An Optimization Model for the Banana Northern Prawn Fishery

Simone Valle de Souza*, Cedric Gondro[τ], Oscar Cacho*

*Agricultural and Resource Economics, School of Business, Economics and Public Policy,
University of New England, Australia
[τ]The Centre for Genetic Analysis and Applications
School of Environmental and Rural Science, University of New England, Australia

This study presents an optimal control model of the Banana Northern Prawn Fishery, one of the most important fisheries in Australia. The life cycle of this species involves migration between the sea, where the catch takes place, and the estuary, where post-larvae and juveniles develop. The model combines a stage-matrix population dynamics model and an economic model of sustainable catch. The controls involve the amount of effort allowed and the length of the fishing season. Life stages are defined in terms of prawn size, allowing catch revenue to be adjusted to the expected proportion of specific sized classes caught in a particular month of the year, hence providing a more realistic projection of profits when price is influenced by size. The model is calibrated based on 18 years of detailed catch data.

Key words: fisheries management, Australia, optimal control, profit maximisation, banana prawns.

Paper presented at the 54th Annual Conference of the Australian Agricultural and Resource Economics Society, Adelaide, February 10-12, 2010

1. Introduction

The Northern Prawn Fishery (NPF) is one of Australian's most mature and valuable fisheries (Wang & Die 1996) with a catch of more than 5,000 tonnes in 2005 (Vieira & Perks 2009) and worth about A$72m in 2008 (AFMA 2010), with more than 90 per cent of the catch exported to Japan, China, Spain and Hong Kong (AFMA 2005). In this multispecies fishery, three of the eight prawn species commercially harvested represent almost 80% of the annual average catch (Wang & Die 1996), the banana prawn (*Penaeus merguiensis*), the brown tiger prawn (*Penaeus esculentus*) and the grooved tiger prawn (*Penaeus semisulcatus*). Other species caught in the NPF are endeavour prawns (*Metapenaeus endeavouri* and *Metapenaeus ensis*) and red legged banana prawns (*F. indicus*) (Kompas & Che 2004). The average distribution of catch between banana and tiger prawns, from 1970 to 2005 was 40% tiger prawns, both brown and grooved, and 60% banana prawns.

Despite the smaller proportion caught, tiger prawns have represented most of the revenues in the last 5 years because of their higher market price. Since 2006 tiger prawn average price has been AU$19.20 per kg, while banana prawns had an average price of AU$9.50 per kg.

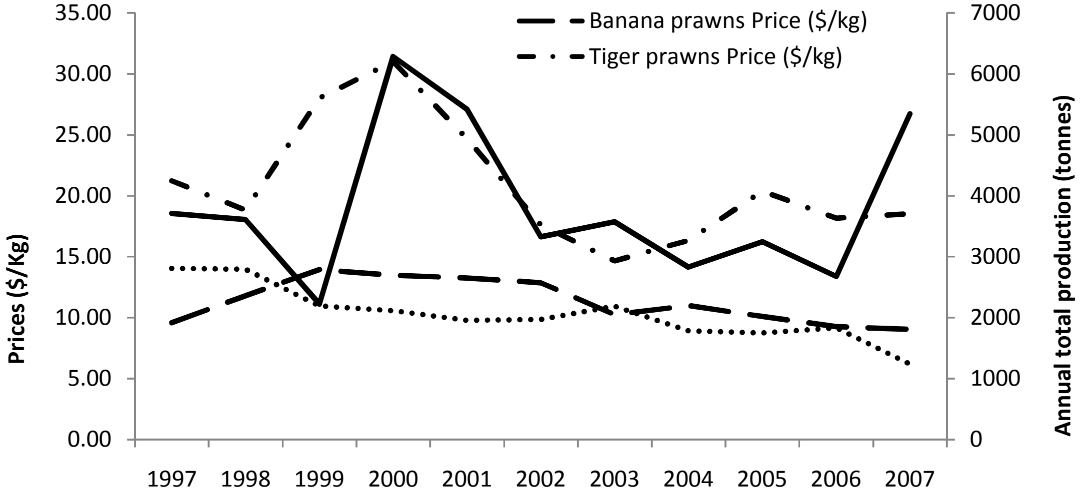

Figure 1: Prices of banana and tiger prawns caught in the NPF from 1999 to 2007 and equivalent yearly production. Source: Australian Fisheries Statistics 2000 to 2009 (ABARE, 2000-2010).

Even with the considerably higher price of tiger prawns, the increase in banana prawn catches raised NPF's gross value of production by 12% from the 2006-2007 season to the 2007-2008 season (Vieira and Perks 2009). While tiger prawn catches reached their lowest level in 2008 since the opening of the fishery, banana prawn catches had their highest catch since 2002 (Figure 1). There is no evidence of fishers transferring effort from banana prawn to tiger prawn fishery (Figure 2). What can be seen is a small variation from a 10 years average of catch per unit of effort in tiger prawn fishery, around 0.22 tonnes per boat days, while banana prawn fishery catches per unit of effort follows a steep growth trend since 1978 having reached 1.74 tonnes per boat days in 2008 to be compared against an average of 0.95 during the last 10 years.

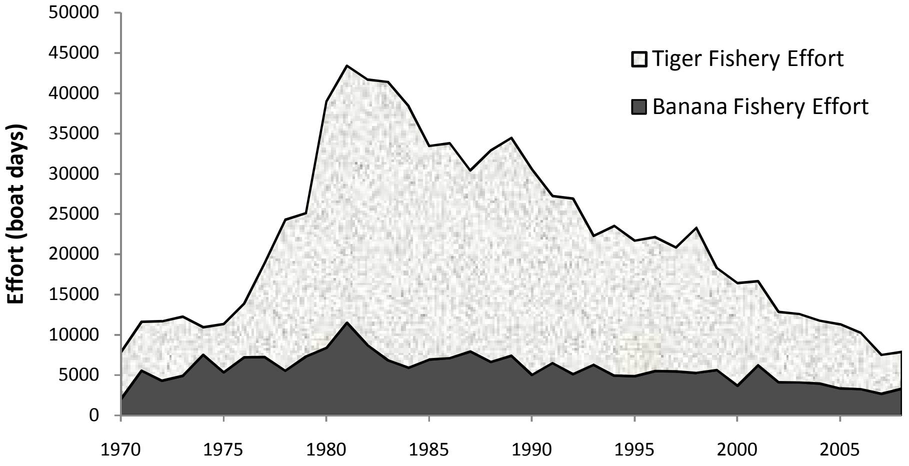

Figure 2: Total effort in boatdays applied to tiger and banana prawn fisheries from 1970 to 2008. Source: NPF Data Summary 2008.

Estimates of catch per unit of effort reveal the difference between the amounts of effort applied to catch tiger prawns in relation to banana prawns. The aggregation behavior, a particular characteristic of the banana prawn population (Die and Ellis 1999), not common in the Penaeid family, can explain the different effort effectiveness in the Banana Northern

Prawn Fishery. The other members of this family tend to be uniformly distributed over their habitat (Lucas, Kirkwood et al. 1979) but banana prawns form aggregations at about 13 to 20 meters depth (Munro 1975) after migrating about 32 km seaward, which occurs when they reach early juvenile stages. These aggregations lift bottom sediments that surface, being easily spotted by small spotter planes, color echo-sounders and vessels' crew members (Die and Ellis 1999; Vance, Bishop et al. 2003). This normally occurs from early March to September (Munro 1975). During this period, a range of prawns from 20 to 45 mm carapace length can be found in the fishery catches.

The optimal model developed below is based on the assumption that the vulnerability of the aggregations formed by this species allows graded catch data to be used as a proxy for population when dividing population into life stages and estimating parameters of recruitment between life-stages. The model requires at least monthly catchability rate in calculating effects of catch specifically on banana prawn populations. Although this is a multispecies fishery the optimal effort can be specified for the banana prawn fishery only because vessels targeting banana prawns operate during the day due to the aggregation behavior of these prawns, while tiger prawns are caught at night. Furthermore the banana prawn season occurs during the early months of the year, while tiger prawns are caught in later months (Die and Ellis 1999). The model uses a profit maximizing algorithm for testing the effects of policies adjusting sustainable levels of effort.

2. Characteristics of Prawn Population

As with many species of Penaeid prawns, the prawns of the Gulf migrate between different habitats during their one-year life cycle (Vance, Bishop et al. 2003). The eggs are spawned in offshore waters (Fig.3) and shed into the sea, differently from other shrimps, crabs or lobsters

(Rothlisberg and Staples 1983). After about three days eggs hatch in the open sea (Munro 1975) and larvae (*nauplius*) move inshore and settle in the upper estuarine of mangrove-lined creeks and rivers after about a month (Somers 1990). Their avection occurs with the tidal and wind-driven currents from offshore waters to estuarine areas. After 2 or 3 days, *nauplius* develop into *zoea*, which in a week grow into the *mysis* phase completing the post-larvae phase after another week (Munro 1975; Vance, Bishop et al. 2003). Post larvae and juveniles can be found in rivers all through the year but are more active and abundant in summer (Munro 1975). The smallest juveniles start to appear in November according to sampling done by Munro (1975) in 1966 to 1968, which assessed composition of a virgin stock before commercial exploitation of the fishery started. After one or two months of rapid growth, still during summer (Munro 1975; Rothlisberg and Staples 1983; Kompas and Che 2004) or wet season (Vance, Haywood et al. 1998), juvenile prawns migrate offshore. By the end of March male juveniles have grown into sexually mature adolescents (Munro 1975) while females will only achieve maturity after migrating into the sea, when they reach their adult stage. Both ages, adolescents and adults, are targeted by commercial fisheries. Females mature by about 6 months of age producing up to half million eggs per spawning (Somers 1990; Vance, Bishop et al. 2003), when they are at 16 to 32 km offshore and at carapace length in excess of 30 mm (Munro 1975). In the southeast of the Gulf of Carpentaria, the spawning of banana prawns occurs throughout the year (Vance, Bishop et al. 2003) at monthly intervals (Munro 1975) but a large peak occurs during the months of March and April and a smaller peak occurs in September and October (Staples and Vance 1986). However these peaks can vary in different regions, mainly due to characteristics of the region’s wet season (Rothlisberg and Staples 1983). For example, in the South East spawning occurs mostly during autumn while in the west the September-October peak is much larger than the autumn peak and in the North East a much higher year-round background level of reproduction is identified (Staples 1983).

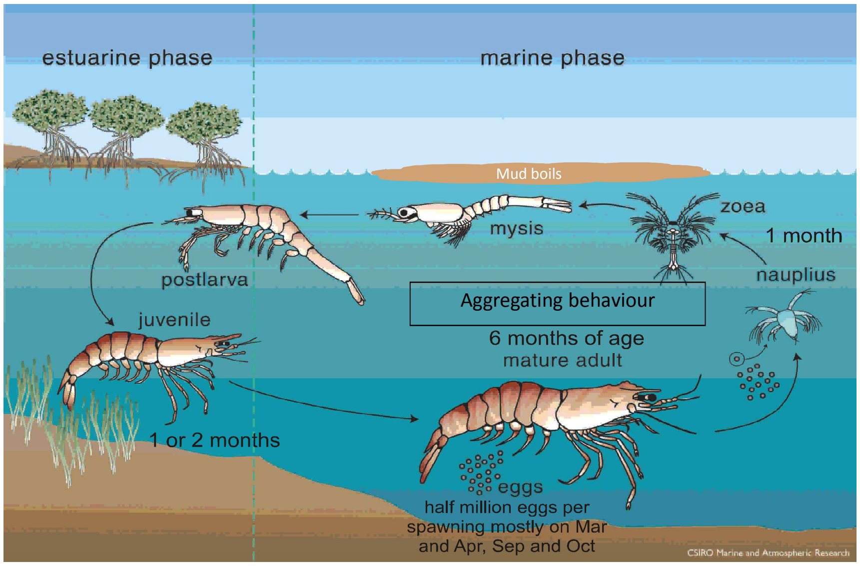

Figure 3: Life cycle of a Penaeid prawn in the Gulf of Carpentaria, Australia (Source: (Vance, Bishop et al. 2003), diagram by Louise Bell, supplied by the CSIRO Marine and Atmospheric Research)

3. Management Controls

Since 1987 the Northern Prawn Fishery was opened annually for two seasons from April to May and sometimes early June and later from August, or sometimes late July, to November. During the last 20 years the number of weeks per season was reduced from 34 to about 23 weeks (Vance *et al.* 2003). Season dates vary every year generally coinciding with spawning and recruitment phases of prawn populations (Kompas & Che 2004). The mid-season closure is set to reduce fishing effort for brown tiger prawns (Wang & Die 1996). The first season is called the banana prawn season while the second is the tiger prawn season according to their main catches. These season regulations operate in combination with spatial controls, gear restrictions and controls of catch per unit of effort (CPUE) exerted by fully transferable Statutory Fishing Rights (SFRs), which regulates the length of head rope and thereby the size of the net that may be towed by vessels. Fishers are then allocated a share of the total gear pool based on the NPF Management Plan. The size of the gear pool is adjusted before the season according to current stock levels (AFMA 2005). The fully transferable Statutory Fishing Rights (SFRs) hence determine the number of trawlers and amount of gear used in the fishery (Haine & Garvey 2005).

These input controls currently applied by the Northern Prawn Fishery management authority balance spawning stock and subsequent recruitment and, in turn, recruitment and subsequent spawning stock while attempts are made to maximise banana prawn yields by adjusting the seasonal open dates (Somers 1990). Other control mechanisms include limited entry, permanent area closures and other operational controls.

4. An Optimization Model for the Banana Northern Prawn Fishery

The optimization algorithm searches for the most efficient distribution of effort within bounds of season closures, based on catchability coefficients given in vector $\mathbf{C}_t$ and given cost of effort and price of adults and juvenile prawns. The most efficient distribution of effort is defined as the one that offers the maximum NPV for a given number of years.

The optimization model follows the standard format:

$$Max\pi = \sum_t v_t(\mathbf{X}_t, U_t)\delta_t \tag{1}$$

where the state variable ($\mathbf{X}$) is the population of prawns, the control variable (U) effort, and δ is the monthly discount factor. The optimization is subjected to the state transition function:

$$\begin{aligned} &\mathbf{X}_{t+1} - \mathbf{X}_t = G(\mathbf{X}_t, U_t) \\ &\mathbf{X}_0 = given \end{aligned} \tag{2}$$

where $\mathbf{X_t}$ is a vector of the number of individuals divided into seven life-stages. $\mathbf{X_0}$ is given from catch data. The net population growth function is:

$$G_t(\mathbf{X}_t, U_t) = \mathbf{L}\mathbf{X}_t - \mathbf{X}_t \circ \mathbf{Q}_t U_t \tag{3}$$

where **L** is a stage population matrix representing the state transition within the population, **Q** is a vector of catchability coefficients per life stage, and U represents effort in units of boat days.

The vulnerability of banana prawns due to their aggregating behavior is the main assumption for the parameterization of the **L** matrix and the **Q** vector. This assumption has also been used by Die and Ellis (1999) to estimate population changes. From the number of aggregations in a season, the number of vessels targeting each aggregation and the number of aggregations targeted each fishing day, Die and Ellis estimated biomass decreases during the fishing season to determine biomass changes. Abundance was estimated based on catch and average size of prawns caught showing a decrease in biomass of aggregating prawns of 99% in the third week of the season while catch per unit of effort data showed a decrease of only 66% of biomass (Die and Ellis 1999). This suggests that the catchability of banana prawns, calculated as the proportion of the total population caught per unit of effort, changes as biomass decreases during the fishing season (Die and Ellis 1999; Vance, Bishop et al. 2003).

5. Data and Methods

The dataset used here was supplied by the Northern Prawn Fishery management and comprises 18 years, from 1991 to and inclusive of the first 4 weeks of the 2008 season. The data provide daily catch classified into more than 100 grades in count per pound (*cplb*). These data were converted into grams and then to carapace length using the coefficients in Table 1.

Table 1: Life stages and their conversion from size of prawns into count-per-pound (*cplb*).

life stages		**max carapace length (*mm*)**		**min number of prawns (*cplb*)**	
		Male	**female**	**male**	**female**
1	**E&PL**	3.6			
2	**J1**	*7.8*		*~ 2000*	
3	**J2**	*10.5*		*~ 500*	
4	**J3**	*12.6*		*~ 300*	
5	**J4**	*13.7*		*~ 200*	
6	**J5**	*26*	*30*	*more than 30*	*more than 21*
7	**A**	*42*	*46*	*6*	*6*

Size per age data of banana prawns in the Gulf of Carpentaria, collected in previous research (Munro, 1975) was used to build a von Bertlanffy growth curve (Fig.4) on carapace length (z in mm) using:

$$z = \alpha_L \left(1 - e^{-\beta_{L,i}(t-t_0)}\right) \tag{4}$$

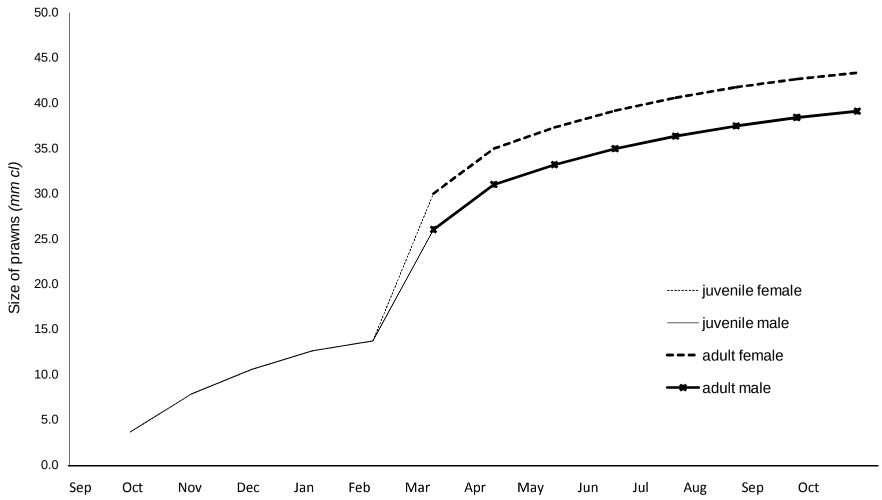

Figure 4: Individuals’ growth curve based on a von Bertalanffy equation using data from Munro (1975).

Carapace length is converted into weight (w in g) as:

$$w = \alpha_W z^{\beta_W} \tag{5}$$

Catch data is converted from grade (size) of the prawns into count per pound (*cplb*) using:

$$cplb = {}^{1000}\!/_{2.24w} \tag{6}$$

where *cplb* is relevant only for juveniles and adults aged 5 to 12 months.

5.1. Stage Population Matrix

The basic dynamics of fish populations are defined by three components: recruitment, growth and mortality (Quinn and Deriso 1999), which in our model are translated into number of individuals passing from one size-classified category to the next (Caswell 1989) or remaining on the same stage for another period. Stage-based matrix models are flexible for animals that can remain several time steps within one stage, not necessarily similar to the number of time steps on other stages (Miller 2001, Holland & Brazee 1996) as they function on a discrete time or stage step (Caswell 2000).

Life stages of banana prawns in our stage-population matrix are eggs, post-larva, juveniles and adults. The juvenile and adult stages are divided into sub-stages for a total of seven life stages (Table 1). The cutoff sizes to classify the life stages were selected to allow stage transitions to occur within a monthly time step (Fig.5).

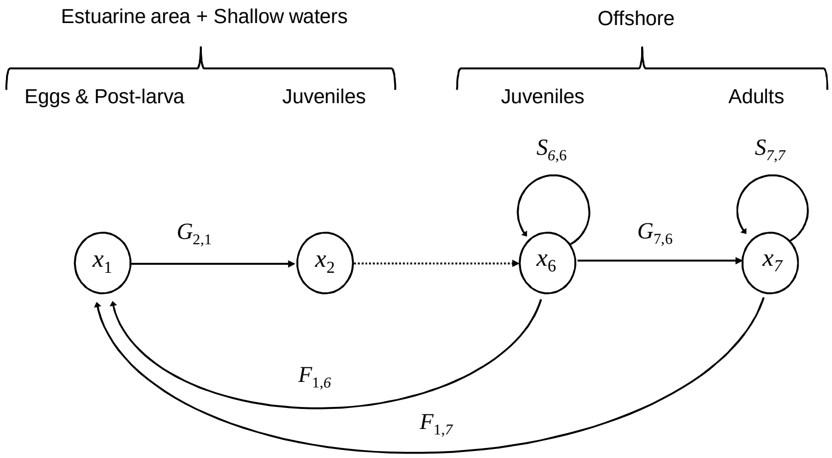

Figure 5: The size-classified life cycle of banana prawns described by the matrix model.

The fertility coefficient $F_{1,j}$ represents the number of eggs produced per individual in life stage *j*, generating recruitment. The growth rate $G_{i,j}$ represents the proportion of individuals in life stage *j* at time *t* that survive and grow into stage *i* at time *t+1*; whereas the survival rate $S_{i,i}$, represents the proportion of individuals that survive and remain in the same life stage *i*.

The population dynamics of banana prawns is represented by the stage matrix **L** of dimensions *n* x *n* and a population vector **X** of dimensions *n*, where *n* is the number of life stage (*n*=7 here). The matrix product **LX** forms a system of equations for population growth. The stage matrix is:

$$\mathbf{L} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & F_{1,6} & F_{1,7} \\ G_{2,1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & G_{3,2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & G_{4,3} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{5,4} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{6,5} & S_{6,6} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{7,6} & S_{7,7} \end{bmatrix} \tag{7}$$

where the first row represents fertility rates (*F*) of age-classified life stages; the diagonal represents the survival rates (*S*) of each stage and the sub-diagonal represents growth (*G*) from one stage to the next (Caswell 1989)

5.2. Catch

The fishing season is represented by a set of monthly vectors q_m, with elements specific to each life stage. Vector $\mathbf{Q}_t$ represents the q_m that applies to the particular month. Only large juveniles and adults are caught, therefore other life stages have $q_i = 0$, **Q** is:

$$\mathbf{Q}_t = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ q_{6,t} \\ q_{7,t} \end{bmatrix} \tag{8}$$

Months when the season is closed have catchability coefficients equal zero.

Catch ($\mathbf{C}_t$) is:

$$\mathbf{C}_t = \mathbf{X}_t \circ \mathbf{Q}_t \circ \mathbf{W} \tag{9}$$

where **W** is a vector of weights (w_i) per life stage using Equation (5), $w_{J5} = 0.008389$ and w_A=*0.040532 (kg per individual).*

5.3. Profit

Once the yield per unit of effort can be determined, the economic model estimates NPV of profits over a given period according to a given effort in boat days. Annual profit is calculated by a vector (V_t) which is a function of price (P_i) differentiated by life stage sizes and effort (E_y) (inputs) equivalent to specific catches of juvenile and adult prawns (C_y) , deducting the total cost (c_E) per units of effort on the same equation:

$$v_t = \mathbf{C}_t' \cdot \mathbf{P}_i - E_t \cdot c_E \tag{10}$$

6. Parameter Estimation

Catchability coefficients were estimated using the data from 2004 to 2007, in order to reflect the latest catch technology. The population dynamics parameters were estimated based on the entire dataset but using only catches within the Gulf of Carpentaria and during the banana prawn season, as a proxy for population. The number of juveniles and adults in the population within intermediate catch grades was calculated based on the probability distribution of carapace length, giving the proportion of large juveniles and small adults within the overlapping sizes.

To calculate the parameters of **L** consider first the unexploited fishery, where survival (S) relates to natural mortality (M) as:

$$S = 1 - M \tag{11}$$

The transition of individuals in a given population stage may occur into three possible states over a given period of time: those that survive within the same life stage (S_{ii}), those which die from natural causes (M) and those which grow from one stage to the next (G_{ij}). Thus equation (11) becomes:

$$S_{i,j} = 1 - (M + G_{i+1,j}) \tag{12}$$

Natural Mortality

The natural mortality (*M*) coefficients for different prawn species vary considerably in the literature. For example, natural mortality coefficients are lower for king and tiger prawns, than for banana prawns (Table 2). Lucas *et al* (1979) estimate of a natural mortality rate of 0.05 per week for banana prawns was obtained 1968, in the early days of the Weipa region, a part of the Northern Prawn Fishery, and before the search area was extended to that region, in 1970. Somers (1990) used a monthly rate of natural mortality of 0.20 as well. All the studies cited in Table 2 assessed fishing mortality based on catch-effort data or samples of adults caught within the fishing zone. From these approximate rates (Table 2) we assumed a mortality rate of 0.20 for juveniles at the sea (*J5*) and adults (*A*), as used by Lucas et al (1979). This is consistent with natural mortality of banana prawns calculated as 0.05 per week by Somers (1990), the equivalent of 0.20 per month. Therefore monthly survival is approximately 0.80, and this value must be allocated between S_{ii} and G_{ij}.

Natural mortality rates of banana prawns in the estuarine area are much higher than in the fishing area. Haywood and Staples (1993) estimated weekly natural mortality for banana prawns during the estuarine phase using samples of 1 to 4 month old prawns. Their estimated rates of weekly natural mortality ranged from 0.23 to 0.94, with a median rate of 0.377. As sampling was done every 2 weeks and results showed mortality over cohorts that were sampled for up to 9 times before exiting the estuarine area, the monthly average mortality of prawns present in cohorts lasting 1, 2, 3 and 4 months, were respectively 0.983, 0.809, 0.891 and 0.8. These values were used here to estimate the corresponding G_{ij}.

Table 2: Natural mortality rates for different species:

Publication	**Species**	**Life Stage**	**Weekly natural mortality**	**Monthly natural mortality**
Penn (1973)	King prawns (*Penaeus latisculatus*)	Adults (32 to 56 mm cl)	0.015 to 0.035 (Sep to Nov)	0.058 to 0.133
Lucas *et al* (1979)	Banana prawns (*Penaeus merguiensis*)	Juveniles at sea and Adults	0.05	0.1998
Garcia and Le Reste (1981)	Penaeid	Juveniles at sea and Adults	0.04 to 0.0625	0.15 to 0.227
Somers (1990)	Penaeid	Juveniles at sea and Adults	0.05	0.185
Haywood and Staples (1993)	Banana prawns (*Penaeus merguiensis*)	Estuarine phase (2 to 20 mm cl)	0.23 to 0.94	0.65 to 0.998
Wang & Die (1996)	Tiger prawns (*Penaeus semisulcatus and P. esculentus*)	Juveniles at sea and Adults	0.045	0.17
Wang (1999)	Tiger prawns (*Penaeus semisulcatus*)	Juveniles at sea and Adults	0.03 to 0.065	0.115 to 0.236
Wang & Haywood (1999)	Banana prawns (*Penaeus merguiensis*)	Estuarine phase (2 to 15 mm cl)	0.89 to 0.02	0.985 to 0.077

Growth and Survival

Samples taken in 1963-65 (Munro 1975) showed that growth of larvae phases up to 10 to 12 mm carapace length will occur from September to February (Fig.5). Similar growth rates were found also for banana prawns of the Gulf of Carpentaria by Lucas *et al.* (1979). This results in growth rates of between 1 and 2 mm per month, which was the value used by Vance *et al* (2003). The early life stages, up to *J4*, achieve full transition within a month therefore $S_{ij} = 0$ and

$$G_{i,j} = 1 - M_i \tag{13}$$

for these early stages.

Subject to tidal movements, location and wind, the natural mortality of eggs, larvae and post-larvae is approximately 99% (Somers 1987), therefore $G_{2,1} = 0.01$. Using natural mortalities from previous research (Haywood and Staples 1993) G_{ij} for life stages 2 to 5, respectively:

$$\begin{aligned} G_{3,2} &= 1 - 0.892 = 0.108 \\ G_{4,3} &= 1 - 0.775 = 0.224 \\ G_{5,4} &= 1 - 0.874 = 0.125 \\ G_{6,5} &= 1 - 0.778 = 0.221 \end{aligned}$$

Adolescents in stage 6, *J5*, grow from about 11 mm to 30 mm carapace length in one to two months before achieving adult stage. Stage *J5* is the only stage when $S_{ij} > 0$. To separate those surviving at the same stage ($S_{6,6}$) from those growing to the next stage ($G_{7,6}$), the normalized monthly CPUE of prawns in stage *A*, were used to estimate coefficients through linear regression. Since *A* is the last stage, changes in this population result from either natural mortality or from new recruits from previous stage *J5*. $G_{7,6}$ is then the average of the rate of change in *J5* population per month excluding natural mortality:

$$G_{i+1,j} = \frac{\eta CPUE_{i,t} - (\eta CPUE_{i,t-1} \cdot (1 - M))}{\eta CPUE_{i,t-1}} \tag{14}$$

The normalized coefficient or decay rate of population was used to estimate the normalized CPUE of juvenile prawns:

$$\eta CPUE_{i,t} = \frac{CPUE_{i,t}}{CPUE_{X,t}} \cdot CPUE_X^{MAX} \tag{15}$$

where $CPUE_X$ is the CPUE for the total population, $CPUE_X^{MAX}$ is the maximum value of this variable in the dataset and $i=6$. CPUE data from banana prawn season of catches within the Gulf of Carpentaria were used in the calculation. From the data $G_{7,6}$, which represents the proportion of prawns leaving the juvenile stage to the adult stage after surviving natural mortality, was calculated to be 0.19 (by equation 14), which results in $S_{6,6} = 1 - M - G_{7,6} = 1 - 0.2 - 0.19 = 0.61$.

Adult population is only parameterized in relation to survival at the same stage. Adults survive for 6 months on average (Munro, 1975), the equivalent monthly survival is:
$S_{7,7} = 1 - M = 0.402$

Fecundity

The spawning stock have carapace length ≥ 30 mm (Munro 1975), which fit stages *J5* and *A*. Spawning occurs monthly after the sixth month of age (Munro 1975; Somers 1990), with a peak when adult female prawns are about 38 mm in carapace length (Munro 1975). Two peaks of spawning occur, one in autumn (March to April) and another one in spring (September to October) (Munro 1975; Staples and Vance 1987). However, autumn larvae seem to contribute much less to the adult population, as they can be carried offshore by currents (Rothlisberg and Staples 1983; Staples and Vance 1987). Also, the survival and development of spring-spawned larvae will benefit from the rainfall of the previous wet season (Staples and Vance 1987; Vance, Bishop et al. 2003).
There is evidence that the quantity of eggs produced by individuals in the Penaeid family vary according to carapace length (Penn 1980). Therefore the number of eggs (*y*) produced per female were calculated as:

$$y = \theta \cdot \alpha_F \cdot z^{\beta_F} \tag{16}$$

where θ represents overall mean of ova per gram of prawns, α_F is the ripe ovary weight in grams and z^{β_F} adjusts for relationship to carapace length in *mm*.

As juvenile and adult population have different male-female ratio ratios (Munro 1975) the percentage of females in each population is then adjusted in the F_{ij} coefficient by f_i (0.45 and 0.51 for *J5* and *A* respectively):

$$F_{ij} = \theta \cdot \alpha_F \cdot z^{\beta_F} \cdot f_i \qquad (17)$$

The values of θ, α_F and β_F are taken from means reported by Penn (1980). The parameters of equations (16) and (17) are given on Table 3.

Table 3: Fertility calculations.

grades (*i*)	**average cl (mm)**	**ripe ova per female (*y*)**	***Fij***
J5	21.5	47238	21257
A	38	248627	126800

Fertility parameters show consistency with previous research that shows fecundity ranging from 44,000 to 534,000 per female per spawning in the Penaeid family (Penn 1980), and *Penaeus merguiensis* producing, when at its maximum carapace length, 500,000 eggs per spawning (Vance *et al* 2003).

Table 4: Parameters used in the model.

Parameters	***Value***	***Equation***	***Source***
α_L	46	(4)	Munro (1975)
$\beta_{L,E\&PL}$	2.386	(4)	Calculated from sizes at age from Munro (1975)
$\beta_{L,J1\ and\ J2}$	1.049	(4)	Calculated from sizes at age from Munro (1975)
$\beta_{L,J3\ and\ J4}$	0.611	(4)	Calculated from sizes at age from Munro (1975)
$\beta_{L,J5}$ (male)	1.773	(4)	Calculated from sizes at age from Munro (1975)
$\beta_{L,J5}$ (female)	1.762	(4)	Calculated from sizes at age from Munro (1975)
$\beta_{L,A}$(male)	0.222	(4)	Calculated from sizes at age from Munro (1975)
$\beta_{L,A}$(female)	0.237	(4)	Calculated from sizes at age from Munro (1975)
α_W (male)	0.001153	(5)	Munro (1975)
β_W (male)	2.905	(5)	Munro (1975)
α_W (female)	0.001273	(5)	Munro (1975)
β_W (female)	2.862	(5)	Munro (1975)
c_E	4,651	(10)	Derived from ABARE Report (ABARE 2008)
P_{J5}	10	(10)	Derived from ABARE Report (ABARE 2008)
P_A	12	(10)	Derived from ABARE Report (ABARE 2008)
$S_{6,6}$	0.61	(12)	
$S_{7,7}$	0.402	(12)	
$G_{2,1}$	0.01	(13)	
$G_{3,2}$	0.108	(13)	
$G_{4,3}$	0.224	(13)	
$G_{5,4}$	0.125	(13)	
$G_{6,5}$	0.221	(13)	
$G_{7,6}$	0.19	(14)	
α_F	0.0000695	(16)	Penn (1980)
β_F	2.916	(16)	Penn (1980)
θ	88,494	(16)	Penn (1980)
$F_{1,6}$	21,257	(17)	
$F_{1,7}$	126,800	(17)	

Effort

Lucas *et al* (1979) suggested that the best unit of effort when studying banana prawns would be days at sea. This idea is based on the fact that banana prawns aggregate forming mud boils, which facilitates their spotting and thus reduces searching time.

Average monthly effort in boat-days units applied only to banana prawn catches from 2004 to 2007 catch data shows that effort during the months of April and May is equivalent to 93% of the effort applied to banana prawns fishing in the whole banana fishing season, which represents about 1,300 boat days per month in April and May, falling down to 182 boat days (a median between 2006 and 2007 fishing seasons) in June.

Catchability

From the effort applied in catching banana prawns, exclusively, we obtained different catchability rates for juvenile and adult banana prawns. With data from 2004 to 2007 with the catch per shot per day of graded banana prawns, life-stage specific daily catchability (q_{id}), as the proportion of juveniles and adult prawns caught from the total population, per unit of effort (boat days) is estimated by:

$$q_{i,d} = \frac{C_{i,d}}{B_d \cdot C_y} \tag{18}$$

where $C_{i,d}$ is the number of individuals of each life-stage (i), caught on day (d), B_d is the number of boats at the sea on that day (d) and C_y is the total catch in year (y).

Daily catchability coefficients have skewed distributions (Fig. 6) through the months, but as changes of life stages in our population matrix will be represented monthly, catchability (q_m) coefficients were selected as the trimmed mean of the daily catchability ($q_{i,d}$) distribution.

These values (Fig.7) show an increase in vulnerability to catch, or probability of catching, these prawns towards the end of each month. Figure 7, shows the greater catchability coefficients of adults in relation to juveniles and the relatively smaller coefficients for catches in June for both life stages.

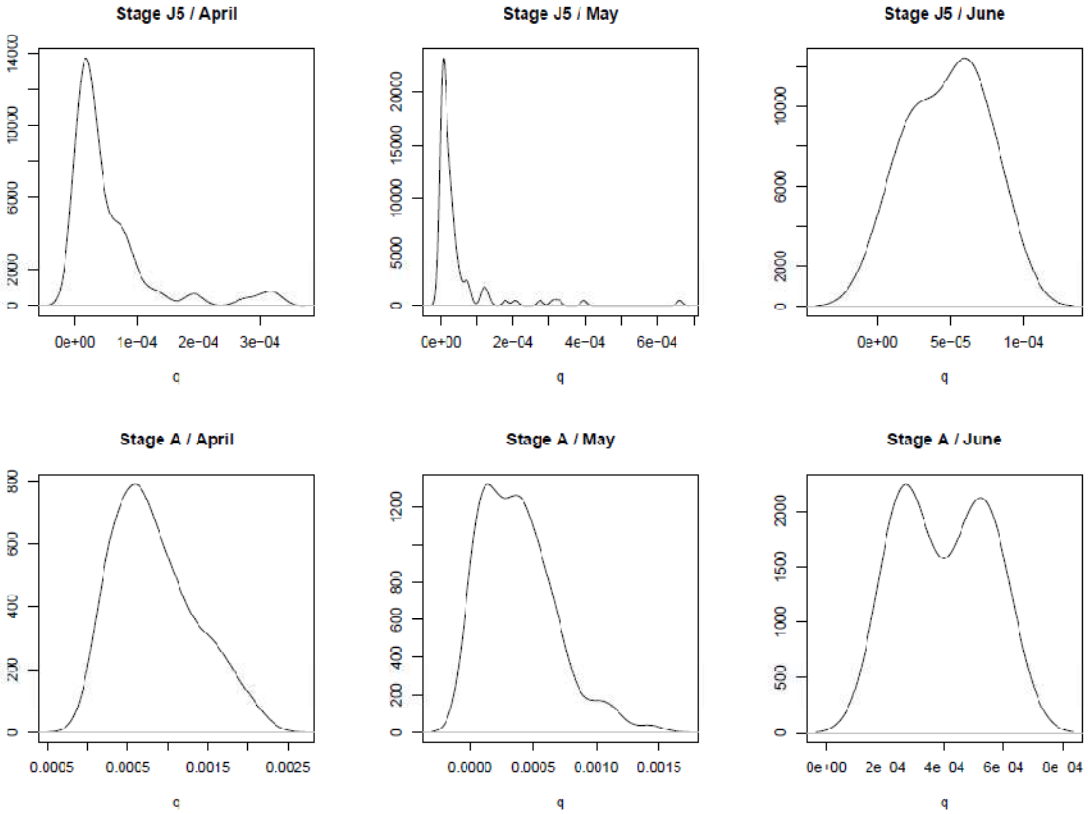

Figure 6: Distribution of daily catchability coefficients (q_d) per boat day in each month (April to June).

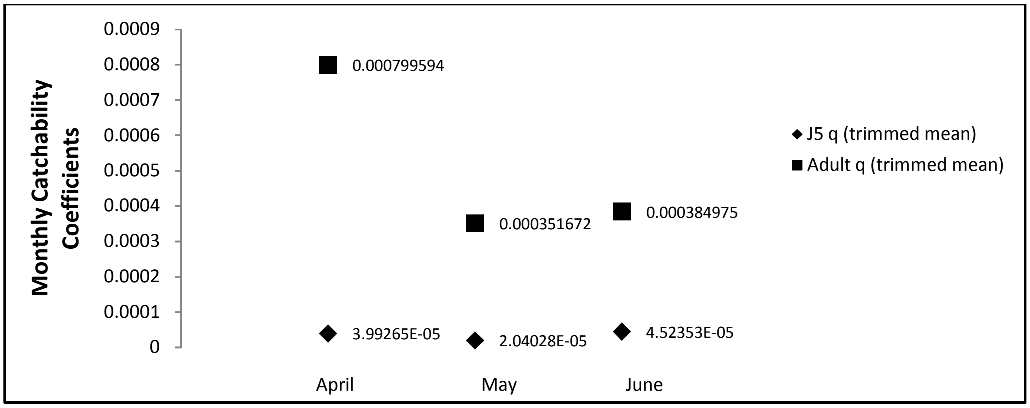

Figure 7: Monthly catchability coefficients (q_m) selected as the q_{id} equivalent to the maximum density in the daily distribution of catchability coefficient.

Catchablity coefficients and the catch model were tested against catch data from 2004 to 2007 by first calculating a stable population structure using the catch data and the **L** matrix and then by applying effort levels in catch data from 2004 to 2007 (Fig 8).

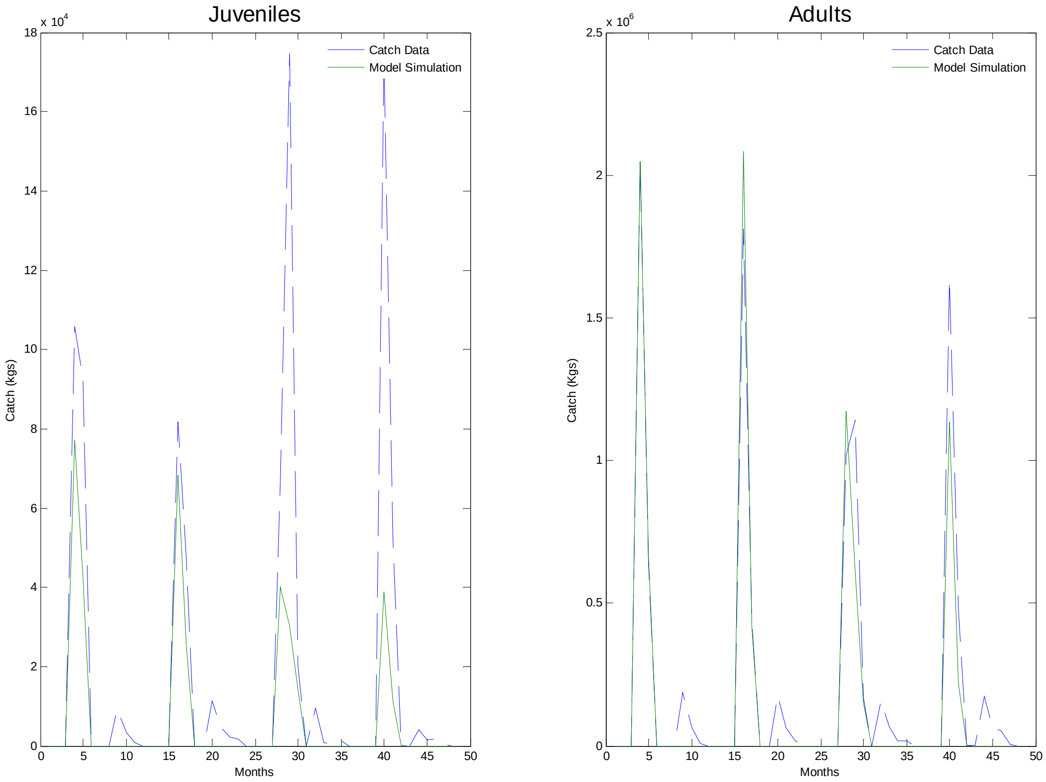

Figure 8: Fitting of the catch model

Costs

When allocating costs associated to the catch of banana prawns and of tiger prawns during the annual fishing season months of April, may June and August to November, we observed that the maximum proportion of effort spent in catching banana prawns represents only about 35% of the maximum proportion of effort spent catching tiger prawn (Fig.9). This representative higher effort is offset by the considerable price difference for tiger prawns in the market (Vieira and Perks, 2009). From the total annual costs of operating at the NPF, about 20% is used in banana prawn fishery.

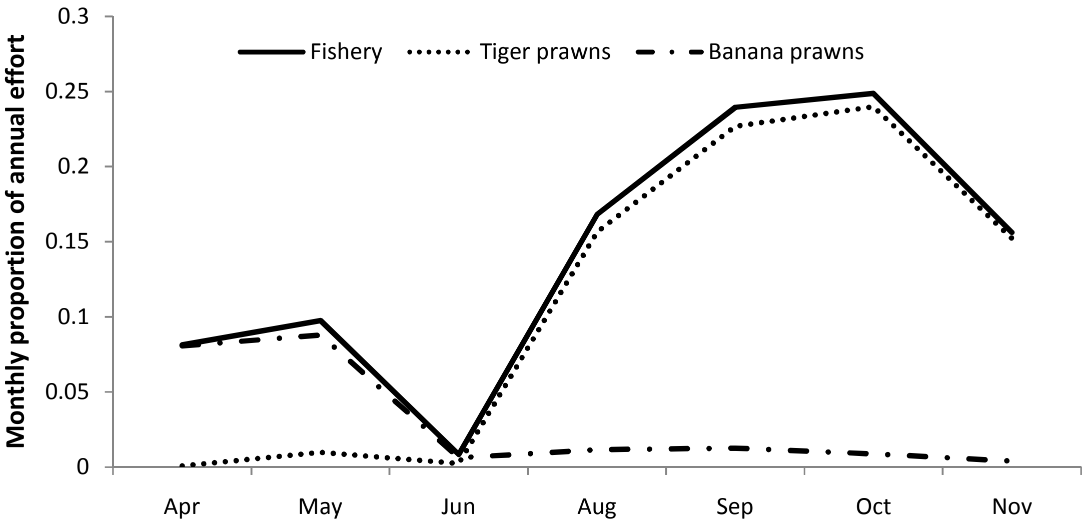

Figure 9: Monthly proportion of annual effort spent on the Fishery in relation to the amount of effort spent on banana prawns and tiger prawns catching, respectively.

The most significant costs include fuel (around 35% of total cost in 2007 – 2008), labour (around 29% of total costs) and repairs and maintenance (about 14% of total costs) (Vieira and Perks 2009). These calculations, however, are based on costs that vessels accrued from operations over not only the NPF but also at three other trawl fisheries.

From effort data in boat days, we obtained the cost per boat for each day operating at the NPF that is allocated specifically to banana prawn catches. Catch of banana and tiger prawns account for 90% of total catch in the NPF (Vieira and Perks 2009). The total cost spent per unit of boat day at the Northern prawn fishery is A$4,651, which includes A$4,261spent on operating costs and A$390 on other costs. Other costs includes owner and family labour, management costs, depreciation, opportunity costs (of not operating in other fisheries) and deducts interests and leasing revenue from quotas or permits (Vieira and Perks 2009).

Prices

Average banana prawn prices have fluctuated between A$9.05 and AS$13.95 from 1997 to 2007, according to data extracted from ABARE Fisheries statistic reports (ABARE 2008), with an average of A$11.33 and a median of A$10.98. The model is based on fixed prices for a common partial equilibrium economic model (Clark 1973) rather than an inverse demand function, because banana prawn prices do not show an explicit relationship with production volume ($R^2 = 0.02$). While data and further research is required to estimate banana prawn prices in relation to carapace length, here we assume a lower price for smaller prawns (A$10.00/Kg) than for larger prawns (A$12.00/Kg).

7. Optimization Runs

Four scenarios were used to test the optimization algorithm. A summary of results is shown in Table 5.

Table 5. Optimization results for the 4 scenarios.

		NPF data	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	
Time frame	*(years)*	**2007**	**10**	**10**	**10**	**1-2**	**3-10**
Season Length	*(months)*	3	3	2	1	0	1
Annual Effort	*(boat days)*	2,125	916.25	838.48	584.35	0	1500
NPV	*(mi $)*		125.82	130.67	142.44	126.21	
Average Annual GPV	*(mi $)*	26.4	13.5	13.5	13.6	0	27.96
Population Steady state	*J5 (millions of individuals)*		185.6	187.1	188.2	206.8	129.4
	Adults (millions of individuals)		56.9	56.2	57.6	65.2	38.39
Monthly Average Catch	*J5 (Kg)*		16,549	19,742	36,636	0	75,747
	Adults (Kg)		348,798	546,406	1,108,175	0	2,268,012
Average Total Catch	*(Tonnes)*	2,674	1,096	1,132	1,144	0	2,343

Scenario One – minimum effort constrained, 3-month season

First we set season length to 3 months, from April to June and a minimum level of effort that guarantees a stable population if fishing would take place for three months. This provides a minimum return to investment to the industry and prevents the optimization model from prescribing unrealistic fluctuations in monthly effort. The optimal solution is to maintain a constant effort for all three months of the season. This monthly average effort, of approximately 305 boat days, relatively low compared to historical fishery effort data, yields annual catches of 1,096 tonnes which is the equivalent to less than half of 2006-7 catches, and an annual production value of A$13.05 million which is the equivalent to half of the annual value of production of the fishery in terms of banana prawns in 2006-7.

Scenario Two – minimum effort constrained, 2-month season

In scenario 2 we set a two-month annual season, during April and May. The effort is again constrained to a minimum during those months. A corner solution is obtained, where the minimum effort is used. NPV increases from A$125 to A$130 million over the ten years of simulations. Gross production value is constant at an annual value of A$13.5 million. Annual effort was reduced to 838.48 boat days in those two months but total annual catch increased by 3%.

Scenario Three – minimum effort constrained, 1-month season

Considering that our target population, the adult stage, has a higher catchability rate in April, scenario three is meant to test the idea that having a one-month season will promote efficiency in the use of effort. Total Annual effort was reduced by 30%, from 838 to 584 boat days resulting in an average catch increase of 1%, to 1,144 tonnes, an annual gross production value of A$13.6 million and an NPV over the ten years increase by 9%, from

A$130 to A$142 million. Population steady states increased by 0.5 and 2% for juveniles and adults respectively.

Scenario Four – A minimum effort unrestricted and 3-month season

Scenario four aimed to test the optimization algorithm without a constraint on minimum effort, with the fishing season set at three months. The fishing pattern that optimized NPV over 10 years had the fishery closed for 2 years (Fig.10), allowing adult population to grow by 13%, resulting in an increase of 100% in annual catches during the remaining 8 years. As the highest catch occurs in April, when catchability coefficient is higher and costs are lower per unit of effort, the optimal fishing pattern shows a single-month fishing season per year, during April, concentrating the maximum effort constraint of 1,500 boat days in this month. Average annual catches in this simulation reach the actual levels of banana prawn catch in the NPF with an average monthly production of 27.9 million dollars and an NPV of A$126.21 million.

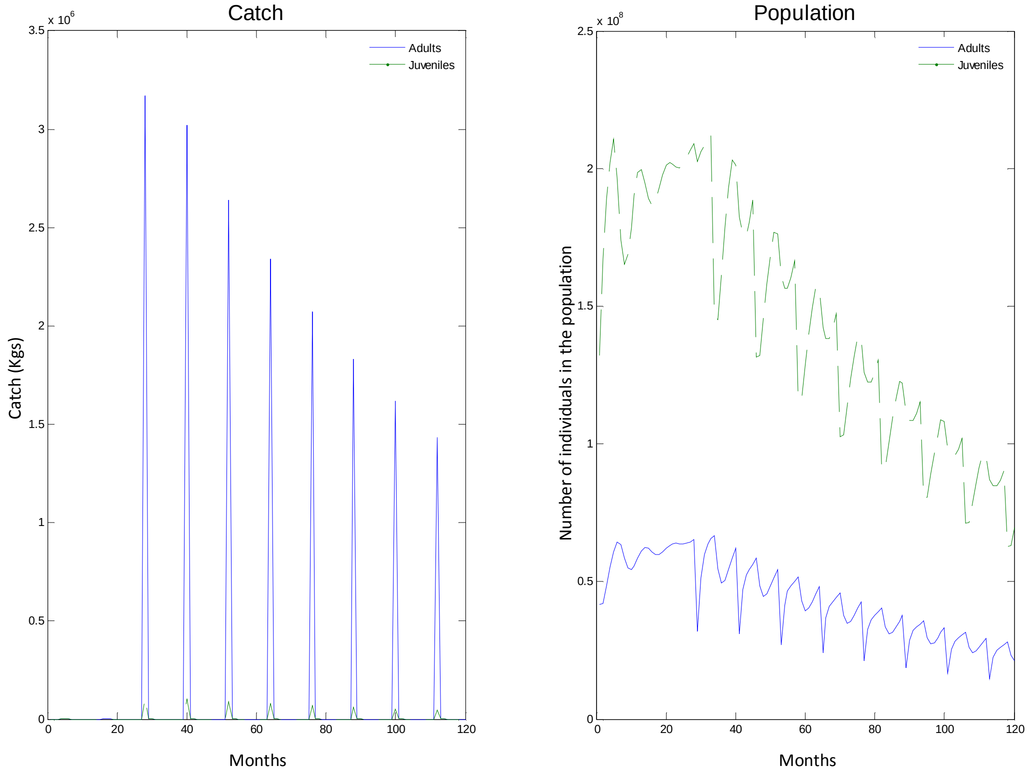

Figure 10: Results from simulation of ten years catch searching for a maximum NPV profit using scenario four: no minimum effort constraints and the possibility of opening the fishery for 3 months.

8. Discussion

Our optimization model uses a stage population matrix and monthly catchability coefficients based on the aggregation behavior of banana prawns, whereby vulnerability of prawns is higher in the first month of the fishing season reducing variable costs of fishing. Results suggest that catches in June would yield a large proportion of juveniles that have not yet reached full size and fetch lower market prices. The optimisation algorithm chooses not to fish during May and June and achieves similar annual catch volume and production value to what the fishery currently yields. While the industry profit is not revealed by data, our simulations found that the same production value can be achieved with 1,500 boat days concentrated in one month per year, April, in contrast with the average annual effort of 3,380 from 2004 to 2007, varying from 2 to 3 months from April.

This is preliminary work based on several assumptions that must be relaxed before the model is used for management purposes. First the matrix must be adjusted to reflect seasonal and stochastic rainfall levels which affect growth and survival of the population. Banana prawn catches in the Northern Prawn Fishery have shown considerable variation through the years. Research indicates that these fluctuations are a consequence of level of recruitment (Lucas, Kirkwood et al. 1979) which is, in turn, a response to rainfall levels on the estuarine area (Rothlisberg and Staples 1983; Vance, Bishop et al. 2003), water temperature (Vance, Staples et al. 1985) and salinity (Neal 1973; Vance, Staples et al. 1985; Vance, Bishop et al. 2003). Another issue for future research is the inclusion of density dependence into the matrix model to account for carrying capacity.

9. Acknowledgments

We wish to thank the Fisheries Research and Development Corporation, Bureau of Rural Sciences (BRS) and the Department of Agriculture, Fisheries and Forestry of Australia for the financial support for this project and Brian Kinghorn, John Gibson and Phil Simmons, from the University of New England, David Galeano from AFMA and Sean Pascoe, from CSIRO, for their valuable inputs.

10. References

ABARE (2008), Australian Fisheries Statistics 2007, Canberra, June.

AFMA., 2005. Northern prawn fishery - fact sheet. Retrieved 6th March, 2007, from http://www.afma.gov.au/information/publications/education/pdfs/fs11_npf.pdf

Caswell, H. (1989). Matrix Population Models. Sunderland, Massachusetts, Sinauer Associates, Inc.

Clark, C. W. (1973). "Profit Maximization and the Extinction of Animal Species." The Journal of Political Economy **81**(4): 950-961.

Csirke, J. and J.F. Caddy 1983. Production modeling using mortality estimates. Can. J. Fish. Aquat. Sci. 40:43-51 (+Errata sheet in 40:255-256).

Caswell, H. (1989). Matrix Population Models. Sunderland, Massachusetts, Sinauer Associates, Inc.

Clark, C. W. (1973). "Profit Maximization and the Extinction of Animal Species." The Journal of Political Economy **81**(4): 950-961.

Die, D. J. and N. Ellis (1999). "Aggregation dynamics in penaeid fisheries: banana prawns (Penaeus merguiensis) in the Australian Northern Prawn Fishery." Marine and Freshwater Research **50**(7): 667-675.

Haywood, M. D. E. and D. J. Staples (1993). "Field estimates of growth and mortality of juvenile banana prawns (Penaeus merguiensis)." Marine Biology **116**(3): 407-416.

Kompas, T. and N. Che (2004). A Bioeconomic Model of the Australian Northern Prawn Fishery: Management Options under Uncertainty. ABARE e-Reports. ABARE. Canberra, ABARE

Lucas, C., G. Kirkwood, et al. (1979). "An Assessment of the Stocks of the Banana Prawn (*Penaeus merguiensis*) in the Gulf of Carpentaria." Marine and Freshwater Research **30**(5): 639-652.

Munro, I. S. R. (1975). Biology of Banana Prawn (*Penaeus merguiensis*) in the South-east corner of the Gulf of Carpentaria. Australian National Prawn Seminar (1st) Maroochydore, Aust. Govt. Printing Services: Canberra.

Neal, R. A. (1973). The Golf of Mexico research and fishery on penaeid prawns. First Australian National Prawn Seminar, 22-27 November, 1973, Maroochydore, QLD, Australia, Australian Government Publishing Service.

Penn, J. W. (1980). "Spawning and fecundity of the western king prawn, <I>Penaeus latisulcatus</I> Kishinouye, in Western Australian Waters." Marine and Freshwater Research **31**(1): 21-35.

Quinn, T. J. I. and R. B. Deriso (1999). Quantitative Fish Dynamics. Oxford Oxford University Press.

Rothlisberg, P. and D. Staples, Eds. (1983). Biology of Banana Prawns in the Gulf of Carpentaria - An Overview. Northern Prawn Fishery Information Notes, CSIRO Marine Research. Cleveland, NPF Publishing.

Somers, I., Ed. (1987). The Status of Tiger Prawn Stocks in the Western Gulf of Carpentaria. Northern Prawn Fishery Information Notes, CSIRO Marine Research. Cleveland, NPF Publishing.

Somers, I. F. (1990). "Manipulation of Fishing Effort in Australia's Penaeid Prawn Fisheries." Aust. J. Mar. Freshwater Res. **41**: 1-12.

Staples, D., Ed. (1983). Northern Prawn Fishery Information Notes. CSIRO Marine Research. Cleveland, NPF Publishing.

Staples, D. J. and D. J. Vance (1986). "Emigration of juvenile banana prawns *Penaeus merguiensis* from a mangrove estuary and recruitment to offshore areas in the wet-dry tropics the Gulf of Carpentaria, Australia." ECOLOGY - PROGRESS SERIES **Mar. Ecol. Prog. Ser. 1**(27): 239-252.

Staples, D. J. and D. J. Vance (1987). "Comparative Recruitment of the Banana Prawn, Penaeus merguiensis, in Five Estuaries of the South-eastern Gulf of Carpentaria, Australia." Aust. J. Mar. Freshw. Res. **38**: 29-45.

Vance, D. J., J. Bishop, et al. (2003). Management of common banana prawn stocks of the Gulf of Carpentaria: separating the effects of fishing from those of the environment. Project No. 98/0716. CSIRO, AFMA.

Vance, D. J., M. D. E. Haywood, et al. (1998). "Seasonal and annual variation in abundance of postlarval and juvenile banana prawns Penaeus merguiensis and environmental variation in two estuaries in tropical northeastern Australia: a six year study." MARINE ECOLOGY PROGRESS SERIES **163**: 21-36.

Vance, D. J., D. J. Staples, et al. (1985). "Factors affecting year-to-year variation in the catch of banana prawns (Penaeus merguiensis) in the Gulf of Carpentaria, Australia." ICES J. Mar. Sci. **42**(1): 83-97.

Vieira, S and Perks, C 2009, *Australian fisheries surveys report 2009: Survey results for selected fisheries, 2006-07 and 2007-08, preliminary estimates for 2008-09*, ABARE report, Canberra, October.