upon which the fishery is based. Of course, if significant factors are not included in the analysis (perhaps because data relating to them are unavailable), then there will still be noise remaining on any signal about the stock size that is present in the CPUE data.

Surplus production models, as used to assess the Tiger prawn stocks of the Northern Prawn fishery (Haddon 1997; Haddon & Hodgson, 2000), attempt to account for changes in observed CPUE in terms of changes in stock biomass through time. Standardization is essential to remove other sources of variation in the CPUE data that have nothing to do with changes in the biomass. For previous assessments based upon the surplus-production model (Haddon, 1997), only annual summary catch and effort data for 10 different fishing areas were available (Robins & Somers, 1994; Sachse & Robins, 1995). Using summary data, only area could be considered in an approximate standardization. In the current assessment, the full commercial catch effort records from 1970-1999 were available. With the full dataset available the standardization has been improved in detail and validity, including many more variables.

5.3 Standardization of Catch-Per-Unit-Effort

Catch and effort records were extracted from the database where the catch of Tiger prawn was greater than zero and the location of the catch was *not* in a 6 minute Grid that was entirely on land (see Hodgson & Haddon, 2000a). Catch effort records in the database (logbook records) only account for between 60 - 100% of total annual landings over the history of the fishery (Sachse, 1995). The catch and effort data that was reported is thus assumed to be representative of the entire annual catch.

Duplicate fisher-day records were removed from the dataset analyzed (see Hodgson & Haddon, 2000a). For instances where different catches were recorded on duplicate fisher-days, the largest catch of Tiger prawns was included for analysis and the other smaller record disregarded.

Using Systat 8, five statistical models were fitted to the CPUE data. Because CPUE data are typically log-normally distributed a General Linear Model was fitted to the natural logarithm of the CPUE for each record. The model was built in a number of steps so as to monitor the increase in the amount of the variation in the catch-effort information that is described by the linear model. Akaike's Information Criterion (AIC) was used to determine the best statistical model: a compromise between the proportion of the variability in the data described by the linear model and the complexity of the model (Burnham & Anderson, 1998). The statistical model leading to the smallest AIC is usually selected as being optimal.

The general log-linear model used was:

$$Ln(CE) = Const + a.Year + b.Month + c.Week + d.Block + e.Banana$$

or subsets of this. The variables Year, Month, Week, Block, and Banana were all put into the analysis as categorical or dummy variables.

Month and Week are included in the model to account for changes in the seasonal patterns of fleet dynamics and catch rates within years. Blocks are 30-minute square areas of fishing ground and standardise for spatial variation in CPUE. The expansion of the fishery into new areas and contraction away from others over time, combined with the introduction of closed areas (Fig. 5.1), may change CPUE in ways that do not necessarily represent changes in actual biomass. We used 30’ blocks instead of the smaller 6’ blocks because the 6’ block is the reported location of most of a nights fishing, but not necessarily all. By extending to 30’, this source of potential bias is removed. The inclusion of the Block factor should remove at least some of these effects. Ideally an interaction term between Block and Year would account for changes in the spatial distribution of effort (fleet dynamics) through time. However, such interaction terms, including the Year factor, alter the meaning of the Year term and these can no longer be used as a simple index of relative abundance through time. Instead, some other way of dealing with changes in fleet dynamics needs to be devised.

The variable Banana comprised 5 categories or levels of Banana prawn catch (Table 5.1). The Banana factor should go some way to removing variability in the Tiger prawn CPUE data attributable to variability in catches of Banana prawns. A low catch rate of Tiger prawns or a high catch of banana prawns may reflect targeting of banana prawns rather than a change in Tiger prawn stock biomass.

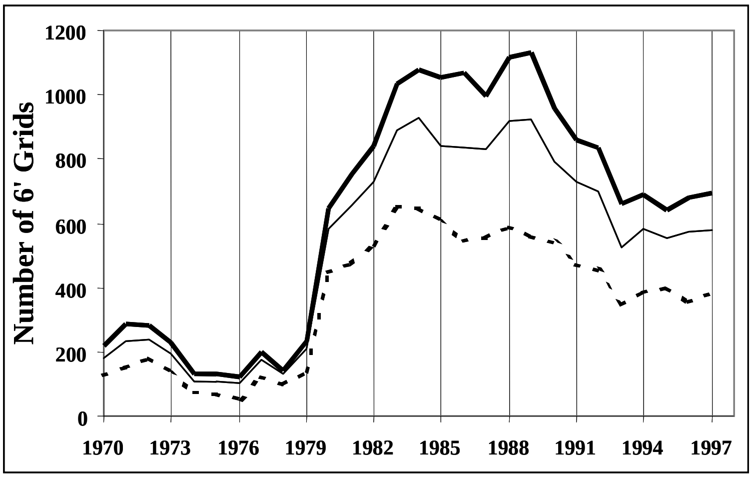

Fig. 5.1 The changing number of 6 nautical mile grids fished for tiger prawns through time. The thick upper line is where the catch of tiger prawns was >0, the fine line below that was where catches were >100kg, and the dotted line below that represents the number of 6' grids where catches > 500kg. The peak area fished occurred in 1983, followed by a steady, slow decline.

Table 5.1 Levels of Banana Prawn catch within the 'Banana' factor. Catches in ranges 3 to 5 may have been targeting banana prawns during the day.

Level	Banana prawn catch range
0	0
1	>0, <100 kg
2	>=100, <500 kg
3	>=500, <1000 kg
4	>=1000, <5000 kg
5	>=5000

It should be noted that the output from a GLM does not guarantee that a relation exists between stock size and standardized CPUE. It is possible that factors not included in the model (through no information being available) may be obscuring any effects of changes in stock biomass. In this case, vessel and hourly effort information are not available for inclusion in the analysis.

Vessel information would allow us to remove variability in the Tiger prawn CPUE that is due to variation in the vessels fishing (not a change in biomass). For example, if several large dominant vessels with experienced skippers were removed from the fishery, it could be expected that the overall annual catch rates for the fishery in the next year would drop considerably. This would not be reflective of a decline in the stock biomass, as the model would assume. Accuracy of the biomass estimates from the surplus production model should improve if or when the vessel data become available. Vessel cannot be used as a factor (a proxy for vessel characteristics) because there are problems identifying individual vessels throughout the history of the fishery.

Hourly effort information is not available for all records in all years (Fig. 4.2). CPUE is thus calculated as catch per fishing day rather than catch per hour. This introduces considerable noise into the dataset as the hours fished per day vary from a few to 24 hours.

5.4 Results

Model 5 (LnCE = Constant + Year + Month + Week + Block + Banana) described the greatest proportion of variation in the catch effort data (31.6%) and had the lowest AIC value (Table 5.2, Fig. 5.2). All variables in the model were significant, however, the inclusion of the term Block (for the first time in Model 4) resulted in a considerable jump in the variance explained by the model (from 13.1 to 29.7%, Table 5.2) and increased the Year indices between 1970 and 1986 considerably above those for Model 1 (Fig. 5.2). After 1986 the standardization had minimal effect on the indices, except in 1995, 1997 and 1998. Models 2 and 3 were intermediate between Model 1 and Model 4 and 5 (Fig. 5.3).

Catch rates have been highly variable over the last 29 years, but generally declining between 1977 and 1986. After 1986 there has been a variable but overall apparent increase in observed catch rates to an all-time maximum in 1995. Catch rates again plummeted to a low in 1996, appeared to recover somewhat in 1997 and 1998, only to drop again in 1999 (Fig. 5.2).

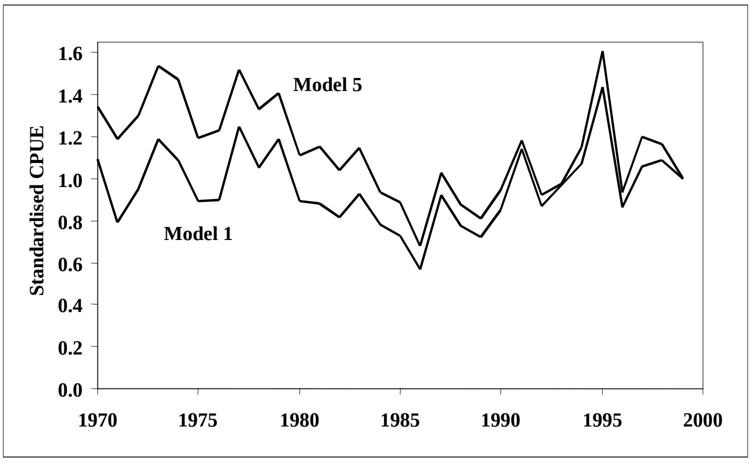

Fig. 5.2 Standardised CPUE for the Northern prawn fishery relative to 1999. Model 1 represents the unstandardized geometric means of the selected raw data. Model 5 is the optimal model Ln(CE) = Constant + Year + Month + Week + Block + Banana (see Table 5.2).

Table 5.2 GLM results for the Northern Tiger Prawn fishery. Week is the week in the year (*i.e.* 1-52), Block refers to the 30-minute square area and Banana relates to the catch of Banana prawns. F is the F-statistic from the ANOVA, the Model SS is the model sum of squared residuals, Resid SS is the residual sum of squares, N is the total number of observations, and AIC is the Akaike's Information Criterion. Model 5 is the optimal model.

Model 1	LnCE = CONSTANT + YEAR				
Model 2	LnCE = CONSTANT + YEAR + MONTH				
Model 3	LnCE = CONSTANT + YEAR + MONTH + WEEKNUM				
Model 4	LnCE = CONSTANT + YEAR + MONTH + WEEKNUM + BLOCK				
Model 5	LnCE = CONSTANT + YEAR + MONTH + WEEKNUM + BLOCK + BANANA				
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
N	477258	477258	477258	477258	477258
Var%	0.067	0.123	0.131	0.297	0.316
F	1181.43	1665.56	783.26	624.75	672.17
Df Params	29	40	92	323	328
Df Resids	477228	477217	477165	476934	476929
Model SS	18403.1	33656.7	36046.7	81683.5	86854.4
Resid SS	256336.4	241082.8	238692.9	193055.9	187885.2
Outliers	149	168	177	210	201
# Param	31	42	94	325	330
AIC	12.45	12.39	12.38	12.17	12.15
YEAR	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
1970	1.09527	1.20202	1.20442	1.36070	1.34313
1971	0.79453	0.90484	0.91759	1.12524	1.19006
1972	0.95313	1.06290	1.07788	1.27634	1.29823
1973	1.18768	1.31390	1.31128	1.49481	1.54034
1974	1.08981	1.17704	1.16532	1.39654	1.47403
1975	0.89494	0.95409	0.95218	1.22998	1.19722
1976	0.89942	0.99302	1.00200	1.24483	1.22875
1977	1.24982	1.35121	1.36343	1.52501	1.52196
1978	1.05548	1.15258	1.16300	1.37026	1.33242
1979	1.19125	1.29953	1.29563	1.42618	1.40776
1980	0.89494	0.98906	0.99402	1.15027	1.11293
1981	0.88073	0.96561	0.97142	1.20081	1.15373
1982	0.81465	0.89404	0.90393	1.08004	1.04081
1983	0.92589	1.02942	1.04394	1.19363	1.14912
1984	0.78349	0.85899	0.87372	0.96561	0.93520
1985	0.72906	0.79453	0.79057	0.90756	0.88870
1986	0.56836	0.59750	0.59631	0.71106	0.68250
1987	0.92127	0.96657	0.97142	1.04812	1.02737
1988	0.77492	0.80816	0.82037	0.89583	0.87372
1989	0.72036	0.74901	0.76567	0.83110	0.81058
1990	0.84874	0.89404	0.88426	0.97824	0.94554
1991	1.13883	1.17234	1.16416	1.19842	1.18057
1992	0.87023	0.90756	0.91119	0.94838	0.92219
1993	0.96754	1.01207	1.02122	0.98807	0.97336
1994	1.07144	1.14454	1.16649	1.18175	1.14798
1995	1.43907	1.51286	1.54342	1.61931	1.60641
1996	0.86589	0.91119	0.90574	0.95983	0.93333
1997	1.06078	1.06503	1.05971	1.23244	1.19842
1998	1.08981	1.15027	1.15488	1.18412	1.16532
1999	1.00000	1.00000	1.00000	1.00000	1.00000

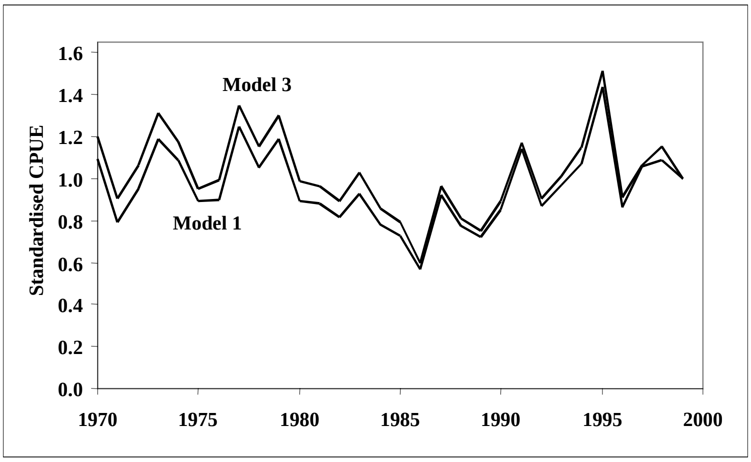

Fig. 5.3 Standardised CPUE for the Northern prawn fishery relative to 1999. Model 1 represents the unstandardized geometric means of the selected raw data. Model 3 is a sub-optimal model Ln(CE) = Constant + Year + Month + Week (see Table 5.2; and *cf.* Fig. 5.2).

5.5 Effect of Geographical Block

The different 30' blocks have a range of influence on the relative catch rates experienced if they are fished. The range of relative effects was from 0.05 to 4.25, implying that some blocks are 165 times more productive than others. There were 23 blocks with a relative effect greater than 2 within the range of 0.05 to 4.25. When all blocks are compared with each other it is clear there are at least two classes of 30' block (Fig. 5.4).

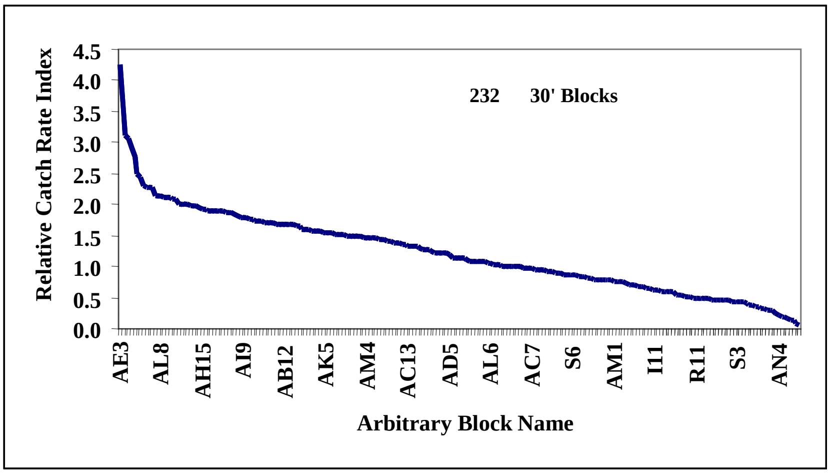

Fig. 5.4 The relative influence on catch rates of the 232 arbitrarily named 30;' minute blocks. The effects range from 0.05 up to 4.25. There were about 10% of blocks above an index of 2; these formed a separate class of blocks that appear to have the highest catch rates.

5.6 Effect of Banana Prawns

Not surprisingly, the presence of banana prawns in the catch had a negative relative influence on the catches of tiger prawns (Fig. 5.5). When catches of banana prawns are greater than 100kg, then serious negative effects on the relative catch rate of tiger prawns begin to appear. Ideally there would be better way to isolate shots that really were targeting tiger prawns from those targeting banana prawns.

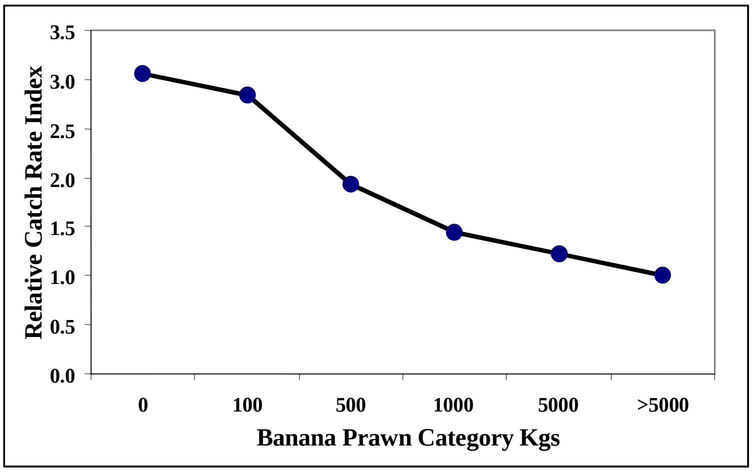

Fig. 5.5 The relative influence on catch rates of the 6 Banana prawn catch categories, with their corresponding expected catch rates relative to category 6 (>5000kg banana prawns). The effects range from 1 up to 3.06. Thus, those fishing days that did not catch banana prawns tended to have a catch rate of tiger prawns that was three times higher than those fishing days that reported the highest catches of banana prawns.

5.7 Discussion

The standardization was limited by the data available so that it was only possible to attempt standardization relative to the factors of week, month, year, 30' block, and the relative abundance of banana prawns in the catch. The obvious factor missing from the analysis was that of 'vessel' or perhaps 'skipper'. Ideally, it would have been possible to have included details of fishing gear used by each vessel for each record of fishing in the database. The factors of vessel and skipper could have acted as proxies for the range and changes of facilities and different abilities within the fleet through time. While such proxies are only an approximation to actual details of the fleet's equipment and vessels, it has nevertheless proved useful in analyses of the South East Fishery fleet (Haddon & Hodgson, 2000b). Unfortunately, in the Northern Prawn Fishery database it is not possible to follow the fate of individual vessels through the 30 years of the fishery. The codes given to individual vessels changed depending upon what agency was responsible for the data collection and these have become confused through time.

Nevertheless, the standardization as it stands accounts for 31.6 % of the variability in the data. It has had a major effect on the trends in the data, especially early on in the history of the fishery. That early period in the time series greatly influences the apparent productivity of the fishery when modelled by a surplus-production type model. Thus, any clarification of the fisheries performance over that period has important implications for subsequent analyses.

The effect of the 30' block factor was marked, which reflects the range of variation of the influence on catch rate that this factor exhibited. Also important was the presence and degree of banana prawn capture. Weeknum, representing the location during each year, only had a small effect, both in terms of the proportion of variation accounted for and in terms of the impact on the standardized yearly indices of relative abundance.

The present analysis is repeatable, understandable, and usable in present models. Without the standardization, the model results are markedly different and unrealistic. The process of standardization should become routine in the stock assessment of northern prawns. Future developments may include the investigation of various interaction terms between factors in the current model, restriction of the analysis to particular geographical regions, and repeating the analysis for different sub-sets of the total period.

6. The Surplus Production Model.

6.1 Introduction.

In the accepted stock assessment for tiger prawns there are no estimates of uncertainty with respect to the model outputs and predictions. This project attempted to provide assessments that included determining the uncertainty deriving from the information and model used to describe the stock dynamics. In the last chapter, a first attempt will be made to describe a method for conducting projections into the future to act as the basis of a risk assessment. A major problem remaining with that is in the definition of effort used in the projections. The model description derives mostly from a paper distributed to the NP Fishery Assessment Group in March 2000 (Haddon, 2000). A summary of the model equations is provided in Appendix 4.

In this chapter the models used in the tiger prawn assessments are described, giving details of their derivation and interpretation. After a description of surplus-production models an interpretation of how these models can validly be used with short-lived species is given. Then the basic model used is defined and described along with its limitations. Next, the solutions used to treat the issue of the effectiveness of effort changing through time are described (along with some innovations in how these solutions may be modelled). Finally, the bootstrap procedures used to determine the level of uncertainty around the model estimates and outputs is described along with the suggested additions required to conduct risk-assessment projections.

6.2 The Use of Such Models with Short-Lived Species

Surplus production models are the simplest analytical method available that provides for a full fish stock assessment. Described in the 1950s (Schaefer, 1954, 1957), they are relatively simple to apply partly because they pool the overall effects of recruitment, growth, and mortality (all aspects of production) into a single production function. The stock is considered solely as undifferentiated biomass, that is, age- and size-structure, along with sexual and other differences, are ignored. The minimum data needed for such a model are time-series of an index of relative abundance and of associated catch data. The index of stock abundance is most often catch-per-unit-effort but could be some fishery independent abundance index (*e.g.* from trawl surveys, acoustic surveys) or both could be used.

Using time-series of catches and associated CPUE observations, surplus-production models relate stock production (growth + recruitment - mortality), in a particular year, to the biomass at the start of the year. The stock dynamics are considered to be a result of the biomass from the previous year, plus a term relating to annual production, and minus the catch taken from the fishery in that year. Given a set of model parameters and a starting biomass such models can produce a time series of predicted stock biomass levels for the duration of the fishery. The CPUE expected in each year of the fishery is also related to stock biomass (Eq. 6.1).

$$B_{t+1} = B_t + f\left(B_t\right) - C_t$$

$$I_t = \frac{C_t}{E_t} = qB_t \qquad \text{Eq. (6.1)}$$

where B_t is the stock biomass at time t, C_t is the catch taken during time period t, E_t is the effort expended in time t, I_t is the average CPUE during time t, q is the catchability coefficient (assumed to be constant, but see later), and $f(B_t)$ is a function relating stock production over time t to stock biomass (a combination of individual growth, recruitment, and natural mortality). In this way, biomass-dynamic models attempt to characterize the relationship between fishing effort and potential yield for a stock, based upon the assumed relationship between production and stock biomass through time.

In a long-lived species B_t can sensibly be included as a term contributing to the stock biomass in subsequent years (Eq. 6.1) because only a small proportion of current biomass would die naturally or be caught during each year. This is not so sensible in short-lived species such as tiger prawns which are essentially recruitment driven fisheries. The only interpretation which would make biological sense would be where the annual production contains the two terms: $B_t + f(B_t)$. This implies that the recruitment driven production each year always replaces itself (B_t) but that there may be further or 'excess' production beyond that ($f(B_t)$). The 'excess' is in quotes because the active production term, $f(B_t)$, could be negative. This combination would imply that reductions in the standing crop each year could have strong density-dependent effects on subsequent stock biomass (Fig. 6.1). Perhaps the name of surplus-production model is well suited to this interpretation of the model terms.

The suggested interpretation of the terms of the model is only an alternative viewpoint. However, it introduces a substantive change, which is that with the new interpretation there would be a testable assumption (the form of the stock-recruitment relationship) whereas the old interpretation was simply false. The use of such biomass-dynamic models with short lived species should be investigated by using a detailed age-structured model with known characteristics to simulate a fished population and determine how well the application of the simple models can recover the assumptions and parameters of the simulations.

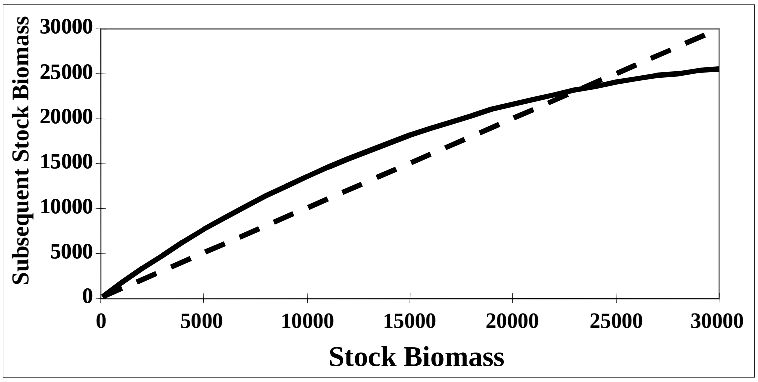

Fig. 6.1 The production from a stock-production model such as Eq. 6.1, where both the B_t term and the $f(B_t)$ term combined represent production. The curved line represents both terms combined while the straight line is simply the line of replacement (the B_t term only). The similarity of the curve to a stock-recruitment relationship such as a Ricker or a Beverton-Holt curve is clear.

6.3 The Surplus-Production Model

In the earliest versions of stock-production models (Schaefer, 1954, 1957), a differential equation was used but Schnute (1977) converted this to the discrete version as above. These simplest equations assumed a linear relation between density-dependent effects and stock-production, which harked back to the classical logistic equation from population dynamics (Pearl & Reed, 1920). The inadequacies of the assumption of linear density-dependence were recognized early on and Pella & Tomlinson (1969) suggested a simple modification to the logistic equation that permitted non-linear density-dependence of production (although their original version was also based upon differential equations). Polacheck *et al.* (1993) provided a convenient form of a non-linear density-dependent production term:

$$f\left(B_t\right)=\frac{r}{p}B_t\left[1-\left(\frac{B_t}{K}\right)^p\right] \qquad \text{Eq. (6.2)}$$

where r relates to population growth rate, K is the virgin or unfished biomass, and p is the asymmetry term. In fact, the interpretation of the parameters r and K is altered from the simple logistic interpretation because their actions are modified by the p parameter. Equations 6.1 and 6.2 can be combined to form a simple biomass-dynamic model:

$$B_{t+1}=B_t+\frac{r}{p}B_t\left[1-\left(\frac{B_t}{K}\right)^p\right]-C_t \qquad \text{Eq. (6.3)}$$

$$I_t=\frac{C_t}{E_t}=qB_te^{\varepsilon} \qquad \text{Eq. (6.4)}$$

Note the e^{ε} term in Eq. 6.4, which indicates that log-normal errors have been assumed (a common assumption with catch-effort data). An assumption of linear density-dependence implies that a plot of rate of production against stock biomass would be symmetrical with maximal surplus production at 50% of the maximum population size (K). Adding the single asymmetry term, denoted by p, permits asymmetry of the production curve (Fig. 6.2). If p = 1 then Eq. 6.3 would revert to a simpler model known as the discrete Schaefer model (Fig. 6.2).

Fitting a biomass dynamic model with the asymmetry term is often more difficult than fitting the simpler Schaefer model (equivalent to p = 1). When estimating model parameters if there are correlations between parameters this will reduce the precision with which they can be determined. Adding the extra parameter p (*i.e.* not fixing its value at one), which can be correlated with some of the other parameters, means that those parameters will all be less well determined.

As the asymmetry term (p) tends to zero the model becomes equivalent to the Fox (1970) stock-production equation. However, if p is set to zero, Eq 6.3 generates a mathematical singularity (because of the r/p term). Also the equation's mathematical behaviour becomes too remote from biological possibility when p takes values less than -1. Very rapidly the equation suggests that extremely high production levels will derive from extremely small stock biomass levels. When fitting the model these mathematically valid but biologically non-sensible solutions need to be avoided. This limitation can be implemented by constraining the model to have values of p greater than zero.

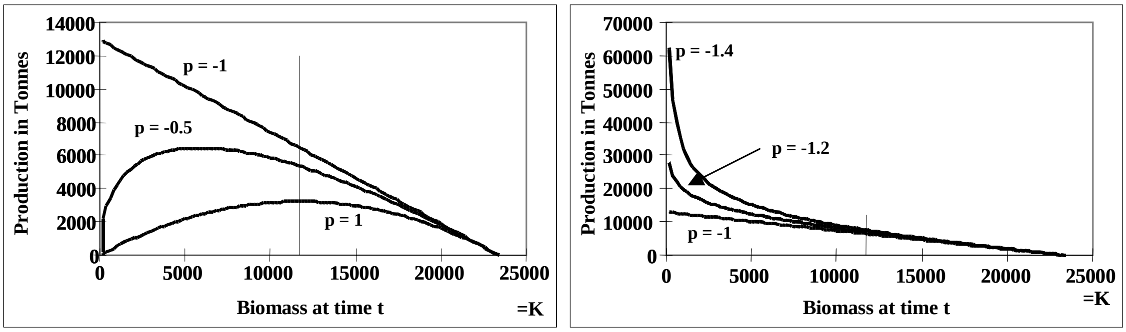

Fig. 6.2 Production curves using Eq. 6.3 with *r* =0.5532 and *K* =23,398 but different values of parameter *p*. The line where *p* = 1, is symmetrical about K/2, where maximum production occurs. The symmetry implies linear density-dependence of population regulation. With values *p* < 1 the population is most productive at smaller population sizes and with *p* > 1 the peak of productivity occurs at larger population sizes. In each case where *p* ≠ 1, the absolute level of production is affected. With *p* values < -1 the production curve becomes very large at very small stock biomass levels. The vertical line in the left panel shows the symmetry at *p* = 1.

Using log-normal errors, the parameter *q* (catchability coefficient - the proportion of the total available stock taken by one unit of effort) may be derived directly from the geometric average of the individual yearly *q* values predicted from the model and its parameters (determined by dividing catch-per-unit-effort by predicted biomass *cf.* Eq. 6.4; Polacheck *et al.* 1993; Appendix 2):

$$\hat{q} = e^{\left(\frac{\sum Ln(I_t / B_t)}{n}\right)} \qquad \text{Eq. (6.5)}$$

where *n* is the number of values in the time-series of data. This produces effectively the same value as obtained when *q* is estimated directly from the fitting process. Equation 6.5 is known as a closed form estimate of the catchability coefficient. The derivation of this method (and others) is given in Appendix 2 (Haddon, 2000).

6.4 Equilibrium Analyses

If the population that is being exploited is assumed to be at equilibrium (*i.e.* $B_{t+1} = B_t$, irrespective of what fishing history it has experienced) then Equations 6.3 and 6.4 can be solved analytically (see Appendix 1; Haddon, 2000), such that:

$$\frac{C_t}{E_t} = \left(a - bE_t\right)^{\frac{1}{p}} \qquad \text{Eq. (6.6)}$$

The assumption of equilibrium is necessary to permit the analytical solution but with virtually all marine populations it is highly unrealistic. This is especially the case for relatively short-lived species, such as prawns, which, because of their variable recruitment and survivorship, would rarely attain a stable population size from year to year, even without any fishing. Somers (1990, 1994) used equilibrium surplus-production models, with linear density-dependence (equivalent to $p = 1$) in his early attempts to model the stock dynamics. A repeat of this equilibrium analysis will be made below, using all the available data. While its results will be compared with the earlier analyses in no way is it being put forward as a formal assessment. The results from the equilibrium analysis must not be used for management purposes. The effect of the assumption of equilibrium is that when catch rates are declining such analyses tend to be over-optimistic, suggesting that effort and catch levels can be maintained at higher levels than are really sustainable.

6.5 Non-Equilibrium Methods

Fortunately, methods of producing non-equilibrium model fits have been developed for these and related equations (Fig. 6.3; Schnute, 1977; Rivard & Bledsoe, 1978), which has increased interest in this approach to providing management advice (Punt, 1992; Polacheck *et al.*, 1993).

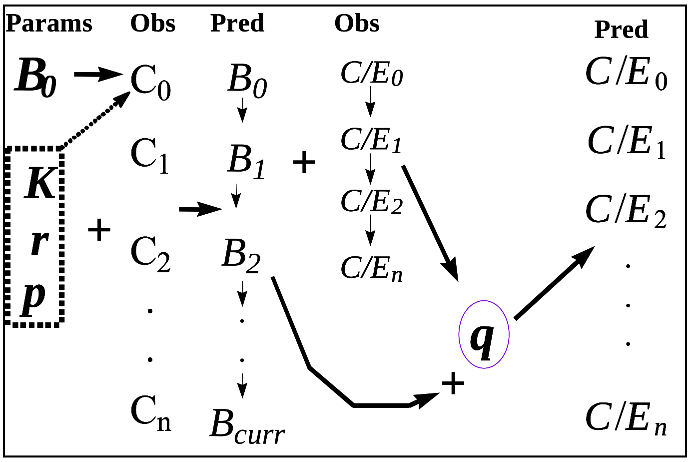

Fig. 6.3 Schematic representation of how non-equilibrium surplus-production models are fitted to time series of observed CPUE and catches. The model parameters (B_0, r, K, and p) are combined with the sequence of catches to generate the sequence of predicted biomass levels, which are used with the observed CPUE to estimate of q the catchability coefficient, which is then used to generate a predicted sequence of CPUE from the expected series of biomasses. The q value determined in this way (Eq. 6.5) is effectively the same as that obtained by direct estimation, as long as sufficient data is available.

The process of fitting a non-equilibrium biomass-dynamic model to observed CPUE and associated catch data involves assuming values for the model parameters (r, K, and p) from Eqs 6.3 and 6.4, plus an initial biomass level B_0, which is needed by Eq 6.3, to calculate a time-series of expected stock biomass levels (B_t). This hypothetical time-series of stock biomasses is used with Eq. 6.4 to generate an expected time-series of catch-per-unit-effort data and then the q parameter may be estimated using Eq. 6.5 (Fig. 6.3). By varying the hypothesized parameter values, the closeness of fit between the observed CPUE and the expected CPUE can be optimized using either least squared residuals or maximum likelihood criteria. Generally, CPUE data is taken to be distributed log-normally around any mean values, so log-normal errors are appropriate whichever criterion is used (alternatives include a square root transformation).

6.6 How Best to Estimate B_0?

There is no set practice on how best to set the initial biomass level (B_0) needed to start the predicted time-series. Punt (1990) recommended that initial biomass be set equal to *K*, the average un-exploited biomass. This constraint was considered by Polacheck *et al*. (1993) often to be necessary to obtain the best estimation performance. It certainly tends to prevent the *p* parameter from becoming extremely negative. However, the alternative of directly estimating B_0 has been investigated when using surplus-production models with short-lived species such as tiger prawns (Haddon, 1998) and was found to be advantageous in terms of producing more precise parameter estimates that have lower bias. Both approaches are more efficient than a further alternative of estimating B_0 as being the initial catch rate divided by the initial catchability coefficient (*i.e.* B_0 = C/Eq). This assumes the initial catch rate is known without error and also reduces the available data by one because this initial point will, obviously, fit the catch rate data perfectly. The approach of directly estimating B_0 (after Haddon, 1998) is used in the current work.

6.7 Changes in Effectiveness of Effort

One major assumption in the use of surplus production models is that the relationship between catch-rates and stock biomass is constant (C/E = qB). This relationship implies that the catchability coefficient, *q*, remains constant through time. In fact, because fishers tend to be good at what they do, there tend to be continual improvements to fishing gear and fishing practices such that the effectiveness of each unit of effort increases through time. This effort creep is often considered in terms of changes in fishing power brought about, for example, by introducing new gear such as radar, coloured echo sounders, and Global Positioning System (GPS) receivers and plotters (Brown *et al*., 1995). By using General Linear Models to compare the catch rates of vessels that had adopted GPS and related plotters in different years, Robins *et al*. (1998) found that vessels in the Australian Northern Prawn Fishery obtained a 4% advantage with the introduction of GPS, and this figure grew to 7% if a plotter was also installed. Over the subsequent two years there were further improvements of between 2 and 3% per year (*i.e.* learning was a factor). Overall, once the complete fleet had adopted the technology (a matter or 3 to 4 years), the increase in fishing power accorded to this alteration alone was 12%. To account for this 12% rise in the effectiveness of fishing effort one could multiply the units of effort by 1.12, however, such an approach would make the units of effort confusing. For example, if effort was in hours fished then it would become necessary to refer to effort as hours standardized relative to some reference year (100 hours in 1996 might be 112 1994-hours). Instead, perhaps the simplest interpretation to place on increases in fishing power is to consider them as changes to the catchability coefficient. In numerical terms, because $C = qEB$, it does not matter whether the *E* or the *q* changes.

Clearly, the assumption that *q* is a constant is rather an over-simplification. Prager (1994) pointed out that if it were suspected that the catchability coefficient had changed rather suddenly then the non-equilibrium model could be applied as if there were two time-series of catches and catch-rates. The same parameters (*r*, *K*, B_0, and perhaps *p*) would apply to each time-series and would be fitted together. However, there would need to be as many *q* parameters as there were separate time-series, and these would need to be fitted separately. Alternatively, two or more sets of closed-form calculations could be produced (as per Eq. 6.5, or see later), but if the number of observations in each time-series becomes very low then the closed-form calculations may become sub-optimal and direct estimation might be more robust. Each suspected major change in catchability would entail the addition of a further parameter. Naturally, as the number of parameters increases one would expect the quality of model fit to improve. Prager (1994) suggests using an F-ratio test to compare the simple models with the more complex. This would be equivalent to using a likelihood ratio test.

Prager (1994) also considers briefly a linear increase in catchability through time. This would be equivalent to a constant absolute increase each year:

$$q_t = q_0 + q_{add} \times t \qquad \text{Eq. (6.7)}$$

where the t subscript denotes the particular year, 0 to n-1, q_0 is the catchability in the first year, and q_{add} is the constant increase added to the catchability each year. Prager (1994) suggested this could be parameterized by estimating the first and last year's q and interpolating for the intervening years. Perhaps this would be more easily implemented by using Eq. 6.7, directly estimating the q_0 for the first year and then the q_{add} that provides the best fit. Alternatively, a closed form estimate of q_0 and q_{add} can be generated by implementing the appropriate linear regression analysis (see Appendix 2 for the derivation).

In the Australian northern tiger prawn fishery it has been suggested that there is a constant proportional increase in catchability each year. The annual proportional increase in the effectiveness of effort formally accepted by managers and Industry (for purposes of discussing effort reduction targets) is 5% per annum (Pownall, 1994). Thus, instead of Eq. 6.7, we would need:

$$q_t = q_0 \times q_{inc}^t \qquad \text{Eq. (6.8)}$$

where q_{t} is the catchability in year t and q_0 is the catchability in the first year. In year 0, the q_{inc} would be raised to the power zero and hence equal 1. For a 5% per annum increase, q_{inc} would = 1.05. As with the additive form of catchability increase, closed form estimates of q_0 and q_{inc} can be obtained if we log-transform the Eq. 6.8 to give it the form of a linear regression (see Appendix 2 for the derivation):

$$\mathrm{Ln}\left(q_t\right) = \mathrm{Ln}\left(q_0\right) + t \times \mathrm{Ln}\left(q_{inc}\right) \qquad (6.9)$$

In the first year the catchability is simply q (*i.e.* qinc^0, which equals one), and from then on this is multiplied by *qinc* each year (i.e. qinc^1, qinc^2, … qinc^{29}). During each round of estimation, the two parameters may be estimated by fitting the linear regression and back transforming the parameters. The parameter estimates one obtains using this 'closed form' method do not differ importantly from a direct estimation but from having fewer parameters to vary when fitting the model to the data, the estimation performance is generally improved.

6.8 Analytical Methods

The analysis consisted of obtaining the set of values for the parameters *r*, *K*, B_0, *p*, *q*, and *qinc*, which optimized the fit of the model to the observed CPUE according to the criterion of maximum log-likelihood with log-normal errors (Eqs. 8 and 9).

$$LL = Ln\left[\frac{1}{\sqrt{2\pi}\hat{\sigma}} e^{\frac{\sum\left[-\left[\left(Ln(I_t)-Ln(\hat{I}_t)\right)^2\right]\right]}{2\hat{\sigma}^2}}\right] \qquad \text{Eq. (6.10)}$$

or

$$LL = nLn\left(\frac{1}{\sqrt{2\pi}\hat{\sigma}}\right) + \frac{1}{2\hat{\sigma}^2}\sum\left[-\left[\left(Ln(I_t)-Ln(\hat{I}_t)\right)^2\right]\right] \qquad \text{Eq. (6.11)}$$

where

$$\hat{\sigma}^2 = \frac{\sum\left(Ln(I_t)-Ln(\hat{I}_t)\right)^2}{n} \qquad \text{Eq. (6.12)}$$

and I_t is the catch-per-unit-effort during time *t*, and *n* is the number of years of CPUE data available. Equation 6.12 is the maximum likelihood estimate of the variance (note the division by *n* and not *n-1*. By expanding Eq. 6.11 using Eq. 6.12 and then simplifying we obtain:

$$LL = -nLn\left(\sqrt{2\pi}\hat{\sigma}\right) - \frac{n}{2} \qquad \text{Eq. (6.13)}$$

which can be simplified further to become (See Appendix 3; Haddon, 2000):

$$LL = -\frac{n}{2}\left[Ln(2\pi) + Ln\left(\hat{\sigma}^2\right) + 1\right] \qquad \text{Eq. (6.14)}$$

The close relationship between the maximum likelihood and the least squares criteria can be seen when we consider the structure of the expected sigma term (see Eq. 6.12). Before one can determine an optimum fit of a model to a set of data, a criterion of quality of fit is required. In this case a maximum likelihood criterion (Eq. 6.14) was used, but, as with all model fitting in biology, this is not sufficient on its own. We would also require any mathematically valid fit of the model to be biologically realistic. As is clear from Eq. 6.16, values of $p < -1$ (mathematically valid) would lead to negative or non-sensible values of MSY as well as other details which would not lead to a sensible biological interpretation. A consideration of the properties of the equations (as illustrated in Fig. 6.2) suggested that a minimum constraint of $p > 0$ should also be part of the criteria of good fit.

6.9 Model Outputs

The model can produce not only parameter estimates but also outputs of more value to management because they can be interpreted in terms of fishery performance indicators or targets. The performance indicators calculated for the fishery included the expected current biomass B_{curr}, the last in the series of predicted biomass values, the ratio of current biomass to unfished biomass B_{curr}/K, the expected MSY, the effort required to attain the MSY, E_{MSY}, assuming the stock is at the appropriate level, and F, the fishing mortality. In this non-equilibrium analysis the *MSY* may be interpreted as the potential long-term average yield of the fishery. Estimates of the long-term potential yield and the effort required to attain that yield can be derived from Eq. 6.6. With $p = 1$, $a = qK$, and $b = (q^2K)/r$, then differentiating Eq. 6.6 with respect to E gives:

$$E_{MSY} = \frac{a}{2b} = \frac{r}{2q} \qquad \text{if } p <> 1 \qquad E_{MSY} = \frac{pa}{b(p+1)} = \frac{r}{q(p+1)} \qquad \text{Eq. (6.15)}$$

substituting Eq. 6.15 into Eq. A.3 (Appendix 1) gives:

$$MSY = \frac{(a/2)^2}{b} = \frac{rK}{4}, \text{ and if } p <> 1, \; MSY = \frac{p}{b}\left(\frac{a}{p+1}\right)^{\frac{p+1}{p}} = \frac{\mathrm{rK}}{(\mathrm{p}+1)^{\frac{(p+1)}{p}}} \qquad \text{Eq. (6.16)}$$

Given the MSY the B_{MSY} (the biomass that would give rise to the MSY given E_{MSY}) can be determined by a simple search routine on Eq. 6.3 or by using $B_{MSY} = MSY/(qE_{MSY})$.

The instantaneous fishing mortality rate can be estimated in two ways, either as a conversion of the annual exploitation rate (catch/biomass) to an instantaneous fishing mortality rate (Haddon, 2000):

$$F_t = -Ln\left(1 - \frac{C_t}{B_t}\right) \qquad \text{Eq. (6.17)}$$

where F_t is the instantaneous fishing mortality rate in year t, C_t is the catch in year t, and B_t is the start-of-year biomass for year t. Alternatively, we could use the standard catch equation so that instantaneous fishing mortality relates to expected effort and the catchability coefficient, q (which would be a combination of q_0 and *qinc*):

$$F_t = qE_t = q\frac{C_t}{C_t / E_t} = q\frac{C_t}{\hat{I}_t} \qquad \text{Eq. (6.18)}$$

Given Eq. 6.18, and that $E_{MSY} = r/2q$ (from Eq. 6.15) we can see that the instantaneous fishing mortality rate at MSY, F_{MSY}, would be:

$$F_{MSY} = qE_{MSY} = q\frac{r}{2q} = \frac{r}{2} \qquad \text{or} \qquad F_{MSY} = q\frac{r}{q(p+1)} = \frac{r}{p+1} \qquad \text{Eq. (6.19)}$$

Prager (1994) described many extensions to standard surplus-production models and one of these was to point out that $F_{0.1}$ is approximately 90% of F_{MSY}. Thus, it would be simple to include both of these potential management targets in the outputs from the model.

The real world interpretation of management targets is not always straightforward. Equilibrium is now assumed to be unlikely in a fished population, so the interpretation of the MSY is more like an average, long-term expected potential yield if the stock is fished optimally. The E_{MSY} is only the effort that should give rise to the MSY if the stock biomass is at B_{MSY}, the biomass needed to generate the maximum surplus production. Clearly, a fishery could be managed by limiting effort to E_{MSY}, but if the stock biomass is depleted then the average long-term yield will not result. In fact, the E_{MSY} effort level may be too high to permit rebuilding of stock biomass.

Few of these potential management outputs are of value without some idea of the uncertainty around their values. It would also be very useful to be able to project the models into the future to provide a risk assessment of alternative management strategies.

6.10 Bias and Confidence Intervals on Parameters and Indicators

Once the optimum fit has been obtained (tested by starting the multi-dimensional searches from many different starting points) the expected CPUE values and their residuals were calculated and stored. Confidence intervals and bias estimates were obtained using bootstrap procedures. In order that the time-series nature of the CPUE and catch data is retained the residuals between the observed and expected values were bootstrapped instead of the raw data; *i.e*. randomly sample from the original residuals, with replacement, to generate a new vector of residuals (Efron & Tibshirani, 1993). Each vector of bootstrapped residuals is combined with the original vector of expected CPUE data to obtain each new bootstrap sample of CPUE data.

With log-normal, multiplicative errors (see Eq. 6.4) we must use the ratio of the CPUE values (Observed / Expected) to calculate the residuals which are to be bootstrap sampled. To obtain the bootstrapped CPUE values the residuals are multiplied by the respective expected CPUE values (Eq. 6.20) derived from the maximum likelihood fit.

$$I_t^* = \hat{I}_t \times \left(\frac{I_t}{\hat{I}_t} \right)^* \qquad \text{Eq. (6.20)}$$

where the ‘hat’ symbol denotes the expected CPUE and the ‘ * ‘ superscript denotes a bootstrap sample. Confidence intervals were fitted by bootstrapping the residuals at least 2,000 times. Each value in the original vector of expected CPUE values was multiplied by the bootstrap residual in the corresponding position in the vector of residuals, and the model refitted to these new bootstrap CPUE values. Bootstrap percentile confidence intervals were then fitted around each parameter and fishery performance indicator using the 25th and 975th ordinal values of the 2,000 replicates (Efron & Tibshirani, 1993).

The proportional bias of each estimated parameter was calculated by subtracting the maximum likelihood parameter value from each bootstrapped estimate (the average of all bootstrap estimates) and dividing by the maximum likelihood parameter value:

$$\%Bias = \frac{100\left(\hat{\theta}_b - \hat{\theta}\right)}{\hat{\theta}} \qquad \text{Eq. (6.21)}$$

where the subscript *b* identifies the bootstrap estimate of the parameter of interest. The bootstrap estimate is simply the average of the bootstrap replicates.

If we wished to account for the bias in any of the parameter estimates then we would do best to calculate bias-corrected percentile confidence intervals (Efron & Tibshirani, 1993). Percentile confidence intervals are determined by using the 25th and 975th ordinal values (out of 1,000 replicates for 95% intervals). Bias-correction leads one to use different percentile values depending on whether the parameter estimates are positively or negatively biased. The procedure begins by determining what proportion (LT) of the bootstrap replicates are less than the original optimal fit estimate of the parameter or output of interest and this value is transformed via the inverse cumulative standard normal distribution (Φ-1) :

$$z = \Phi^{-1}\left(LT\right) \qquad \text{Eq. (6.22)}$$

This z value is used in the cumulative standard normal distribution (Φ) to calculate the appropriate percentile to use instead of the standard 25th and 975th:

$$\begin{aligned} P_{lower} &= \Phi\left(2z - 1.96\right) \\ P_{upper} &= \Phi\left(2z + 1.96\right) \end{aligned} \qquad \text{Eq. (6.23)}$$

where Φ is the cumulative standard normal distribution function. With bias-corrected confidence intervals, if LT were 0.5 then z would be zero and we would, of course, obtain the 25^{th} and 975^{th} percentiles (Haddon, 1998). However, if, for example, LT were 0.459 then z would be -0.10295, which would lead us to use the 16th and 960th percentiles (note they are no longer necessarily symmetrical around the median).

As with likelihood profiles, bootstrap percentile confidence intervals are only approximate and only capture the variability inherent in the data, ignoring other sources of variability (these would include: the simplicity of the model failing to capture the full dynamics of the population (for example, there are two species of tiger prawns that are lumped in the catch and catch rate information), and the short time series of fisheries data not capturing the full range of environmental variation possible).

6.11 Analyses Conducted

A number of alternative scenarios were analyzed using the model and data described here (after the data had been standardized in an attempt to account for spatial variation of effort and changes in seasonality of the fishery through time). This section reflects the contents of a formal report made to the Northern Prawn Fishery Assessment Group (Haddon & Hodgson, 2000).

Four combinations of model and data input were considered (Table 6.1). The first is the model as described in Appendix 4, along with the data standardized in accord with Chapter 5. The second and third models were two variations to the basic structure.

Model (2) was where B0 = K. This is supposed to restrain the model parameters preventing unrealistic but mathematically possible combination sof B0 and K (Punt 1990; Haddon, 1998). The third, Model (3), which had two sets of estimates for a starting catchability (q0) and for the incremental proportional increase (qinc). The first set extended from 1970 to 1986 while the second covered the years 1987 to 1999. This possibility was investigated because 1987 was the year that gear was restricted to double gear instead of quad and daylight closures were introduced. Both management options were felt to have a marked effect upon catchability. The fourth Model (4), involved a variation with the input data and a dropping of one of the parameters to be estimated. Stirling (2000) provided a table relating to estimates of effort creep in the Northern Tiger Prawn fishery from 1970 to 1999. This data was input to Model 4, along with the standardized catch effort data for comparison with model fits where the annual rates of effort creep is estimated directly. Finally, for Model (1) and Model (2), different model runs involved utilizing different periods of the time series of logbook data. The five different periods modelled, 70 – 95, 70 – 96, …., 70 – 99, were considered in order to determine whether there were any trends through time in the parameters and outputs of interest as more data from the fishery became available.

Table 6.1 The four different combinations of model structure and data inputs. All models used the same set of standardized data but model 4 also had the data relating to the increase in proportional fishing power (efficiency) derived by Sterling (2000). Model 2 was implemented as an alternative to estimating the starting biomass independently. Model 3 was implemented to reflect the restriction to double gear instead of quad in 1987. In all models, the constraint $p > 0$ is used to confine the model to a realistic biological space of possibilities.

Model	Parameters Estimated	Comment
Model 1	r, K, B_0, p, q_0, qinc	Basic Model as in Appendix 4, repeated for five different time series.
Model 2	r, K, p, q, qinc (B0 = K)	Basic Model but with added constraint B0 = K, repeated for five different time series.
Model 3	r, K, B_0, p, q_0, qinc, q_2, $qinc_2$	Basic Model but with two sets of starting q and qinc. The first set from 1970 to 1986, the second from 1987 to 1999 (step relates to quad gear restriction and day-time closure in 1987 season).
Model 4	r, K, B_0, p, q_0	Basic model but the qinc value input as data

7. Model Results

7.1 The Data Standardization and qinc.

The standardization of the different sets of years led to only very tiny difference between years (Table 7.1). However, for all years of data there was a large difference between the un-standardized data (geometric mean catch rates) and the optimum statistical model (Table 4. and 7.2; Fig. 4.2). This standardization makes no allowance for the effects of effort creep as no factors could be included that related to relative fishing efficiency. A factor relating to Vessel could not be included because individual vessels cannot be traced accurately throughout the period covered by the database.

Table 7.1 Standardized CPUE for each time series from 1970 to the year indicated. The optimum model in each case was Year, Month, Week, 30-minute block, and banana prawn catches. Each series tends to differ only at the third decimal place.

YEAR	Y1995	Y1996	Y1997	Y1998	Y1999
1970	1.0000	1.0000	1.0000	1.0000	1.0000
1971	0.8799	0.8807	0.8822	0.8831	0.8860
1972	0.9613	0.9626	0.9639	0.9650	0.9666
1973	1.1615	1.1491	1.1447	1.1457	1.1468
1974	1.0945	1.0925	1.0924	1.0948	1.0975
1975	0.8991	0.8938	0.8907	0.8911	0.8914
1976	0.9172	0.9150	0.9133	0.9144	0.9148
1977	1.1316	1.1318	1.1307	1.1316	1.1331
1978	0.9909	0.9914	0.9902	0.9906	0.9920
1979	1.0440	1.0454	1.0454	1.0464	1.0481
1980	0.8264	0.8276	0.8285	0.8282	0.8286
1981	0.8555	0.8578	0.8595	0.8584	0.8590
1982	0.7740	0.7745	0.7753	0.7743	0.7749
1983	0.8511	0.8530	0.8552	0.8551	0.8556
1984	0.6906	0.6942	0.6963	0.6956	0.6963
1985	0.6592	0.6613	0.6623	0.6618	0.6617
1986	0.5047	0.5063	0.5085	0.5077	0.5081
1987	0.7592	0.7618	0.7659	0.7648	0.7649
1988	0.6437	0.6469	0.6508	0.6501	0.6505
1989	0.5985	0.6015	0.6044	0.6034	0.6035
1990	0.6970	0.7000	0.7047	0.7033	0.7040
1991	0.8712	0.8751	0.8797	0.8785	0.8790
1992	0.6788	0.6828	0.6858	0.6854	0.6866
1993	0.7192	0.7229	0.7260	0.7246	0.7247
1994	0.8460	0.8513	0.8553	0.8538	0.8547
1995	1.1796	1.1872	1.1935	1.1942	1.1960
1996		0.6952	0.6956	0.6951	0.6949
1997			0.8951	0.8920	0.8923
1998				0.8664	0.8676
1999					0.7445

Table 7.2 A listing of the standardized catch-effort data from the Northern Tiger Prawn fishery. The factors used in the GLM were Year, Month, Week, 30-minute block, and banana prawn catches. The indices reported in the Standardized CPUE column are the Year parameters from the GLM. These indices barely change as extra years are added after 1995. The geometric means refer to the geometric mean catch rates from the raw data, scaled to be relative to 1999. Sterling's qinc relate to Table 2 in Sterling (2000), q-total relates to the same Table but shows the cumulative effect of the changing effectiveness of effort on catchability. This data was used in Model 4.

Year	Geometric Means	Standardized CPUE	Stirling's qinc	q-total
1970	1.09527	1.34313	1.05525	1.05525
1971	0.79453	1.19006	1.05525	1.11355
1972	0.95313	1.29823	1.07962	1.20221
1973	1.18768	1.54034	1.07962	1.29792
1974	1.08981	1.47403	1.07962	1.40126
1975	0.89494	1.19722	1.07962	1.51282
1976	0.89942	1.22875	1.11360	1.68468
1977	1.24982	1.52196	1.11360	1.87607
1978	1.05548	1.33242	1.11360	2.08920
1979	1.19125	1.40776	1.11360	2.32654
1980	0.89494	1.11293	1.11360	2.59085
1981	0.88073	1.15373	1.09391	2.83416
1982	0.81465	1.04081	1.09391	3.10033
1983	0.92589	1.14912	1.09391	3.39149
1984	0.78349	0.9352	1.06053	3.59677
1985	0.72906	0.8887	1.02013	3.66915
1986	0.56836	0.6825	1.01505	3.72437
1987	0.92127	1.02737	0.63319	2.35823
1988	0.77492	0.87372	1.03716	2.44586
1989	0.72036	0.81058	1.05175	2.57244
1990	0.84874	0.94554	1.03219	2.65524
1991	1.13883	1.18057	1.01544	2.69623
1992	0.87023	0.92219	1.02620	2.76688
1993	0.96754	0.97336	1.07527	2.97513
1994	1.07144	1.14798	1.04767	3.11695
1995	1.43907	1.60641	1.04556	3.25895
1996	0.86589	0.93333	1.05556	3.44003
1997	1.06078	1.19842	1.02614	3.52996
1998	1.08981	1.16532	0.99694	3.51916
1999	1.00000	1.00000	0.98888	3.48004

7.2 Model 1

The optimum statistical solution in each of the five time series of data, in terms of maximum likelihood, presses the model solution up against the constraint of $p > 0$ (Fig. 7.1; Table 7.3). If this constraint is relaxed, the optimum statistical solution always generates a set of model parameters and fisheries performance indicators that are biologically unrealistic (Table 7.4). The unrealistic results are rejected and the optimum realistic results are used instead. The unrealistic results are more a reflection of the mathematics used to define the model than biological reality.

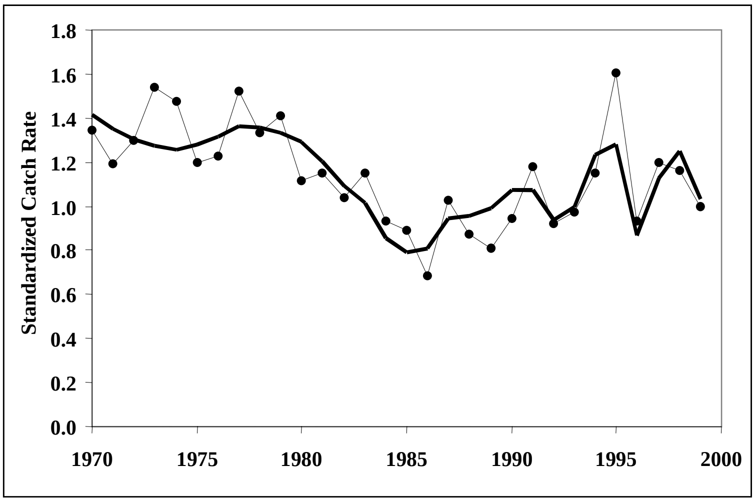

Fig. 7.1 The optimum fit to the basic model for the year 1999. There is a failure to capture the behaviour of the fishery in 1973 and 1974, and the extreme oscillations in 1989, 1991 and 1995 have not been reflected well. This model predicts a steadily decreasing stock biomass; the apparent recovery in the 1990s is merely a reflection of the increasing effectiveness of fishing effort. It does not reflect a stock recovery.

Table 7.3 The parameters and model outputs for the basic model and standardized catch-effort data over the years 1995 to 1999, showing how the optimum parameter estimates change through time. Note the *p* parameter was constrained to be greater than zero.

	70 - 95	70 - 96	70 – 97	70 - 98	70 - 99
r	0.2841	0.2890	0.2907	0.2974	0.3334
K	31513.2	30287.3	30070.7	29452.9	27104.2
p	9.952E-06	9.952E-06	9.952E-06	9.952E-06	9.952E-06
B0	37382.0	40728.5	41560.4	42381.0	40691.1
q0	2.273E-05	3.617E-05	2.768E-05	2.832E-05	3.488E-05
qinc	1.05050	1.06420	1.06693	1.07120	1.07806
Bcurr	10341.6	6407.4	6455.3	5581.3	3459.7
Bcurr/K	0.3282	0.2116	0.2147	0.1895	0.1276
MSY	3293.7	3220.4	3215.5	3222.7	3324.3
B0/K	1.186	1.345	1.382	1.439	1.501
LogLike	19.7399	19.2504	20.4045	21.0783	21.6964

By constraining the *p* parameter to greater than zero the values of *qinc* and the ratio of B_0/K remain within realistic bounds (*cf.* Table 7.4). As the number of years of data increase the perception from the model is that the level of depletion appears worse as time goes on (*i.e.* the ratio B_{curr}/K suggests depletion is down to 13% of unfished biomass; Fig. 7.2).

Table 7.4 The parameters and model outputs for the basic model and standardized catch-effort data over the years 1995 to 1999, showing how the optimum parameter estimates change through time. In these outcomes there is no constraint on the *p* parameter. The negative values of *p* lead to relatively unrealistic model outputs. Consider the *qinc* and B_0/K values.

	70 - 95	70 - 96	70 – 97	70 - 98	70 - 99
r	0.1628	0.1772	0.1667	0.1708	0.1763
K	23114.2	21656.9	25241.2	28083.7	27689.7
p	-0.9729	-0.8946	-0.8068	-0.6923	-0.6830
B0	214749.6	250097.3	157991.1	108812.9	108812.0
q0	3.962E-06	5.855E-06	7.271E-06	1.109E-05	1.302E-05
qinc	1.16956	1.19817	1.16738	1.14249	1.14585
Bcurr	4577.4	1611.9	2318.5	2434.1	1530.4
Bcurr/K	0.1980	0.0744	0.0919	0.0867	0.0553
MSY	3403.9	2944.3	2838.3	2841.3	2864.1
B0/K	9.291	11.548	6.259	3.875	3.930
LogLike	22.6889	23.5216	23.5498	22.9850	24.0613

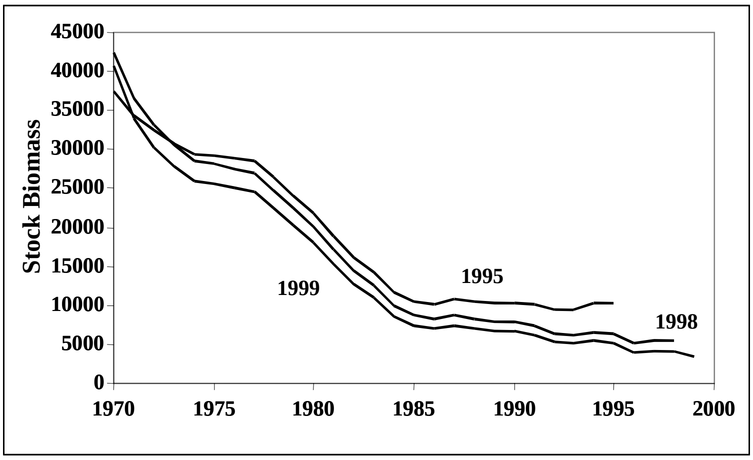

Fig. 7.2 The predicted biomass trajectories for 1999, 1998, and 1995. That for 1996 and 1997 were largely overlapped by the line for 1998 except in the 1990s where they were slightly higher than the 1998 line. As the number of years of extra data are included the image of a failure to recover, despite large reductions in the number of vessels, becomes more and more severe.

With the constraint of $p > 0$ removed in 1999, a slightly better statistical fit to the available data can be found but, biologically, the results are non-sensible. The remaining biomass (Bcurr = 1,530 t) would not be able to sustain fishing, the annual increment in catchability coefficient to far too large (qinc = 14.5%), the negative p value (p = -0.687) implies an unrealistic production curve (Fig. 6.2), and the stock appears to have been driven down to only 5% of the starting biomass (Bcurr/K = 0.0553), which suggests a stock collapse in most fisheries. The initial biomass is nearly four times the unfished biomass (B0 = 108,812 t while K = 27,689 t). According to this unrealistic model fit, the history of the fishery appears to have been one of low production and a fishing down of a large amount of accumulated biomass. The shorter time series exhibit even worse scenarios (Table 7.4). All of these results are a product of the mathematics of the production function going beyond the biologically realistic when $p < 0$, hence, we retain the constraint of limiting $p > 0$.

With increasing years of data available the current biomass has declined, the annual increment in catchability coefficient has increased slightly, the ratio of current biomass to unfished biomass has declined, and the long term potential yield has remained relatively stable at about 3,300 tonnes (Table 7.4; Fig. 7.2). The extra years of data have provided no indication of recovery. In fact, the situation appears to have steadily become worse with each year of additional data (Table 7.4; Fig. 7.2). This model appears to behave consistently.

A total of 5,000 bootstrap replicates were made to produce first-order bias-corrected percentile confidence intervals around all of the model parameters and outputs. The 95% confidence intervals were skewed about the expected value of a number of parameters (Table 7.5; Fig. 7.3). This was especially evident with the estimates relating to stock biomass (Table 7.5; Fig 7.4). This is not surprising as the stock could not biologically have been much lower than the predicted line else it would not have been able to sustain any fishing. The broad confidence intervals indicate the high level of uncertainty in this analysis. Despite this uncertainty it is clear that the stock is extremely depressed from its unfished level and is not close to its most productive state.

Table 7.5 The optimum model fitted parameters along with the mean of 5000 bootstrap replicates and the 95% first-order, bias-corrected bootstrap percentile confidence intervals. Data is standardized from 1970 to 1999. None of parameter estimates, except those relating to biomass, were especially biased (compare the bootstrap mean values with the optimum values).

	Optimum	U95%	Mean	L95%
r	0.3334	0.4579	0.3339	0.2136
K	27104.164	36940.887	27711.564	21515.657
p	0.000009952	0.000011712	0.000009926	0.000009886
B0	40691.145	62198.783	41844.293	29003.050
q0	0.0000349	0.0000462	0.0000351	0.0000237
qinc	1.0781	1.0893	1.0769	1.0580
Bcurr	3459.661	7961.155	3909.340	2037.091
Bcurr/K	0.1276	0.2293	0.1362	0.0912
MSY	3324.296	3646.208	3315.964	2894.023
B0/K	1.5013	2.1299	1.5139	1.1711

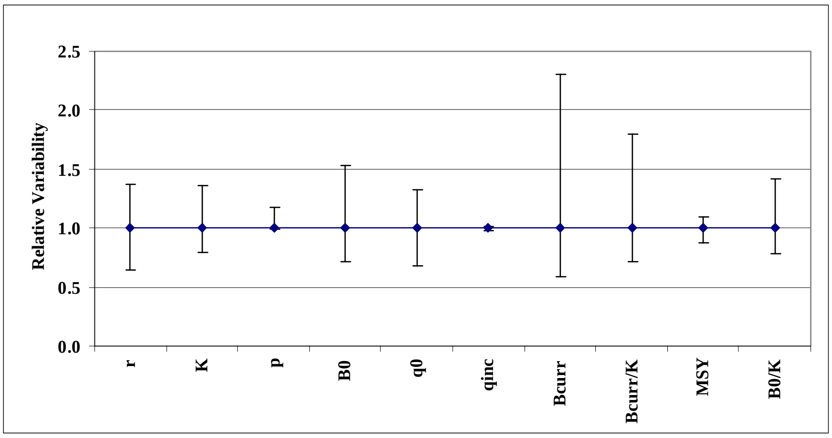

Fig. 7.3 The relative variability of each of the parameters relative to their 95% percentile confidence intervals, defined by dividing the 95% limits and the mean by the mean. The line at 1.0 locates the mean value in each case. Note the strong skew in the biomass related parameters and in the asymmetry parameter *p*. The parameter qinc is very tightly determined, this is not surprising as its effect in the model is exponential and so big differences would have large effects.

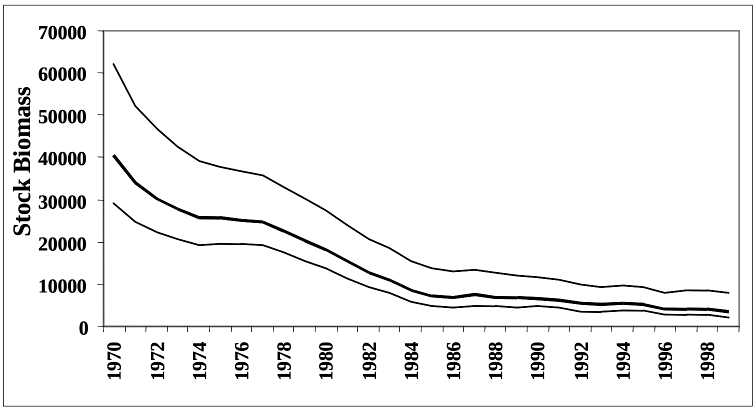

Fig. 7.4 The predicted stock biomass trajectory from the full range of data (1970 – 1999) illustrating the rapid decline in the late 1970s and early 1980s. In addition, the impact of vessel reductions taking effect in 1985 is visible by a change in the gradient. Unfortunately, the lack of stock recovery since 1985 is also clear. The uncertainty at the start of the time series is large so the apparent trends there should be interpreted with caution.

In the process of adding more years of data the model gradually becomes more unstable. While the optimum is relatively well defined in the early time-series as more years of data are added a second, false minimum implying biologically non-sensible dynamics to the population approaches the quality of fit of the optimum solution (including the constraint of $p > 0$). When the effect of the increase in effectiveness of effort are accounted for, the extra years of data only corroborate the apparent decline of the stock. This extra data is not very informative because it has little contrast with the immediately preceding years. The fishery has entered what Hilborn & Walters (1993) termed a one-way trip (downwards). A real recovery would have a major impact upon the assessment and make it stable, this extra data is having the reverse effect.

7.3 Model 2 - $B_0 = K$

In model 2, the B_0 parameter was set equal to the unfished biomass K. This should have the effect of stabilizing the model if there are any problems fitting the data (the necessary constraint of $p > 0$ is suggestive of such problems). The outcomes are certainly consistent as with increasing years of data available the current biomass levels decline (with a slight rise in 1998), the annual increment in catchability coefficient has increased slightly (though it is less than the accepted level of 5%), the ratio of current biomass to unfished biomass has declined steadily, which can be interpreted as the level of depletion has increased steadily, and the long term potential yield has steadily declined from about 4,200 to about 3,700 tonnes (Table 7.6). As with the basic model, the extra years of data have provided no indication of recovery and the situation appears to have steadily become worse with each year of additional data (Table 7.6). However, even with the full data set, conditions appear to be relatively stable (Fig. 7.5), which is a brighter outlook than with the full optimum model.

Table 7.6 The progression of parameter values for the five-year progression of standardized data available. In this case the *p* parameter is consistently greater than 1 suggesting a production curve with a mode to the right of center.

	1995	**1996**	**1997**	**1998**	**1999**
r	1.638512	1.35973	1.348406	1.034339	0.768246
K	16241.2	17608.51	17654.39	20054.8	21292.14
p	2.942557	2.523813	2.501584	2.047866	1.242640
B0	16241.2	17608.51	17654.39	20054.8	21292.14
q0	4.98E-05	7.56E-05	5.8E-05	5.24E-05	5.56E-05
qinc	1.028835	1.034963	1.036584	1.038844	1.048740
Bcurr	8665.761	6580.36	6874.206	7266.846	5046.22
Bcurr/K	0.533566	0.373703	0.389377	0.36235	0.236999
MSY	4234.679	4124.981	4119.467	3949.513	3807.941
B0/K	1	1	1	1	1
LogLike	21.77081	19.18156	20.08777	20.25637	19.96666

The high values for p for all time series, all indicate that the production curve is skewed to the right and not the left (which means the stock is most productive at higher stock sizes; see Fig. 6.2). The members of the Northern Prawn Fishery Assessment Group did not consider this aspect of the predicted dynamics to be realistic and it does not accord with any other prawn species known. The model fit is relatively flat in that it fails to capture the variability in the fishery over the years (Fig. 7.6).

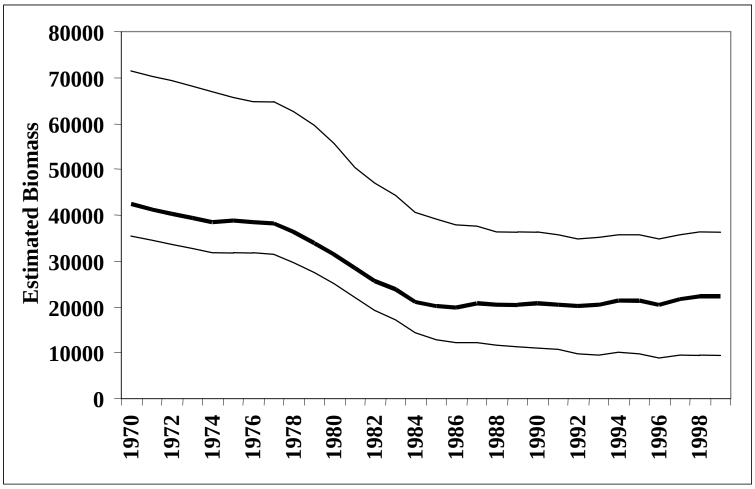

Fig. 7.5 The predicted stock biomass trajectory from the full range of data (1970 – 1999) for Model 2 where B_0 = K. The situation with the stock appears to be much more stable. It appears as if the effort reductions through the 1980s had the effect of stabilizing the fishery at a lower but steady stock size. However, there is a great deal of uncertainty over these stock estimates and this becomes worse in more recent years.

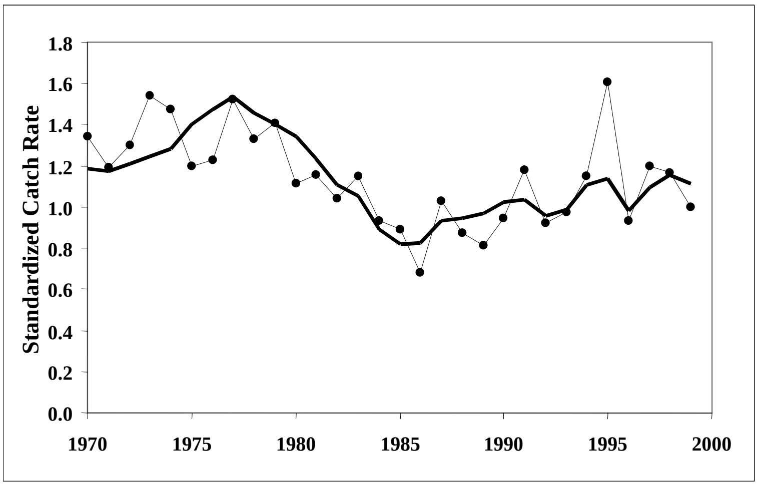

Fig. 7.6 The optimum fit to model 2 for the year 1999 (where B_0 = K). There is a failure to capture the variability in the fishery over all years, especially the oscillations from 1986 onwards. This model suggests that the stock is not so badly depleted as the full model nor is the depletion becoming worse. On the other hand the quality of fit to the data is not as good as the full model.

Even though the population biomass appears to be recovering (Fig 7.6) when the 4.9% annual increment to the catchability coefficient is accounted for the stock is still in a decline. This model is consistent with Model 1 in its conclusion that there is no sign of stock recovery and the stock is still in decline.

7.4 Model 3 – Two Separate Series of Catchability Estimates

In the case of model 3 (with two independent series of *q* and *qinc* split at 86/87), note was taken of the fact that in 1987 day-time closures were introduced and quad gear was banned in favour of twin gear. This should have introduced quite an effect on the catchability coefficient and so the data series was treated as two time series and separate estimates of a starting catchability and a constant annual rate were made for 1970-1986 and 1987 to 1999 (Table 7.7). This suggests an annual increment of the effectiveness of effort of 5.15% between 1970 and 1986 followed by an increased rate of 11.7% over the period 1987 – 1999. This is the reverse of that suggested by Stirling (2000) in his empirical study. The 5% value early on is encouraging but the high value of almost 12% per annum suggests that the time series from 1987 onwards is less informative about the dynamics than the earlier data.

Table 7.7 Optimum values for the model with two separate time series of catchability coefficients 1970-1986 and 1987-1999.

Parameter	Optimum
r	0.2035
K	37532.31
B0Est	46757.576
p	1E-08
q – 1970 - 1986	2.8679E-05
qinc - 1970 - 1986	1.05158
Bcurr	3858.431
Bcurr/K	0.1028
MSY	2810.296
B0/K	1.2458
LogLikelihood	23.858
Average F	0.4083
q0_2 – 1987 - 1999	6.83288E-05
qinc2 – 1987 – 1999	1.1177

This model was not particularly stable and these results must be regarded as provisional. Each solution had to be searched for carefully and bootstrapping would have had to have been conducted by hand and so was not pursued. The expected decline in the catchability in 1987 is not supported by the model predictions.

A reconciliation of this with the available data might be forthcoming from an inspection of the hours fished per day. The total number of hours fished only declined a small amount in 1987 and then increased in later years (Fig. 7.7) while the average number of hours fished hardly declined at all (Fig. 7.8).

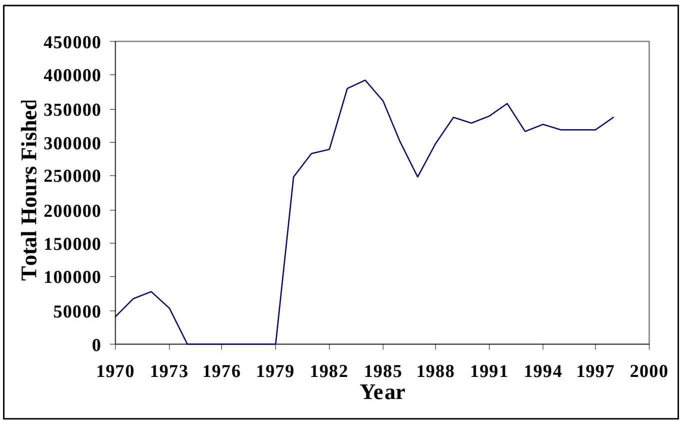

Fig. 7.7 The total number of Hours fished in the Northern Prawn fishery as recorded in the database. The empty period in the 1970 was when hours fished were not recorded. The dip in 1987 is clear but by 1990 the total had recovered and has remained approximately the same ever since.

The argument used by Stirling (2000) was that the introduction of day-light fishing bans had a detrimental effect on the effectiveness of fishing effort in 1987. However, the average number of hours fished per day does not appear to have altered significantly during that period (Fig. 7.8). If, as Stirling (2000) suggests the catch rates of Tiger Prawns was significantly higher during the night period than during the day then forcing fishers to fish at night would not reduce the effectiveness of effort but increase it, which might be enough to offset any decrease in amount of hours. The decline in total hours fished appears to be more a result of closed periods than of fewer hours fished per day. If the catch rates in the closed periods were higher than at other times this could be argued to have introduced a decline in the effectiveness of effort. At very least the proposed decline in catchability in 1987 due to day-light closures should be reviewed.

Industry comment at the Northern Prawn Fishery Assessment Meeting at Cleveland in November 2000 was of the opinion that 1987 was a year when there were plenty of prawns to be caught. Thus, the expected decline in catch rate due to the reduced catchability was offset by an unusual relative abundance of prawns. The surplus-production model assumes a consistent production function so exceptional recruitment could not be predicted and it must conclude that catchability was not affected. The possibility of a higher than normal recruitment happening in the same year as the change in the fishing regulation is beyond its dynamics. A model with a different structure, such as the Wang & Die (1996) model, which has an explicit recruitment term, could, and does, predict a higher recruitment in 1987 to account for the failure of the reduced catchability to lead to a lowered catch rate.

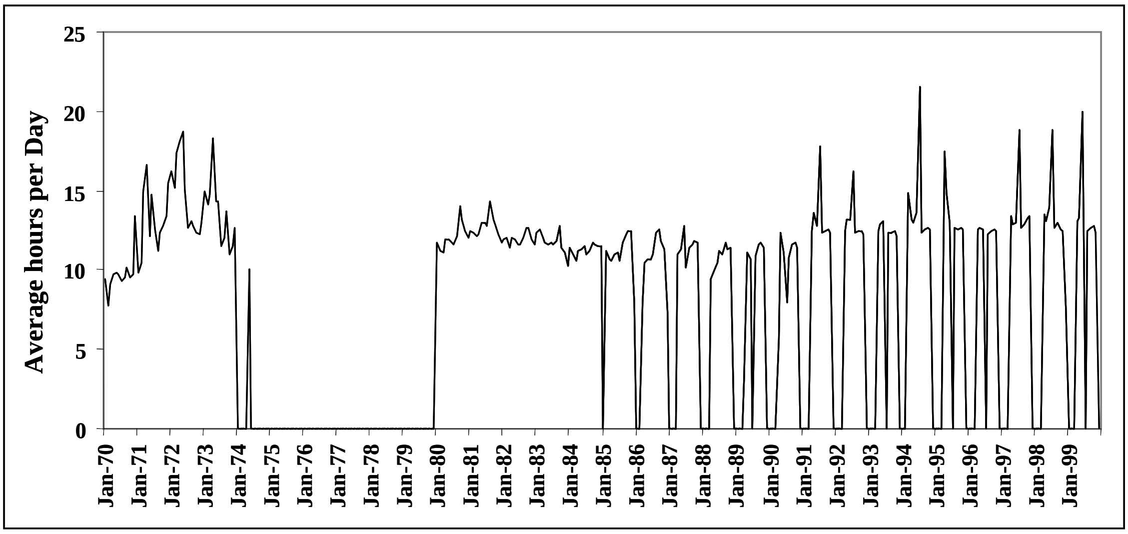

Fig. 7.8 The average number of hours fished per day, per month, across all years recorded in the Northern Prawn fishery database. The introduction of closed periods in the fishery becomes clear from 1986 onwards. The period when hours fished was not recorded in the 1970s is also clear. The average number of hours fished when fishing occurred does not appear to alter significantly through the period 1985 to 1988, although early in the 1987 season small difference can be seen.

7.5 Model 4 – Empirical Estimates of Catchability

When using Stirling's (2000) estimates of catchability (Table 7.2), obtaining a reasonable quality of model fit to the data is difficult. The optimum statistical fit retains some unlikely outcomes (Table 7.8; Fig. 7.9) with the predicted catch rates not reflecting those observed at all well.

Table 7.8 Optimum statistical fit of the data to Model 4 (where the annual increment in catchability was input as data). The qinc here is only an average across the years and is not an estimate. This suggests the stock has only been reduced to approximately 50% of the unfished biomass, but B0 is almost twice the unfished biomass. The very low Log-likelihood indicates the poor quality of the fit of the data to the model (Fig. 6). By removing the effect of Daylight saving the catchability multiplier changes from 0.6331 to 0.7278. The final column is where this term is set equal to 1. The ratio of B0/K remains high but the current Biomass declines and the quality of fit increases.

Parameter	**Optimum Fit**	**DayLight Effect Removed**	**Annual Increment in 1987 set to 1**
r	0.3147	0.2960	0.2846
K	30969.22	31348.11	30779.21
B0Est	60544.67	60321.75	60406.78
P	1E-07	1E-08	1.16E-08
q	2.58E-05	2.54E-05	2.59E-05
qinc	1.0661	1.0423	1.0601
Bcurr	15839.79	13785.08	8883.788
Bcurr/K	0.5115	0.4397	0.2886
MSY	3584.853	3413.688	3222.087
B0/K	1.9550	1.9243	1.9626
LogLike	6.1418	8.8878	15.0762
Average F	0.1812	0.2059	0.2913

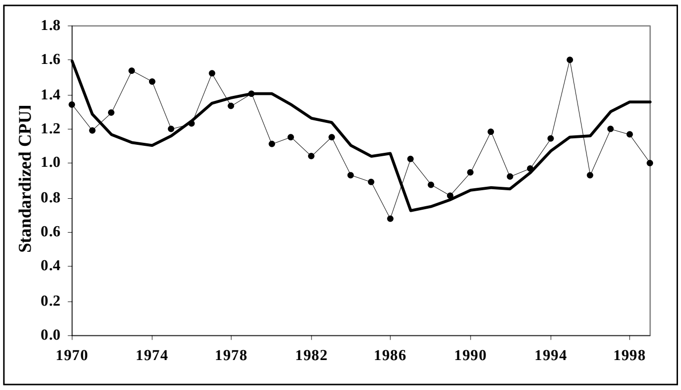

Fig. 7.9 Optimum fit to the model when the annual increment in catchability is input as data (from Stirling, 2000; see Table 7.2). The fit is a poor compromise attempting to balance the years 1970 to 1986 with those following.

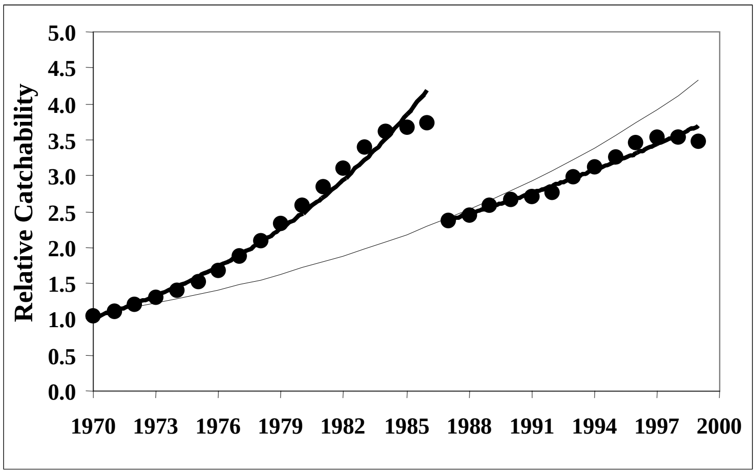

Fig. 7.10 The relative catchability from Stirling's (2000) table 2 (see Table 7.2), with best fitting exponential equations providing the average annual percentage increment to catchability for the two separate time series. The split is at 86/87 when gear went from quad down to twin trawls and daylight closures were enacted for the second part of the season. From 1970 to 1986 the annual increment averaged at 8.84%, while for 1987 to 1999 the average was 3.68%.

The average levels of annual increment to catchability from Stirling's (2000) Table 2 (Fig. 7.9) were very different from the fit to Model 3 (the order of largest increase to smallest was reversed). Interestingly, the impact of using the empirical estimates of q on the perception of the stock is that the stock is not depleted but is at approximately 50% of its unfished biomass. This conclusion does not appear to be consistent with the contraction of the areas in which fishing now occurs (see Fig. 4.1), nor with the difficulty currently experienced in finding prawns to catch. At the same time the low rate of increase in the later part of the period does not coincide with the increases due to the introduction of GPS and plotters (or ignores any other changes during that time).

The empirical estimation of catchability is a sound and useful direction to pursue, but the estimates so far appear inconsistent with the behaviour of the stock and other facts and events.

7.6 Discussion

The basic model performs in a stable manner. Unfortunately, the model analyses suggest that despite having a number of years of data from a period when effort had supposedly declined, all indications are that there has been no sign of a stock recovery. In fact, with each year of additional data the implications from the model have become extremely dire with the present analysis suggesting that the stock is depleted down to approximately 13% of the unfished biomass (between 9% and 22%). While the uncertainty in this analysis is not small (as indicated by the bootstrap analysis of confidence intervals), nevertheless, the indication that there has been severe and ongoing stock depletion is clear. This analysis appears to be inconsistent with that produced from the Wang and Die (1996) model, which suggests that the fishery is near E_{msy}. However, while the effort levels may be close to the predicted optimum, if the stock is in a depleted state, then E_{msy} may not necessarily permit a re-building of the spawning biomass. The model analysis suggests that further reductions in fishing effort are urgently required.

The modifications implemented with the model both corroborated the overall picture of a serious stock decline, however, not unexpectedly, the particular values of particular model parameters altered significantly. The important point to stress is that surplus-production models focus upon the relative productivity of the stock. All of these model variants (except that using the empirical estimates of catchability) suggest that the stock is at a low level of productivity at present, which implies that it cannot sustain high levels of catch or effort.

The model with two time series of catchability coefficients is deserving of further investigation. In its present form it suggests that the rate of increase of catchability before 1987 was only half that after 1986. This was inconsistent with the table of independent estimates derived from a consideration of gear and management changes in the fishery (Stirling, 2000). The impact on the effectiveness of effort of the switch to twin trawl gear and the ban on daylight fishing in 1987 needs review. The available data appear to suggest that the switch to night-time trawling for tiger prawns may actually have increased the effectiveness of imposed effort. Because the average number of hours reported fishing per day did not alter greatly in 1987 there was presumably not that much daytime Tiger Prawn fishing or what there was switched to the nighttime.

The use of the independent estimates of catchability deriving from Stirling (2000) did not appear consistent with the pattern of standardized catch rates observed in the fishery. This also suggests that a further review of the independent estimates of catchability through time would be valuable.

8. Risk Assessment Projections

8.1 Introduction

Invariably, there will be many sources of error and uncertainty that are not accounted for in the model. Determining the uncertainty in an analysis only tells us that we need to be careful when attempting to interpret the model outcomes, it cannot inform resource managers about the risk level associated with a particular management option. To answer such questions a risk assessment is required. The suggestion and preliminary work below are summarized from Haddon (2001).

Risk assessment implies projecting the population dynamics model into the future under the constraint of different management options (for example, a particular catch or effort regime, or different open and closed areas, etc). Given the selected catch or effort we need to be able to model the projected recruitment levels in a stochastic manner, with the variability of that recruitment reflecting the stock dynamics observed in the available time series of data. The projected recruitments would be offset against the catches and the trajectory of the stock biomass through time could thus be generated. The problem, when using surplus-production models is to generate these stochastic recruitments.

8.2 Bootstrap Projections

Prager (1994) suggested that because surplus-production models imply a recruitment function, they could be used to make projections based upon hypothetical catch or effort allocations. In the standard operation of surplus-production models the stock biomass is projected forwarded under the constraint of the time series of catches and catch rates (*e.g.* Eq. 8.1). To do this for a risk assessment would be simply to extend this stock biomass projection beyond the years for which data is available. The projected catches or efforts (which, given the catchability and stock biomass would imply catches) would be dictated by proposed management options. The stock biomass projections are deterministic so a mechanism for introducing the required stochastic element is still required. Prager's (1994) suggestion for varying the population projections was to conduct a bootstrap analysis and project each bootstrap forward to obtain a risk assessment at the same time as a determination of the level of uncertainty in the analysis. This mechanism uses the variation inherent in each bootstrap sample to represent the variation likely to occur in the stock dynamics of the species concerned. The variation is represented by the residuals between the observed and predicted catch rates, which are assumed to relate back to stock biomass via the catchability coefficient ($C/E = qB$).

8.3 Projections with Set Catches

Many fisheries are now managed through output controls in the form of a Total Allowable Catch (TAC). In such fisheries, a vital management control is to set the TAC at a level consistent with stock sustainability and, often, with optimizing production.

Investigation of the implications of setting different catch levels is relatively simple with the surplus-production models described in this chapter. If the stock dynamics are assumed to be described by the deterministic equation:

$$B_{t+1} = B_t + \frac{r}{p} B_t \left(1 - \left(\frac{B_t}{K} \right)^p \right) - C_t \qquad \text{Eq. (6.24)}$$

or any production function from which a catch is subtracted, then forward projection only requires those catches to be defined and the projections can be implemented.

Exactly what characteristic of the population to consider in the projections can vary depending on circumstances and what would be most informative. For example, a common performance indicator would be to determine whether the predicted stock biomass in any given projection year is greater than a selected reference year. If many replicate projections are generated then, in any year, the proportion in which the stock biomass is greater than that in the reference year, can represent the probability that the modelled stock will have increased in size in that year (Figs. 8.1 and 8.2). Alternatively, if there is a risk of stock collapse, then the number of replicates under a given set of management constraints, that led to collapse (defined as some low biomass level) can also be collated and graphed.

8.4 Projections with Set Effort

The northern Australian tiger prawns is an input controlled fishery so the management controls used to constrain the projections will involve considering the impact of different effort levels. There is also the problem of effort creep to attend to in the risk assessment. In theory, it should be possible to constrain the annual proportional increase in the effectiveness of effort. The presently accepted level is 5% per annum but it is recognized that this level cannot continue so alternative, lower levels will also need consideration. The best strategy is to conduct a grid analysis, running the projections for each of the selected effort level and all the levels of the annual increment in catchability (*qinc*) that are to be considered (Figs. 8.1 and 8.2). Thus, with a given catchability in each of the projection years q_t, and a projection biomass B_t, and a given effort level E_t, we can calculate the expected catch (which can then be subtracted from the biomass and so the loop continues). This is just derived from the catch equation:

$$C_t = q_t E_t B_t \qquad \text{Eq. (6.25)}$$

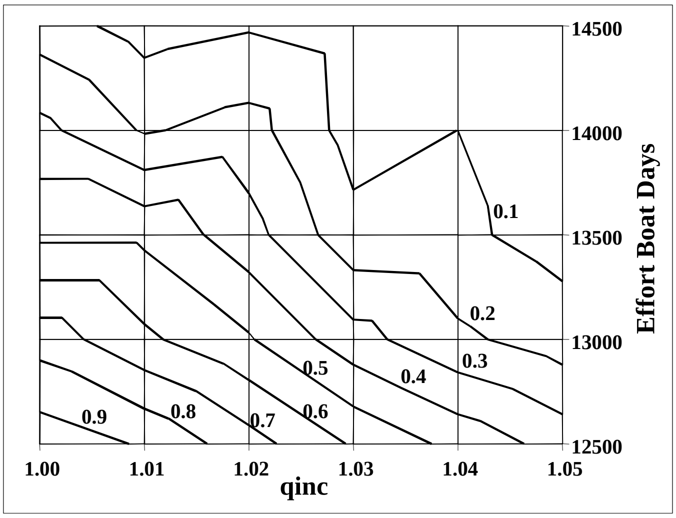

Fig. 8.1 The contours are the probability of stock biomass being greater in the year 2002 than it was in 1998. The contours are not particularly smooth because each intersection is only represented by 100 bootstrap projections, using a fixed effort strategy in the northern Australian tiger prawn fishery. It is clear that positive stock growth, relative to 1998, will only have a greater than 50% chance of occurring if effort creep (*qinc*) is kept below 3.5% per annum, and effort is less than 13,500 fishing days. Data used was published catch rates and catch to 1998.

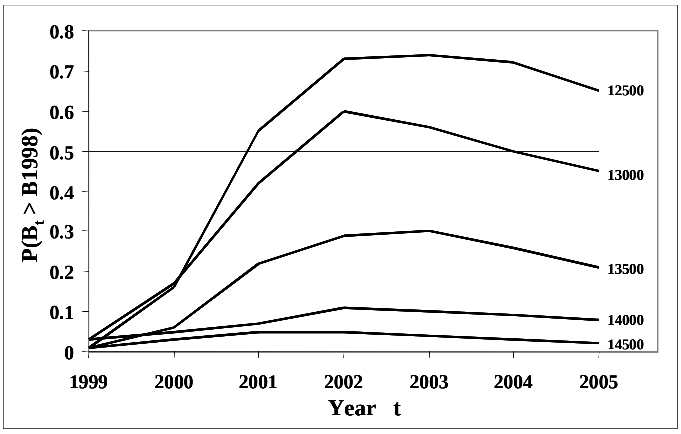

Fig. 8.2 An alternative view of risk assessment output for the northern Australian tiger prawn fishery. The vertical axis is the probability of the stock biomass in a projected year being greater than the stock biomass in 1998. Each curve relates to a given effort level. The annual increase in catchability was set at 2% (*qinc* = 1.02) for all series. The fine horizontal line is at 50%, indicating the desirability of fixing effort at less than 13000 fishing days to encourage stock rebuilding if qinc = 1.02. Data used was published catch rates and catch to 1998.

The analyses illustrated in Figs. 8.1 and 8.2 are purely for illustrative purposes only. The meaning of effort now that the fishery has moved to gear units will mean that the assessment will need to be modified to take into account the markedly different quality of effort now being used.

9. Conclusions

The current stock assessment (Wang & Die, 1996) makes a range of assumptions that strongly influence the outcome of the stock assessment. This present work details an alternative assessment approach that relies on alternative assumptions with the aim of providing an assessment that could be contrasted with that which is presently accepted.

Stock assessments in the Northern Prawn Fishery are reliant upon information contained within the commercial logbook database. Unfortunately, on inspection for internal consistency, it was found that the spatial data fields in the Northern Prawn Fishery commercial logbook database hold a small number of errors. These relate primarily to the identification of the location of 6-minute grids within larger regions but also include at least 91 records that are on land. If any part of a 6-minute grid contained water it was assumed that any record was not on land. This assumption may have led to fewer records being found on land than really exist. The grid identifiers are no longer used in analyses, although these problems add to any uncertainty in assessments up to 1998 after which actual latitude and longitudes were used to identify location. However, at very least the records that are definitely on land should be removed before this data is utilized in any formal stock assessments (although so few records would make very little difference in any assessment).

There were also 1379 duplicate records found in the database over the period 1971 to 1989. Those containing no catch data would have had little effect but those that were identical duplicates or varied in a few of the catch fields would have had an effect, though probably slight. Simple duplicates (empty or identical) are easily removed but the 649 records where the catch data differed between the duplicates required a strategy for removal. In this work the record reported the largest catch was retained. This option was not opposed by Industry representatives on the Northern Prawn Fishery Assessment Group.

Standardization of the catch effort data was attempted as a means of reducing the influence of spatial and seasonal variations between years on our perception of the relationship between catch rates and stock size in any particular year. The standardization is necessary because it was demonstrated that the seasonality has markedly altered through time as has the general location of fishing effort. Not un-expectedly, the shifts in the area of most fishing reflect moves to areas where the catch rates, on the long term average, are higher. It is unfortunate that hours-fished per day was not recorded in all years of the fishery. While in recent years there is little variation in hours-fished per day per boat there was a wide range of times given in the early years of the fishery and this could have been used to reduce some of the variation in catch rates observed in the fleet. The reason it was not used in the past was because it was believed that using hours-fished would have introduced more uncertainty than it removed. The present inability to track individual vessels through the years of the fishery is also unfortunate as this is often a major source of variation that has little to do with the state of the stock. This problem is being addressed by other projects.

The algorithm used to determine the published catch rates from the 1970s to mid 1980s does not appear to have been recorded appropriately because it was not possible to reproduce the published values from the raw data. Nevertheless, the standardization of catch rates across the years was successful in improving on the simple geometric mean of raw catch rates across the fleet. The data standardization did not take into account the changes in the effectiveness of effort that is a major issue within the Northern Prawn Fishery. Instead, this was estimated from the model.

The non-equilibrium surplus-production model developed for the Northern tiger prawn fishery was described in detail. Minor theoretical advances were made by deriving new closed form estimators for a number of options relating to changing the catchability coefficient (as a proxy for changes in effectiveness of effort). The previously undescribed options were that of a constant absolute annual increment in catchability and a constant proportional increase in catchability. A number of different combinations of model and data were analysed and compared in an effort to determine if any trends visible were a reflection of the data or of the particular model. The model and data combinations compared were the basic model, as described in this work, the same model but constraining the initial biomass in 1970 to equal the long-term unfished average biomass ($B_0 = K$), the basic model but with estimates of the changes in the catchability broken into two independent time series pivoting on 1987 (to reflect the change away from daylight trawling and away from quad-gear. Finally, the basic model was used but additional data, in the form of empirical estimates of the proportional changes to the catchability coefficient, were included in the analysis.

The basic model performed in a stable manner. Unfortunately, the model analyses suggest that despite having a number of years of data from a period when effort had supposedly declined, all indications are that there has been no sign of a stock recovery. With each year of additional data, from 1995, the implications from the model have become extremely dire with the present analysis suggesting that the stock is depleted down to approximately 13% of the unfished biomass (between 9% and 22%). While the uncertainty in this analysis is not small, the indication that there has been severe and ongoing stock depletion is clear. This analysis appears to be inconsistent with that produced from the Wang and Die (1996) model, which suggests that the fishery is near E_{msy}. However, while the effort levels may be close to the predicted optimum, if the stock is in a depleted state, then E_{msy} may not necessarily permit a re-building of the spawning biomass. The model analysis suggests that further reductions in fishing effort are urgently required.

The modifications implemented with the model both corroborated the overall picture of a serious stock decline, however, not unexpectedly, the particular values of particular model parameters altered significantly. The important point to stress is that surplus-production models focus upon the relative productivity of the stock. All the model variants (except that using the empirical estimates of catchability) suggested that the stock is at a low level of productivity at present, which implies that it cannot sustain high levels of catch or effort.

The model with two time series of catchability coefficients is deserving of further investigation. In its present form it suggests that the rate of increase of catchability before 1987 was only half that after 1986. This was inconsistent with the table of independent estimates derived from a consideration of gear and management changes in the fishery (Stirling, 2000). The impact on the effectiveness of effort of the switch to twin trawl gear and the ban on daylight fishing in 1987 is in need of further review. The available data appear to suggest that the switch to night-time trawling for tiger prawns may actually have increased the effectiveness of imposed effort. Because the average number of hours reported fishing per day did not alter greatly in 1987 there was presumably not that much daytime Tiger Prawn fishing or what there was switched to the night-time.

The use of the independent estimates of catchability deriving from Stirling (2000) did not appear consistent with the pattern of standardized catch rates observed in the fishery, nor the severe contraction apparent in the geographical extent of the fishery. This also suggests that a further review of the independent estimates of catchability through time would be valuable.

Finally, a strategy for conducting risk-assessment projections was suggested and illustrated. The trial runs were also not encouraging and suggest the tiger prawn stock is stressed. However, with the change to gear units the quality of fishing effort will change markedly and this means that the suggested algorithm will need to be modified before a formal risk assessment can be undertaken.

Formal papers were presented to the Northern Prawn Fishery Assessment Group during 2000 dealing with the database, the standardization of catch effort data, and the surplus-production model and its results (Haddon & Hodgson, 2000b, 2000c; Hodgson & Haddon, 2000). A less formal paper was produced for the Northern Prawn Fishery Strategic Planning Workshop held in Cairns in June 2000 (Haddon, 2000b, 2000c) dealing with performance indicators and Harvest strategy evaluation. A verbal presentation based upon the same material was presented at the same meeting.

10. Benefits

This study has generated an alternative stock assessment for the Northern tiger prawn fishery, a major component of the Northern Prawn Fishery. As such it provided a needed contrast to the present accepted assessment. It reinforced the need to use performance indicators, such as the stock biomass, that relate to the health of the stock over a series of years, and to develop fishery management targets such as B_{MSY} (known as S_{MSY} in the tiger prawn fishery, standing for spawning stock biomass) instead of, or as well as, the effort target of E_{MSY}. The presently accepted assessment indicates that the fishery is close to E_{MSY} whereas the assessment from this study indicates severe depletion. The two are not inconsistent because an effort of E_{MSY} will only lead to the optimum yield if the stock in at S_{MSY}. If the stock is depleted then E_{MSY} may even lead to greater depletion. Thus, if the results from this study's model are accepted, the overall management advice will be more conservative, which should be beneficial to the stock.

The Fishing Industry may not all appreciate that increasing the number of models used and increasing the number of targets and performance indicators is a positive step. However, by improving our understanding of the uncertainty associated with the stock assessment of the tiger prawn resource the chances of fishery collapse should be reduced. In the end, the Northern Prawn Fishing Industry will benefit from this research.

The review of the internal consistency of the Northern Prawn Database should be of assistance to all researchers using this database for stock assessment purposed in the future.

The general standardization of the data also suggests ways of treating the data to provide summary statistics that could be generated by anyone with access to the raw data.

The modelling developments relating to the new closed form estimators for the changes in catchability, as well as the explicit implementation of one algorithm for generating projections using surplus-production models will be of value to future modellers. Once the risk assessment procedures are developed to become compatible with the recent introduction of gear units, they will become of direct benefit to the Fishing Industry and Managers in the Northern Prawn Fishery.

11. Intellectual Property

No commercial intellectual property arose from this work.

12. Further Work

This project has highlighted to need for the development of more meaningful performance measures for the Northern Prawn Fishery in general and the tiger prawn fishery in particular. The management of the fishery must move away from the using the simple effort based target of attaining E_{MSY} to formally recognizing alternative performance indicators and management targets that more closely reflect the recruitment driven variability of the fished stocks.

The issue of effort creep requires further investigations to obtain a better understanding of the empirical estimates of the yearly proportional increases in catchability that have occurred through the history of the fishery. At present a start has been made but the results obtained to date appear inconsistent with other sources of evidence available for the fishery (such as changing catch rates and a contracting geographical area within which the fishery is prosecuted. Because of the influence upon the assessment of this effort creep, this issue of independent estimates of the increment should receive urgent attention.

The data standardization could be greatly improved if it became possible to follow the fate of individual vessels through the database. Tracing each vessel and provide then each with a unique vessel identity number would entail a great deal of accounting work but should be possible.

The stock assessment used in the Northern tiger prawn fishery should extend the diversity of models used to assess the state of the stock. The model developed in the present work is based upon a yearly time step and has been developed as far as is reasonable. The reduction in stability of this model as more and more years of data are add, in which there is no sign of recovery, indicates that there is a need for a model with a finer time scale. Either a surplus-production model with an explicit monthly time scale or a delay-difference model based upon monthly or fortnightly steps should be developed in the near future.

There is an urgent need to develop means of running risk assessments that can be associated with alternative management strategies. The suggestion implemented in the present work could be developed further to account for the current changes in how effort is managed in the fishery. In addition, alternative algorithms, based more on Monte Carlo methods and less on bootstrap methods, should be developed. In order to take full advantage of the new strategy of adopting gear units to manage effort, the continued development of risk-assessment methods should be receive urgent attention.

13. Staff

Associate Professor Malcolm Haddon	Principal Investigator
Ms Kate Hodgson	Research Assistant

All staff were Marine Research Laboratories, Tasmanian Aquaculture and Fisheries Institute, University of Tasmania. Kate Hodgson was externally funded.

14. Acknowledgements

We would like to thank Janet Bishop for providing us with the database in its raw form. We would also like to thank the members of the Northern Prawn Fishery Assessment Group for their critical commentary on the working papers presented to the working group.

15.

Bibliography

Buckworth, R. (1987) Changes in fishing effort and catching power in the DMZ tiger prawn fishery. *Northern Prawn Fishery Information Notes*, February 1987, CSIRO Division of Fisheries, Cleveland Australia.

Burnham, K.P. & D.R. Anderson (1998). *Model Selection and Inference. A practical Information-Theoretic approach.* Springer-Verlag, New York Ltd. 353p.

Caputi, N. (1993) Aspects of spawner-recruit relationships, with particular reference to crustacean stocks; a review. *Australian Journal of Marine and Freshwater Research 44* : 589

Chatterjee, S. & B. Price (1991) *Regression Analysis by Example*. 2nd Ed. John Wiley & Sons, New York, 278 p.

Crocos, P.J. (1987) Reproductive dynamics of the Tiger Prawn, *Penaeus esculentus*, and a comparison with *p. semisulcatus*, in the north-western Gulf of Carpentaria, Australia. *Australian Journal of Marine and Freshwater Research 38* : 91

Dann, T. & S. Pascoe (1994) *A Bioeconomic Model of the Northern Prawn Fishery*, ABARE Research Report 94.13, Canberra

Die, D. & B. Taylor (comp.) (1997) *Fisheries Assessment Report. Northern Prawn Fishery 1995*. (edited by the Northern Prawn Fishery Assessment Group).

Efron, B. & R.J. Tibshirani (1993) *An Introduction to the Bootstrap.* Chapman & Hall, New York 436 p.

Fox, W.W. (1970) An exponential surplus-yield model for optimizing exploited fish populations. *Transactions of the American Fish Society 99*: 80-88.

Haddon, M. (1996) The use of biomass-dynamic models for short-lived species: the fishery for the Northern Australian tiger prawn. NPFAG Working Paper 96/4, 18p.

Haddon, M. (1997) A biomass-dynamic model of the Northern Tiger Prawn Fishery: An alternative estimate of potential long-term yield. NPFAG Working Paper 97/1, 24p.

Haddon, M. (1998) The use of biomass-dynamic models with short-lived species: Is B0 = K an appropriate assumption? Pp 76-91 in *Statistics in Ecology and Environmental Monitoring* (eds) Fletcher, D.J. & B.F.J. Manly. University of Otago Press, New Zealand.

Haddon, M. (2000a) A stock production model of the Northern Tiger Prawn Fishery: Stock status and potential long-term yields. Unpublished Manuscript.

Haddon. M. (2000b) Management Strategy Evaluation. Northern Prawn Fishery Strategic Planning Workshop; Background Papers for Tuesday 20 June 2000.

Haddon, M. (2001) *Modelling and Quantitative Methods in Fisheries.* Chapman & Hall/CRC. 406 pp.

Haddon, M. & K. Hodgson (2000a) Standardization of Catch/Effort data from the South-East Blue Grenadier trawl fishery – 1986 – 1999. Blue Grenadier Fishery Working Group Paper 00/??

Haddon, M. & K. Hodgson (2000b) Standardization of Catch and Effort data from the Northern Prawn fishery 1970 – 1999: Tiger Prawns. NPFAG Working Document 00/??

Haddon, M. & K. Hodgson (2000c) Preliminary Analyses from a surplus-production model of the Northern Tiger Prawn fishery. NPFAG Working Document 00/??

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

Hodgson, K. & M. Haddon (2000) Spatial errors in the Northern Prawn Fishery Database 1970-1998. NPFAG Working Document 00/??

Klaer, N. L. (1994) Methods for standardisation of catch/effort and data requirements. 86-90 *In*: Hancock, D.A (*ed*) *Population Dynamics for Fisheries Management*. Australian Society for Fish Biology Workshop Proceedings, Perth 24-25 August 1993. Australian Society for Fish Biology, Perth.

Mesplé, F., Troussellier, M., Casellas, C. & P. Legendre (1996) Evaluation of simple statistical criteria to qualify a simulation. *Ecological Modelling 88*: 9-18.

Nelder, J.A. & R. Mead (1965) A simplex method for function minimization. *Computing Journal 7*: 308-313.

Pearl, R. & L.J. Reed (1920) On the rate of growth of the population of the United States since 1790 and its mathematical representation. *Proceedings of the National Academy of Science of the USA 6*: 275-288.

Pella, J.J. & P.K. Tomlinson (1969) A generalized stock-production model. *Bulletin of the Inter-American Tropical Tuna Commission 13*: 421-458.

Polacheck, T., Hilborn, R. & A.E. Punt (1993) Fitting surplus production models: Comparing methods and measuring uncertainty. *Canadian Journal of Fisheries and Aquatic Sciences. 50*: 2597-2607.

Pownall, P.C. (*ed*) (1994) *Australia's Northern Prawn Fishery: the first 25 years*. NPF25, Cleveland, Australia. p 179.

Prager, M.H. (1994) A suite of extensions to a nonequilibrium surplus-production model. *Fishery Bulletin 92*: 374-389.

Press, W.H., Flannery, B.P., Teukolsky, S.A. & W.T. Vetterling (1989) *Numerical Recipes in Pascal. The Art of Scientific Computing.* Cambridge University Press, Cambridge. 759 p.

Punt, A.E. (1990) Is B1 = K an appropriate assumption when applying an observation error production-model estimator to catch-effort data? *South African Journal of Marine Science. 9*: 249-259.

Punt, A.E. (1992) Selecting management methodologies for marine resources, with an illustration for South African hake. *South African Journal of Marine Science 12*: 943-958.

Rivard, D. & L.J. Bledsoe (1978) Parameter estimation for the Pella-Tomlinson stock production model under non-equilibrium conditions. *Fishery Bulletin 76*: 523-534.

Robins, C. and I. Somers (1994) Fishery statistics. p 141-164 *In*: Pownall, P.C. (*ed*) (1994) *Australia's Northern Prawn Fishery: the first 25 years*. NPF25, Cleveland, Australia. p. 179.

Robins, C.M., Wang, Y., & D. Die (1998) The impact of Global Positionnig Systems and plotters on fishing power in the Northern Prawn Fishery, Australia. *Canadian Journal of Fisheries and Aquatic Sciences* **57**: 1123-1135.

Sachse, M. (1994) Monitoring Systems. p 165-169 In: Pownall, P.C. (ed) (1994) Australia's Northern Prawn Fishery: the first 25 years. NPF25, Cleveland, Australia. p 179.

Sachse, M. and C. Robins (1996) *Northern Prawn Fishery Data Summary 1995*. AFMA & CSIRO, Australia. 26 p.

Schaefer, M.B. (1954) Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Bulletin, Inter-American Tropical Tuna Commission 1*: 25-56.

Schaefer, M.B. (1957) A study of the dynamics of the fishery for yellowfin tuna in the Eastern Tropical Pacific Ocean. *Bulletin, Inter-American Tropical Tuna Commission 2*: 247-285

Schnute, J. (1977) Improved estimates from the Schaefer production model: Theoretical considerations. *Journal of the Fisheries Research Board of Canada 34*: 583-603.

Sokal, R.R. & F.J. Rohlf (1995) *Biometry.* 3rd ed. WH Freeman and Cp. New York. 887p.

Somers, I.F. (1987) Sediment type as a factor in the distributions of commercial prawn species in the Western Gulf of Carpentaria, Australia. *Australian Journal of Marine and Freshwater Research 38* : 133

Somers, I. (1990) Expected long term average catch in the NPF. *Australian Fisheries 49*: 16-20.

Somers, I. (1994a) Counting prawns: Stock Assessment. p 89-102 *In*: Pownall, P.C. (*ed*) (1994) *Australia's Northern Prawn Fishery: the first 25 years*. NPF25, Cleveland, Australia. p 179.

Somers, I.F.(1994b) Species composition and distribution of commercial Penaeid prawn catches in the Gulf of Carpentaria, Australia, in relation to depth and sediment types. *Australian Journal of Marine and Freshwater Research 45* : 317

Taylor, B. (1994) A delicate balancing act: Management of the fishery. p 113-130 *In*: Pownall, P.C. (*ed*) (1994) *Australia's Northern Prawn Fishery: the first 25 years*. NPF25, Cleveland, Australia. p 179.

Taylor, B. (1994) Chronology of Closures. p 171-174 *In*: Pownall, P.C. (*ed*) (1994) *Australia's Northern Prawn Fishery: the first 25 years*. NPF25, Cleveland, Australia. p 179.

Wang, Y. and D. Die (1996) Stock-recruitment relationships of the Tiger Prawns (*Penaeus esculentus* and *Penaeus semisulcatus*) in the Australian Northern Prawn Fishery. *Marine and Freshwater Research 47*: 87-95.

16. Appendices

16.1 Appendix 1 - Derivation of Equilibrium based stock-production

The steps between Eq. 6.3 and Eq. 6.6 are as follows:

$$B^* = B^* + \frac{r}{p} B^* \left(1 - \left(\frac{B^*}{K} \right)^p \right) - C^* \tag{A.1}$$

where the * superscript denotes an equilibrium level. The left hand B^* and first B^* on the right hand side can be cancelled and the C^* can be moved across:

$$C^* = \frac{r}{p} B^* \left(1 - \left(\frac{B^*}{K} \right)^p \right) \tag{A.2}$$

substituting $B^* = C^*/qE^*$ (Eq. 10.5), by assuming equilibrium at all times, we obtain:

$$C_t = \frac{rC_t}{pqE_t} \left[1 - \left(\frac{C_t}{qE_t K} \right)^p \right] \tag{A.3}$$

$$pqE_t = \frac{rC_t}{C_t} \left(1 - \left(\frac{C_t}{qKE_t} \right)^p \right) \tag{A.4}$$

$$\frac{pqE_t}{r} = 1 - \left(\frac{C_t}{qKE_t} \right)^p \tag{A.5}$$

$$\left(\frac{C_t}{qKE_t} \right)^p = 1 - \frac{pqE_t}{r} \tag{A.6}$$

$$\frac{C_t^p}{(qK)^p E_t^p} = 1 - \frac{pqE_t}{r} \tag{A.7}$$

$$\frac{C_t^p}{E_t^p} = (qK)^p - \frac{pq^p K^p E_t}{r} \tag{A.8}$$

$$\left(\frac{C_t}{E_t} \right)^p = (qK)^p - \frac{pq^{p+1} K^p E_t}{r} \tag{A.9}$$

and finally:

$$\frac{C_t}{E_t} = \left[\left(qK \right)^p - \frac{pq^{p+1} K^p E_t}{r} \right]^{\frac{1}{p}} \tag{A.10}$$

If we re-parameterize by defining $(qK)^p$ to be a new parameter *a*, and the second term: $(pq^{p+1})/r$ to be the new parameter *b*, this would lead to the form:

$$\frac{C_t}{E_t} = \left(a - bE_t \right)^{\frac{1}{p}} \tag{A.11}$$

If $p = 1$, Eq. A.11 collapses to C/E = (a – bE).

16.2 Appendix 2 - Closed Form Estimates of the Catchability Coefficient

16.2.1 Version 1: Constant q

Derivation of the statement that we can directly estimate the value of *q*, which relates to the maximum likelihood fit of the model, by using the geometric average of the time series of *q* estimates $I_t / \hat{B}_t$:

$$\hat{q} = e^{\frac{1}{n}\sum \ln\left(\frac{I_t}{\hat{B}_t}\right)} \qquad \text{(A.12)}$$

By definition we have: $\hat{I}_t = \hat{q}_t \hat{B}_t$ (A.13)

where $\hat{I}_t$ is the expected CPUE in a given year *t*, $\hat{q}_t$ is the expected catchability coefficient in year *t*, and $\hat{B}_t$ is the predicted biomass in year *t*. However, the assumption is that the catchability coefficient is a constant and each $\hat{q}_t$ is only an estimate of the overall $\hat{q}$. We can either directly estimate this expected catchability coefficient by using non-linear estimation or we can modify Eq. A.13 to include observed data instead of purely expected values. In this way we can generate the expected catchability coefficient; this is known as a closed form of the equation.

Using observation errors which are lognormal, multiplicative, and with a constant variance, we could fit the model using the sum of squared residuals criterion. The model residuals are related to the observed data in the usual way for log-normal errors:

$$I_t = \hat{I}_t e^{\varepsilon} \quad \text{or} \quad \frac{I_t}{e^{\varepsilon}} = \hat{I}_t \qquad \text{(A.14)}$$

where $\mathbf{I_t}$ is the observed CPUE in a given year *t*. In order to obtain the closed form of Eq A.13, we can substitute the right hand version of Eq. A.14 into Eq A.13 to include the observed CPUE values instead of the expected values:

$$\frac{I_t}{e^{\varepsilon}} = \hat{q}_t \hat{B}_t \qquad \text{(A.15)}$$

which is equivalent to:

$$I_t = \hat{q}_t \hat{B}_t e^{\varepsilon} \quad \text{or} \quad \frac{I_t}{\hat{B}_t} = \hat{q}_t e^{\varepsilon} \qquad \text{(A.16)}$$

and log-transforming this gives:

$$Ln\left(\frac{I_t}{\hat{B}_t}\right) = Ln\left(\hat{q}_t\right) + \varepsilon \qquad \text{(A.17)}$$

The value of $\hat{q}$ that minimizes the residuals, ε, in Eq A.17 (remember because of the normalized error term this would be the same as maximizing the likelihood) would be the value which minimized the residuals of Eq. A.17 for all the observed values of catch-effort (**I_t**) and biomass **B_t**. If there are *n* observations then the best estimate of the log of the constant, $\hat{q}$, is simply the mean of the *t* estimates from the set of observed catch-effort values with associated expected biomass values:

$$Ln(\hat{q}) = \frac{\sum_{t=1}^{n} Ln(\hat{q}_t)}{n} = \frac{\sum Ln\left(\frac{I_t}{\hat{B}_t}\right)}{n} \tag{A.18}$$

To obtain the expected value of *q* we clearly need to anti-log the outcome of Eq. A.18 which is, in fact, the geometric mean of the original estimates of q_t :

$$\hat{q} = e^{\frac{1}{n}\sum Ln(\hat{q}_t)} = e^{\frac{1}{n}\sum Ln\left(\frac{I_t}{\hat{B}_t}\right)} \tag{A.19}$$

16.2.2 Version 2: Additive Increment to Catchability

In the case where the catchability is assumed to increase by a constant absolute amount each year then the *q* value for each year, q_t can be determined using a simple linear equation:

$$q_t = q_0 + t \times q_{add} \tag{A.20}$$

where q_t is the catchability in year *t*, q_0 is the catchability in the first year for which data is available (time zero), and q_{add} is the constant absolute amount by which the catchability is incremented each year. Estimation of the two parameters involves finding the gradient, q_{add}, and intercept, q_1, of a linear regression between q_t and time *t*, where *t* ranges from 0 to n-1 years (a total of n years).

In the model, for each year, the implied estimate of q_t is obtained by dividing each observed catch rate (I_t) by the estimated biomass for that year:

$$\hat{q}_t = \frac{I_t}{\hat{B}_t} \tag{A.21}$$

In the maximum likelihood fit, one would have a time series of expected catchability coefficients which would be described in the model by equation A.20 or A.21. Equation A.20 has the form of a linear regression, so the equations to find the closed form parameter estimates are thus:

$$q_{add} = \frac{\sum_{0}^{n-1}\left((t-\bar{t})\left[\left(\frac{I_t}{B_t}\right) - \left(\sum\left(\frac{I_t}{B_t}\right)\right)/n\right]\right)}{\sum(t-\bar{t})^2} \tag{A.22}$$

$$q_0 = \frac{\sum\left(\frac{I_t}{B_t}\right)}{n} - \left(q_{add}\right)\bar{t} \qquad \text{(A.23)}$$

where n is the number of years of data, t-bar is the mean of the t values representing the 0 to n-1 years of data (i.e. with 9 years of data t-bar would equal 4.0, *i.e.* the mean of 0…8).

By estimating these parameters using the closed form the number of parameters directly estimated by the fitting procedure is reduced, which simplifies the procedure and speeds the process.

16.2.3 Version 3: Constant Proportional Increase - q_{inc}

In the case where the catchability is assumed to increase annually by a fixed proportion then the q value for each year q_t is determined as in exponential growth or compound interest :

$$q_t = q_0 \times qinc^t \qquad \text{(A.24)}$$

which, when log-transformed takes the form:

$$Ln\left(q_t\right) = Ln\left(q_0\right) + t \times Ln\left(q_{inc}\right) \qquad \text{(A.25)}$$

where t ranges from 0 to n-1 years. In the final maximum likelihood fit one would have a time series of expected catchability coefficients which would be described in the model by the equation A.24 or A.25 (*cf*. Fig. A10.1).

Thus, the estimation of the two parameters involves finding the gradient ($Ln(q_{inc})$) and intercept ($Ln(q_0)$) of a linear regression between $Ln(q_t)$ and time t, where time t ranges from 0 to n-1 years. The equations are thus:

$$Ln\left(q_{inc}\right) = \frac{\sum_{0}^{n-1}\left(\left(t-\bar{t}\right)\left[Ln\left(\frac{I_t}{B_t}\right) - \left(\sum Ln\left(\frac{I_t}{B_t}\right)\right)/n\right]\right)}{\sum\left(t-\bar{t}\right)^2} \qquad \text{(A.26)}$$

$$Ln\left(q_0\right) = \frac{\sum_{t=0}^{n-1} Ln\left(\frac{I_t}{B_t}\right)}{n} - Ln\left(q_{inc}\right)\bar{t} \qquad \text{(A.27)}$$

where n is the number of years of data, t-bar is the mean number of years of data. The final parameter estimates are determined by anti-logging the values from Eqs. A.26 and A.27.

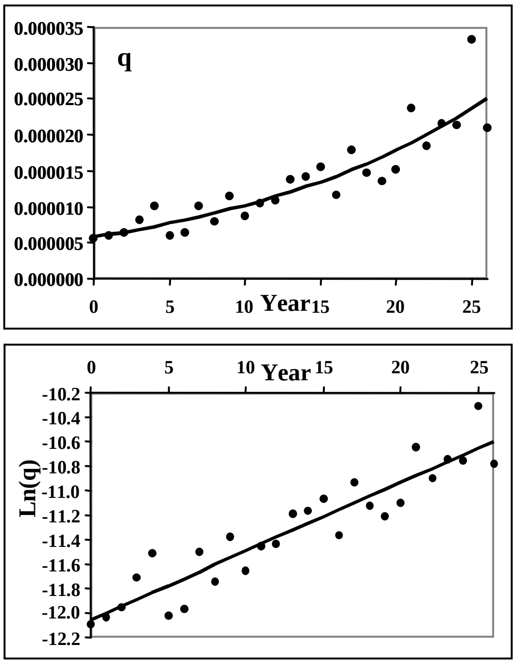

Figure A10.1. The top panel is the final distribution of expected catchability coefficients with the fitted curve of form Eq. A.24. In order to estimate the two parameters q_0 and q_{inc} instead of a simple geometric average of the expected q values we have to fit the curve. By log-transforming each q_t value and plotting these against the number of times the q_{inc} is applied to the starting value a straight line is obtained as in the lower panel. The straight line is defined by Eq. A.25, so the two parameters may be determined by anti-logging the two parameters from the linear regression. Data is a bootstrap sample from the northern Australian tiger prawn fishery (see Example Box 10.6).

16.3 Appendix 3 – Simplification of the maximum likelihood estimator

Showing the simplification of the Maximum Likelihood estimator for log-normal random errors. Given :

$$\mathrm{L}\left(\text{data}|B_0, r, K, q\right) = \frac{1}{\sqrt{2\pi}\hat{\sigma}} \prod_t e^{\frac{-\left(\mathrm{Ln}\, I_t - \mathrm{Ln}\, \hat{I}_t\right)^2}{2\hat{\sigma}^2}} \quad \text{(A.28)}$$

we can convert this to a log-likelihood:

$$LL = \sum Ln\left[\frac{1}{\sqrt{2\pi}\hat{\sigma}} e^{\frac{-\left[\left(Ln(I_t) - Ln(\hat{I}_t)\right)^2\right]}{2\hat{\sigma}^2}}\right] \quad \text{(A.29)}$$

Simplifying this by removing constants from the summation and cancelling the Ln and *e*, we obtain:

$$LL = nLn\left(\frac{1}{\sqrt{2\pi}\hat{\sigma}}\right) + \frac{1}{2\hat{\sigma}^2} \sum\left[-\left[\left(Ln(I_t) - Ln(\hat{I}_t)\right)^2\right]\right] \quad \text{(A.30}$$

where the maximum likelihood estimator of the standard deviation σ is given by:

$$\hat{\sigma} = \sqrt{\frac{\sum\left[\left(Ln(I_t) - Ln(\hat{I}_t)\right)^2\right]}{n}} \quad \text{(A.31)}$$

Note the division by *n* instead of *n*-1 to give the maximum likelihood estimate (Neter *et al*. 1996). Given Eq. A.31, we can simplify Eq. A.30 much further by substituting one into the other:

$$LL = nLn\left(\frac{1}{\sqrt{2\pi}\hat{\sigma}}\right) + \frac{-\sum\left(Ln(I_t) - Ln(\hat{I}_t)\right)^2}{\frac{2\sum\left(Ln(I_t) - Ln(\hat{I}_t)\right)^2}{n}} \quad \text{(A.32)}$$

Both of the terms can be further simplified:

$$LL = nLn\left(\left[\sqrt{2\pi}\hat{\sigma}\right]^{-1}\right) + \left(\frac{-1}{2/n}\right) \quad \text{(A.33)}$$

which simplifies again to become:

$$LL = -nLn\left(\sqrt{2\pi}\hat{\sigma}\right) - \frac{n}{2} \quad \text{(A.34)}$$

A little algebra leads to an alternative final version in A.38:

$$LL = -n\left[Ln\left(\left[2\pi\right]^{\frac{1}{2}}\right) + Ln\left(\hat{\sigma}\right)\right] - \frac{n}{2} \tag{A.35}$$

$$LL = -n\left[\frac{1}{2}Ln\left(2\pi\right) + Ln\left(\hat{\sigma}\right)\right] - \frac{n}{2} \tag{A.36}$$

$$LL = -\frac{n}{2}\left(Ln\left(2\pi\right) + 2Ln\left(\hat{\sigma}\right)\right) - \frac{n}{2} \tag{A.37}$$

$$LL = -\frac{n}{2}\left(Ln\left(2\pi\right) + 2Ln\left(\hat{\sigma}\right) + 1\right) \tag{A.38}$$

16.4 Appendix 4. The Model Equations

The basic dynamics of the stock are described by:

$$B_{t+1} = B_t + \frac{r}{p} B_t \left[1 - \left(\frac{B_t}{K} \right)^p \right] - C_t \qquad \text{Eq. (A.39)}$$

$$I_t = \frac{C_t}{E_t} = q_t B_t e^{\varepsilon} \qquad \text{Eq. (A40)}$$

where B_t is the stock biomass at the start of year *t*, *r*, *K*, and *p*, are parameters of the model, C_t is the catch in year *t*, e^{ε} denotes lognormal residuals errors, and E_t is the effort in year *t*. The parameter *p* was constrained to be greater than zero. Equations A.39 and A.40 imply that the dynamics are deterministic but that observations of catch rates are made with error (we are using an observation error model). The catchability coefficient q_t in year *t* is defined by the closed form equation:

$$q_t = q_0 \times q_{inc}^t \qquad \text{Eq. (A.41)}$$

where q_0 is the catchability in the first year and *t* ranges from 0 to 29. Closed form estimates of q_0 and q_{inc} can be obtained if we log-transform the Eq. A.41 to give it the form of a linear regression:

$$\mathrm{Ln}(q_t) = \mathrm{Ln}(q_0) + t \times \mathrm{Ln}(q_{inc}) \qquad \text{(A.42)}$$

The model is fitted to the data using maximum likelihood to fit the expected catch rates to those observed:

$$LL = -\frac{n}{2}\left[Ln(2\pi) + Ln(\hat{\sigma}^2) + 1 \right] \qquad \text{Eq. (A.43)}$$

where

$$\hat{\sigma}^2 = \frac{\sum \left(Ln(I_t) - Ln(\hat{I}_t) \right)^2}{n} \qquad \text{Eq. (A.44)}$$

and I_t is the catch-per-unit-effort during time *t*, and *n* is the number of years of CPUE data available. Model outputs included:

$$E_{MSY} = \frac{r}{q(p+1)} \qquad \text{Eq. (A.45)}$$

$$MSY = \frac{\mathrm{rK}}{(\mathrm{p}+1)^{\frac{(p+1)}{p}}} \qquad \text{Eq. (A.46)}$$

Given the MSY the B_{MSY} (the biomass that would give rise to the MSY given E_{MSY}) can be determined by a simple search routine or by using $B_{MSY} = MSY/(qE_{MSY})$.

The instantaneous fishing mortality rate can be estimated using the standard catch equation so that instantaneous fishing mortality relates to expected effort and the catchability coefficient, q (which would be a combination of q_0 and $qinc$):

$$F_t = qE_t = q\frac{C_t}{C_t / E_t} = q\frac{C_t}{\hat{I}_t} \qquad \text{Eq. (A.47)}$$

The instantaneous fishing mortality rate at MSY, F_{MSY}, would be:

$$F_{MSY} = \frac{r}{p+1} \qquad \text{Eq. (A.48)}$$

$F_{0.1}$ is assumed to be approximately 90% of F_{MSY}.