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Simulation Estimates of Annual Yield and Landed Value for Commercial Penaeid Prawns from a Tropical Seagrass Habitat, Northern Queensland, Australia

Reg A. Watson, Robert G. Coles and Warren J. Lee Long

Northern Fisheries Centre, Box 5396, Cairns, Qld 4870, Australia.

Abstract

Concern over the loss of seagrass habitat has prompted examination of the value of the production of commercial prawns from such habitat. Cairns Harbour in tropical northern Queensland has 876 ha of mixed seagrasses, dominated by *Zostera capricorni* and *Halodule pinifolia*, that support a multispecies commercial penaeid prawn fishery offshore. Densities of juvenile commercial prawns estimated from seagrass surveys were used to project estimates of annual yield and landed value, using a deterministic simulation model employing lunar-period time steps. Estimates of the potential total annual yield from Cairns Harbour seagrasses for the three major commercial prawn species (*Penaeus esculentus*, *P. semisulcatus* and *Metapenaeus endeavouri*) were 178 t (range 81–316 t) year^{-1} with a landed value of \$A1·2 million (range \$0·6 million to \$2·2 million) year^{-1}.

Introduction

Seagrass meadows are found in sheltered inshore waters throughout the tropics (den Hartog 1970). These habitats commonly support juvenile fishes and crustaceans. Artisanal and commercial fisheries exist for many of the species. Several tropical species of penaeid prawns depend on this habitat for their survival (Staples 1984; Coles and Lee Long 1985; Staples *et al.* 1985). Development of coastal areas has caused concern over the removal of seagrass habitat and the effect that this may have on commercial fisheries.

Cairns Harbour (Fig. 1) is typical of mangrove-lined bay and inlet systems in northern Queensland, Australia. A related study has examined the seagrasses of Cairns Harbour and their fish and prawn populations (Coles *et al.* 1993). Our joint aim was to establish a baseline for the harbour against which future changes could be assessed and quantified. In this context, the present study attempted to estimate the annual expected yield and landed value of commercial prawns that use the seagrass habitats within Cairns Harbour.

One way to estimate the prawn annual yield and landed value for the seagrass habitat of Cairns Harbour is to examine commercial logbook records. Although the requirement for seagrass habitat by juveniles of several commercial prawn species has been demonstrated by their co-distribution along the tropical Queensland coast, it has been difficult to verify the relative contributions of different juvenile-prawn habitat areas to commercial landings. There is strong spatial partitioning between commercial prawn species between different habitats (Staples *et al.* 1985) and between seagrass sites (Coles *et al.* 1987). Even within closely associated seagrass areas, Turnbull and Mellors (1990) found considerable variation in the density of juvenile prawns. With the uncertainty of directly relating commercial landings to production from seagrass sites, it was more appropriate to use landing records for comparative purposes only and to estimate expected yield and landed values by computer simulation from juvenile-prawn densities estimated from samples taken from seagrasses.

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In this way, commercial yields could be attributed to different seagrass areas. Much was already known about the life history and biology of the major commercial prawn species in the region of the Cairns fishery (Coles *et al.* 1987), which enabled a simulation model to be developed. Detailed monthly surveys of seagrass habitat provided size–density data for juvenile commercial prawns that made possible estimation of the annual yield and landed value of commercial prawns in Cairns Harbour.

Materials and Methods

Study Site

Cairns Harbour in northern Queensland (10°55′S,145°47′E) is a wide, shallow bay at the head of a tidal estuary (Fig. 1). The estuary is mangrove-fringed except at the rocky outcrops of False Cape and at the retaining wall adjacent to Cairns city. Data were collected from an area between Ellie Point to the west and Cape Grafton to the east (Fig. 1). Coles *et al.* (1993) described three main seagrass areas within Cairns Harbour: the western harbour (230 ha), the eastern harbour (270 ha) and Mission Bay (376 ha) (Fig. 1). Their estimates of seagrass areas were used to extrapolate potential prawn yield and landed values to the whole harbour.

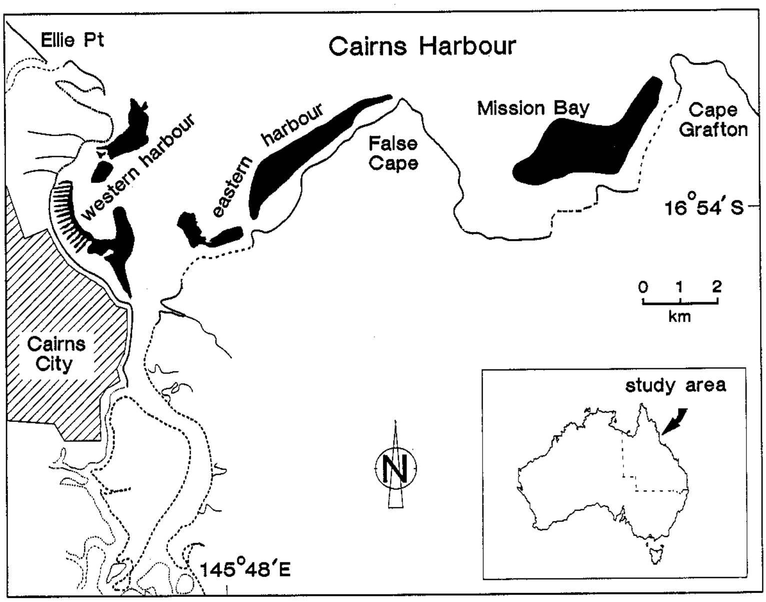

Fig. 1. Cairns Harbour, showing seagrass areas sampled (after Coles *et al.* 1993).

Juvenile Penaeid Prawns

Samples of prawns were collected at night by using a small trawler towing two identical beam trawls. Each beam trawl was 1·5 m wide and 0·5 m high and was fitted with a 2-mm-mesh net. They were towed at a speed of 0·5 m s^{-1}, usually for 2·5 min, as described by Coles and Lee Long (1985). Sample efficiency was calibrated by taking an exhaustive sample from a fixed-area device (Table 1). This method, described by Coles (1986), provides a method of estimating the actual number of prawns present in a square metre of bottom and the water column above.

Between November 1987 and December 1989, four replicate beam-trawl samples were taken each month at the time of the new moon at each of the three seagrass localities: the western harbour, the eastern harbour and Mission Bay (Fig. 1). Only those prawns with a carapace length (CL) greater than 3 mm were identified to species according to Grey *et al.* (1983) and sexed.

Table 1. Species and sex-related model parameters
Values for the growth function (L_∞, k and t_0), weight–length relationship (α, β), beam-trawl efficiencies (S) and commercial trawl-net selectivity parameters (σ, L_{50}). All rates are per lunar period, and all sizes are for carapace length (mm). Females (F) and males (M) are shown separately where appropriate

Species	L_∞		k		t_0		α		β		S	σ	L_{50}
	F	M	F	M	F	M	F	M	F	M			
P. esculentus	44	35	0·18	0·19	0	0	0·0026	0·0024	2·67	2·72	0·35	0·30	21·5
P. semisulcatus	62	38	0·10	0·24	0	0	0·0021	0·0017	2·73	2·81	0·49	0·30	21·5
M. endeavouri	43	32	0·12	0·23	0	0	0·0015	0·0017	2·81	2·79	0·39	0·40	19·7

Simulation Model

General description

The simulation model incorporated traditional mathematical relationships employed to model fish population dynamics. It was a length-based deterministic simulation model, based on that developed for adult prawns in the Torres Strait (Watson 1990), employing time steps of one lunar month. Size–density estimates of juvenile commercial prawns from lunar monthly samples from seagrasses were used as the basis for the numbers of prawns used in the model. These animals were followed every lunar cycle as we simulated growth and size-related natural and fishing mortalities. Size-related fishing mortality for each month was determined by the product of a logistic selection curve and the base level of fishing effort in that lunar cycle (Table 2). The potential yield of prawns was calculated from the sizes and numbers of prawns caught. Landing prices from local prawn buyers were used to calculate harvest values (Table 3). All of these calculations were made on a per-area basis, and the model was run separately for each of the four beam-trawl samples in the eastern harbour, the western harbour and Mission Bay to give a range of values.

Table 2. Instantaneous rates for fishing mortality for lunar periods ($q.f_i$)
Values are before size-related trawl-net selectivity is applied

	Lunar period												
	1	2	3	4	5	6	7	8	9	10	11	12	13
$q.f_i$	0·00	0·70	0·33	0·20	0·16	0·13	0·22	0·25	0·14	0·15	0·10	0·02	0·00

Prawn recruitment

The numbers of juvenile prawns added to the model were based on density estimates from beam-trawl samples collected during each lunar period. Separate estimates of juvenile numbers were made for each of the four beam-trawl samples, and each estimate was used as the basis of a separate simulation yield and value projection. These initial estimates of juvenile prawn numbers by species, sex and size class (1-mm-CL groups) were adjusted by using species-specific beam-trawl efficiencies (Table 1). Sexes were separated because of known differences in their growth rates and weight–length relationships.

The simulation model relied on length-based density estimates from beam-trawl samples collected every lunar period in seagrass beds. Length–frequency results from each lunar sample were examined individually to assess which juvenile prawns were newly settled and therefore should be used in the model. Juvenile prawns that were large enough to have been accounted for in the previous lunar sample (on the basis of known growth rates) were ignored so that they would not be counted twice. We used all prawns, regardless of size, from the first lunar period of the simulation and thereafter only the prawns that we had not accounted for previously. All juveniles under 10 mm CL were accepted as newly settled prawns because our observations suggested that prawns can achieve this size within one month of settling in seagrass areas.

The yield for a typical year would include not only juvenile prawns recruiting that year but also catches of adult prawns existing when the year commenced. To include these adult prawns in our calculations required that we estimate the number of prawns that would still be alive at the end of the

Table 3. Size-related instantaneous natural mortality rates for lunar period, $M_{i,j}$, and landed prices for prawn species, $A_{i,j}$

Values are presented in 2-mm carapace length (CL) groups. Landed prices are in \$A kg^{-1}. Females (F) and males (M) are shown separately where appropriate

CL (mm)	$M_{i,j}$	*P. esculentus* F	*P. esculentus* M	*P. semisulcatus* F	*P. semisulcatus* M	*M. endeavouri* F	*M. endeavouri* M
0–2	0·28	0·00	0·00	0·00	0·00	0·00	0·00
3–4	0·28	0·00	0·00	0·00	0·00	0·00	0·00
5–6	0·28	0·00	0·00	0·00	0·00	0·00	0·00
7–8	0·28	0·00	0·00	0·00	0·00	0·00	0·00
9–10	0·23	1·75	1·75	1·75	1·75	1·75	1·75
11–12	0·23	1·75	1·75	1·75	1·75	1·75	1·75
13–14	0·23	1·75	1·75	1·75	1·75	1·75	1·75
15–16	0·18	1·75	1·75	1·75	1·75	1·75	1·75
17–18	0·18	1·75	1·75	1·75	1·75	1·75	1·75
19–20	0·18	1·75	5·00	1·75	1·75	1·75	1·75
21–22	0·18	5·00	5·00	5·00	5·00	2·50	2·50
23–24	0·18	5·00	5·00	5·00	5·00	2·50	2·50
25–26	0·18	7·00	7·00	7·00	7·00	5·00	5·00
27–28	0·18	9·75	9·75	7·00	7·00	5·00	5·00
29–30	0·18	9·75	9·75	7·00	9·75	5·00	5·00
31–32	0·18	9·75	9·75	9·75	9·75	7·00	7·00
33–34	0·18	9·75	9·75	9·75	9·75	7·00	7·00
35–36	0·18	9·75	9·75	9·75	9·75	7·00	7·00
37–38	0·18	15·25	15·25	9·75	15·25	7·00	7·00
39–40	0·18	15·25	15·25	15·25	15·25	11·00	11·00
41–42	0·18	15·25	15·25	15·25	15·25	11·00	11·00
43–44	0·18	15·25	15·25	15·25	15·25	11·00	11·00
45–46	0·23	15·25	15·25	15·25	15·25	11·00	11·00
47–48	0·23	15·25	15·25	15·25	15·25	11·00	11·00
49–50	0·23	15·25	15·25	15·25	15·25	11·00	11·00
>50	0·28	15·15	15·25	15·25	15·25	11·00	11·00

simulated calendar year. These adult prawns were included as recruits at the beginning of subsequent simulations from which total estimates were recorded.

Model processes and parameters

Prawn growth was modelled on the von Bertalanffy growth equation (von Bertalanffy 1938),

$$L_{i,j} = L_{\infty}[1 - e^{-k(t-t_0)}],$$

where $L_{i,j}$ is the CL (mm) of prawns of age i (months) in month j. The growth parameters were determined by tagging experiments for *P. esculentus* (Derbyshire, personal communication), *P. semisulcatus* (Kirkwood and Somers 1984) and *M. endeavouri* (Buckworth 1989) (Table 1).

The weight–length relationship was modelled as

$$W_{i,j} = \alpha L_{i,j}^{\beta},$$

where the parameters were determined by measurement of samples (Table 1).

Change in population size due to mortality was represented by an exponential decline such that

$$N_{i+1,j} = N_{i,j} e^{Z_{i,j}},$$

where the total instantaneous mortality rate for the lunar period, $Z_{i,j}$, is the sum of size-related natural mortality, $M_{i,j}$ (Table 3), for the lunar period plus fishing mortality for the lunar period determined by the product of size-related selectivity, $S_{i,j}$ (defined below), and fishing effort, f_i (Table 2), for that lunar period, so that

$$F_{i,j} = S_{i,j} f_i;$$

in other words,

$$Z_{i,j} = F_{i,j} + M_{i,j}.$$

The annual instantaneous rate for natural mortality was assumed to equal the average value of 2·4 from Garcia (1985). His estimate was derived from a survey of the literature and represents the mean for adult prawns across a range of tropical penaeids. It was important, however, that we estimate the natural mortality of all sizes. Caddy (1990) suggested that there is a rapid decline in natural mortality in short-lived invertebrates from egg to first maturity. Accordingly, we assigned natural mortality rates for our smallest prawns at approximately 150% of those of commercial sizes (Table 3). Of lesser importance is the estimation of natural mortality rates for prawns larger than the mean commercial size (14–44 mm CL) because prawns seldom survive long enough to attain these sizes. Few tropical prawns survive for more than one to two years, and in a fishery their survival is considerably limited. Tagging studies in the Torres Strait (Derbyshire *et al.* 1990) suggest that few *P. esculentus* individuals live more than 12 months, so the natural mortality rate assigned to prawns larger than the mean commercial size makes little difference to our estimates.

The seasonal pattern of fishing effort was taken from logbook data (Watson *et al.* 1990) and assumes a seasonal fisheries closure of approximately two months starting in mid-December because this has been the management practice since 1985 for prawn fisheries in northern Queensland. The instantaneous fishing mortality rates for the lunar periods (Table 2) were adjusted so that their sum would equal the assumed annual natural rate. Francis (1974) suggested that the maximum sustainable yield could be achieved when fishing and natural mortality rates were equal if recruitment was assumed to be density-independent. Our model assumes this independence in the absence of an established stock–recruitment relationship for the Cairns fishery.

Selectivity is defined as

$$S_{i,j} = \frac{1}{1 + e^{\sigma(L_{i,j} - L_{50})}},$$

where the parameters were experimentally determined (Sterling *et al.* 1990).

Catch is calculated as

$$C_{i,j} = F_{i,j} \bar{N}_{i,j},$$

the product of fishing mortality and average monthly population size, with the latter defined as

$$\bar{N}_{i,j} = \frac{N_{i,j}(1 - e^{-Z_{i,j}})}{Z_{i,j}}.$$

The value of this catch is

$$B_{i,j} = C_{i,j} W_{i,j} A_{i,j},$$

where $A_{i,j}$ is a size-related landed price based on quotations from processors in Cairns in March 1991 (Table 3).

Results and Analysis

There were considerable differences in the estimated potential yields of commercial prawns between the three seagrass areas sampled (Table 4). Although ranges overlapped, the western harbour was the most productive, followed by the eastern harbour and then Mission Bay. In the eastern and western harbours, the estimated potential yields were highest for *P. semisulcatus*, followed by those for *M. endeavouri* and then *P. esculentus* (Table 4). In Mission Bay, however, yields of *M. endeavouri* were slightly more than those of *P. semisulcatus*.

P. semisulcatus contributed as much or more to the estimated total value of landings then did the other species combined. The landed price paid for *P. esculentus* and *P. semisulcatus* was more than that paid for *M. endeavouri*. This meant that despite lower potential yield estimates, *P. esculentus* was worth more to the fishery than was *M. endeavouri*, except in

Table 4. Estimated yield of commercial prawns from seagrass habitat in Cairns Harbour
Average values in kg ha^{-1} $year^{-1}$

Area	*P. esculentus*	*P. semisulcatus*	*M. endeavouri*	Total (min.–max.)
Mission Bay	2	13	15	29 (7–65)
Eastern harbour	37	71	64	172 (45–351)
Western harbour	142	200	184	526 (288–855)

Mission Bay where yields of *P. esculentus* were negligible (Table 5). Total landings from the western harbour, with its greater densities of *P. esculentus,* were estimated to contribute more dollars to the fishery per hectare of seagrass than did the eastern harbour and Mission Bay combined.

When estimates of seagrass areas were applied, the largest total annual potential yield was still from the western harbour, followed by the eastern harbour and then Mission Bay (Table 6). Estimated average total annual potential yield from all seagrass areas in Cairns Harbour was 178 t, with estimates ranging from 81 to 316 t. The ranking of the estimated dollar values of landings followed the same pattern as the potential yields, and 69% of the estimated total annual landing value came from the western-harbour seagrass beds. The estimated average annual landed value of all commercial prawns produced from all seagrass areas in Cairns Harbour was \$A1·24 million, with estimates ranging from \$0·56 million to \$2·24 million (Table 6).

Table 5. Estimated landed value of commercial prawn yields from seagrass habitat in Cairns Harbour
Average values in \$A ha^{-1} $year^{-1}$

Area	*P. esculentus*	*P. semisulcatus*	*M. endeavouri*	Total (min.–max.)
Mission Bay	17	113	58	183 (41–407)
Eastern harbour	308	639	238	1185 (343–2381)
Western harbour	1184	1806	697	3687 (1953–6272)

Table 6. Estimates of total annual yield and landed value for Cairns Harbour
Average values for yield (t $year^{-1}$) and landed value (\$A million $year^{-1}$) for all seagrass areas, with ranges included for total-harbour estimates

	Mission Bay	Eastern harbour	Western harbour	Total harbour
Yield	11·0	46·4	121·0	178·5 (80·9–315·7)
Value	0·07	0·32	0·85	1·24 (0·56–2·24)

Discussion

The landed value of the Queensland eastern-coast prawn fishery is in excess of \$A55 million each year (Anon. 1991). The major species of prawns involved in this fishery are dependent during the early part of their life cycles on inshore seagrass beds for shelter and survival (Staples 1984; Coles and Lee Long 1985).

An estimate from a simulation model is based on a series of initial parameter estimates, none of which are known exactly. Values of parameters are known with different degrees of certainty; some parameters, such as the rate of natural mortality, were taken from average literature values, others were estimated from our previous work, and still others, such as landing prices, are known to vary annually and even seasonally. Penaeid prawns are a luxury food item, and the market price can vary enormously depending on economic conditions. This factor alone could result in variations of up to 50% each year in the value of prawns recruiting to the fishing grounds from seagrass beds.

In our simulation, we have assumed that natural and fishing mortality rates are essentially equal. Estimated mortality rates have a considerable influence on potential yields. If natural mortality rates have been underestimated, then potential yields would be overestimated; more prawns will die from natural causes before they are harvested than is predicted. Conversely, if fishing mortality rates have been underestimated, then actual yield could be higher than estimated; however, the ability of a fishery to sustain fishing rates that greatly exceed the natural mortality rate is questionable. Present estimates of mortality rates for tropical penaeids are crude; we expect these rates to vary through time and between fisheries, and it must be remembered that yield and value estimates would change accordingly.

Yield and value estimates from the simulation model are also dependent on estimates of the numbers of juvenile prawns in seagrass areas. The abundance of prawns in seagrass can vary considerably. Turnbull and Mellors (1990) found variation between years, between months, between beds and within beds in the Torres Strait. Coles (1982) believed that the number of prawns caught in a beam trawl is not necessarily directly related to the size of the prawn population present but is a function of population size, sampling-net efficiency and uncontrolled variation due to experimental error and random variation.

Some of the monthly variation in juvenile prawn numbers must have originated from the seasonal cycles of population fecundity of adult prawns that Crocos (1987) documented for *P. esculentus* and *P. semisulcatus*. Penaeid prawn fisheries are noted for their year-to-year fluctuations in landings. The number of prawns settling in coastal seagrasses is dependent not only on this variable breeding stock but also on the vagaries of intervening oceanographic processes that affect the survival of larvae until settlement. Although different seagrass beds differ in their ability to nurture juvenile prawns, it is likely that some of the observed variability originates through differences in the sampling efficiency of beam trawls between sites.

Seagrass may have patchy distributions within a single seagrass bed or sampling area. If these patches are of a larger scale than the distance covered in a single beam-trawl shot, then they would contribute to between-shot variation when few samples are collected. Tides and currents can also influence beam-trawl efficiency on an hourly scale (Turnbull and Watson 1990). Between-shot variation accounted for much of the range of yield estimates in our study.

Our simulation assumes that juvenile prawns migrate from seagrass areas to offshore areas where they recruit into the fishery. Tagging studies of these and similar species have demonstrated that such migrations occur (Somers and Kirkwood 1984), and most penaeid trawl fisheries depend on this migration. The existing trawl fishery operates for more than 100 km to the north and south of Cairns Harbour, which is about the maximum migration distance expected for these species (Derbyshire *et al.* 1990); therefore, we have assumed that all prawns will enter the fishery if they survive long enough.

Interannual variation in seagrass quality and quantity would affect the yields of penaeids dependent on these areas by changing natural mortality rates. Fluctuations in juvenile-prawn mortality rates would have a profound influence on the numbers of juvenile prawns surviving until they migrate to the fishery. The degree of bias that this introduces to yield estimates depends on how much of the natural mortality process has occurred before samples are collected. We believe that most of the interannual changes in mortality due to variations in seagrass habitat would occur very early in the life history of these prawns, before samples are collected and numbers estimated, and therefore would introduce relatively little bias to estimates.

Despite the limitations, our estimates of yields from Cairns Harbour are comparable with logbook landing records for the Cairns area. Reported landings of *P. esculentus*, *P. semisulcatus* and *M. endeavouri* for an area within approximately 100 km of Cairns Harbour were 228 t for 1988 and 275 t for 1989 (N. Gribble, personal communication).

These are comparable to our estimate of 178 t for the estimated yield from seagrasses in Cairns Harbour. Some underreporting by fishermen is likely, especially through the discarding of undersized prawns, but most prawns large enough to be retained by commercial nets have at least a nominal value (Table 3). It is also possible that prawns may recruit from other seagrass areas to the north of Cairns that were not included in our model, but tagging studies in the Torres Strait (Derbyshire *et al.* 1990) show that large-scale migrations of *P. esculentus* further than 100 km are unlikely.

Estimating the potential value of seagrass habitat to local fisheries within the duration of most assessment studies is difficult. The use of computer simulation is a powerful tool that can offer resource managers and developers alike initial estimates that can be refined as more data are collected.

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