Computer Simulation of Fisheries Closures

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Summary

Simulation modelling was used to examine the benefits of seasonal and spatial closures of two prawn fisheries which differed in their recruitment patterns; one had a single annual recruitment pulse (annual) while the other had two each year (biannual). An optimization procedure was used to assign monthly fishing effort (within realistic constraints) which would maximize annual catch value. Reductions in values resulting from uncertainty in recruitment timing were examined.

An 'ideal' pattern of monthly fishing effort for each fishery was fitted using an exhaustive search method because other methods could not find the global optimum. Catch values resulting were used as a basis of comparison within each fishery with closure results. For the annual fishery, the best seasonal closure produced 98% of the value of the 'ideal', spatial closures 102%, and combined seasonal and spatial closures 104%. Relative values for the biannual fishery were similar except for combined closures which produced 116%. Generally, however, spatial closures outperformed combined and seasonal closures when recruitment timing was uncertain. Egg production was generally 30–40% of an unfished stock and was highest for combined closures.

Introduction

Modification of fishing effort levels and patterns through seasonal and spatial closures is common in the management of many fisheries. Closures are used to protect breeding stocks (Morgan 1984; Penn *et al.* 1997), and in annual fisheries (those with a single recruitment pulse) they are widely used to maximize the value of landings by delaying the harvest of individuals until they are of a preferred size (Morgan 1984; Somers 1985).

Before closures are introduced as part of the management of a fishery it is usually necessary to project the likely impact on fish stocks, the economic performance of the fishery and even the effect on individual fishers. Accurate predictions are difficult because of the complexity of these systems, the annual variation due to environmental effects, and the necessity to predict the way in which the pattern of fishing effort will be altered. This requirement to predict the response of fishers to the proposed changes is a major determinant in the success of any management strategy, and yet may be the least predictable part of the system.

Simulation modelling offers an approach to exploring the possible consequences of fisheries closures and has been used to investigate a range of fisheries closures (Nichols 1982; Gribble and Dredge 1994; Watson and Restrepo 1994). Penaeid fisheries are particularly amenable to this approach as most species are short-lived, recruitment patterns are generally simple, and the commercial value of individuals often increases rapidly with size. Moreover, many of these fisheries are annual or nearly so in nature so that closures can be developed to prevent both recruitment and growth overfishing.

Computer models of tropical penaeid fisheries have been used to investigate seasonal (Watson *et al.* 1993*b*) and spatial closures (Die and Watson 1992*a*). They have also been used to assess the importance of critical habitat to the value of penaeid fisheries (Watson *et al.* 1993*a*). Critical to these models is the basis for determining and representing recruitment patterns (Carothers and Grant 1987; Watson *et al.* 1996), rates of migration and growth (Cohen and Fishman 1980; Watson and Turnbull 1993), and the response of fishers to closures (Allen and McGlade 1986; Watson *et al.* 1993*b*).

To consolidate this work we propose to model two tropical fisheries, one with an annual, and the other with a biannual recruitment pattern (two pulses each year), and to examine the relative advantages of seasonal, spatial, and combined seasonal-spatial closures on yields, catch values, and egg production. Annual recruitment is often assumed in models of prawn fisheries; however, in tropical fisheries such as northern Australia, biannual recruitment also occurs. The performance of closures will also be examined under circumstances where the timing of the recruitment pattern or offshore migration is stochastic as in nature.

Model

Model equations

Equations for the processes included in the simulation model (such as growth and natural mortality) have been published elsewhere (Restrepo and Watson 1991; Die and Watson 1992*a*; Watson *et al.* 1993*b*) and space restriction do not allow their duplication here.

Model parameters

Parameters specific to the prawn species and fishery being simulated were drawn from descriptions of the fishery for *Penaeus esculentus*, the brown tiger prawn, in the Torres Strait of northern Queensland, Australia (Watson *et al.* 1993*b*). Size-specific prices represent those for the same species in the northern fisheries of Western Australia (WA Dept of Fisheries unpublished data). There was no information available on the seasonal variation of prices, therefore we used the same price structure for all months of the simulation but acknowledge that variations by season do occur and that production levels also influence prices paid. The maximum monthly (11 000 hrs) and maximum annual (108 000 hrs) fishing efforts used were taken from the prawn fishery of Shark Bay, Western Australia.

Annual recruitment fishery

In this scenario all recruits (1.6×10^8) entered the fishery in the month of January at age 0+ months (within their first month) (Fig. 1).

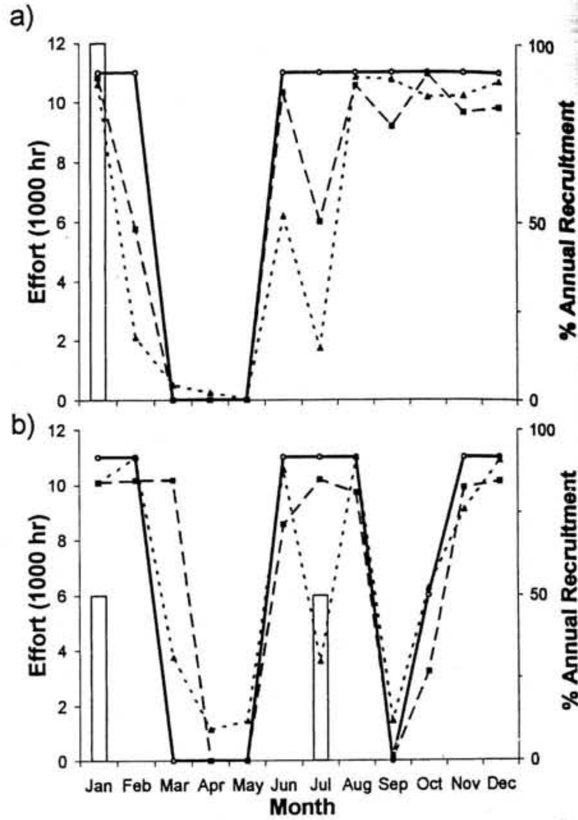

Fig. 1. Recruitment and monthly fishing effort patterns used in the simulation of the (a) annual recruitment and (b) biannual recruitment prawn fisheries. Bars are recruitment numbers, solid lines are 'ideal' (exhaustive search) monthly efforts producing maximum annual catch value, dotted lines are monthly efforts optimized (simplex method) to maximize value without a closure, and dashed lines are monthly efforts optimized (simplex method) to maximize value in the presence of a seasonal and/or spatial closure.

Biannual recruitment fishery

As in the annual recruitment scenario, 1.6×10^8 recruits entered the fishery during their first month of age except there were two recruitments of prawns each year, half entering in January and half in July (Fig. 1).

Stochastic recruitment timing

In order to evaluate the effects of the variation in recruitment timing, often observed with wild prawn fisheries, on the performance of closure strategies, the timing of recruitment used was stochastic in nature. For these evaluations 200 trials were completed during which the recruitment patterns described above were shifted by a random factor drawn from a normal distribution (mean=0 months, s.d.=0.23 month). The approximate 95% confidence limits of recruitment timing are two weeks in advance and two weeks after the mean shown in Figure 1.

Fishing effort optimization and ideal value fishery

An exhaustive search was used to determine the 'ideal' monthly pattern of fishing effort to maximize commercial value in the absence of any seasonal or spatial closures (Fig. 1 solid lines).

This will be referred to as the 'ideal value' for each of the annual and biannual recruitment fisheries. Note: as the lifespan of these prawns is about 18 months there is residual stock from the previous year available to the fishery. The annual yields, values, and egg productions resulting from this pattern of fishing effort in the annual and biannual recruitment fisheries were used as the basis for comparison with subsequent investigations of seasonal and spatial closures.

The exhaustive method of investigating the best distribution of monthly fishing effort was not practical for assessing a wide range of possible seasonal and/or spatial closures; therefore we used a modification of the downhill simplex method of Nelder and Mead (Sprott 1991). Parameter estimates of monthly fishing effort were constrained to 11 000 hours (the maximum for the modelled fishery) and similarly to an annual maximum of 108 000 hours. This was achieved by a combination of constraining individual monthly effort parameter searches within the simplex program and through the use of a penalty function when the sum of monthly fishing effort exceeded 108 000 hours in total. The optimum pattern of fishing efforts resulting were similar to, but not identical to, those resulting from exhaustive searches (Fig. 1); therefore the results of closure evaluations are expressed as a percentage of the maximum produced by the ideal fishery described above. During the evaluation of a closure the closed months were assigned no fishing effort and were not included in the optimization procedure.

RESULTS

The 'ideal' value fishery

The ideal monthly pattern for the biannual recruitment fishery had two periods of no fishing compared to the single period for the annual recruitment fishery (Fig. 1). The maximum value from the biannual recruitment fishery using the exhaustive search was 88% of the annual recruitment fishery. As expected the ideal pattern of monthly fishing effort for the biannual recruitment fishery included two periods without fishing; however, these periods were expected to be symmetrical. The first no-fishing period, corresponding to the January recruitment, was, as expected, identical to that for the annual recruitment fishery which also had a January recruitment. The second no-fishing period, corresponding to the July recruitment, was expected to be of a similar duration but to occur six months later. This was not the case (Fig. 1b), and in addition, the ideal fishing effort for October in the biannual recruitment fishery was 6000 hours which was different from that for all other months, which were either at the monthly maximum of 11 000 hours or had no fishing (closed). There are two explanations for this lack of symmetry. Two months after the July recruitment, when individuals are becoming vulnerable to fishing gear (through gear selectivity), the fishery should be closed for three months to prevent the harvest of these individuals until they increase in value; however, valuable individuals from the January recruitment are still numerous and this moderates the duration of the ideal closure. It would also appear that monthly time steps are too long or coarse to allow symmetry in the closure periods. Smaller time steps such as weeks might have allowed the fishery to be closed for the first half of October and open (fished at maximum rate of 11 000 hours month^{-1}) for the second half.

Using different values for the initial guess, the optimization program converged to solutions with noticeably different parameter (monthly effort) estimates and with similar resulting commercial values. This behaviour suggests that this is a global rather than a local optimization problem, and that appropriate global optimization methods such as simulated annealing (Kirkpatrick *et al.* 1983) or genetic algorithms (Gallagher and Sambridge 1994) should be used.

Seasonal closure

Value

A plot of the response surface of value to closure starting month and duration reveals that some closures approached to within 5% of that produced by the ideal value fishery (black shaded areas of Figure 2). The optimum seasonal closure (with no accompanying spatial closure) for the annual recruitment fishery was a three-month closure starting in March (two months after recruitment) (Figure 2a marked with white cross). This closure produced values that were 98% of the ideal value fishery (which had a very similar distribution of fishing effort — Figure 1). Adding uncertainty to the recruitment timing in conjunction with this closure reduced fishery value by a small margin to 97%.

The best closure for the biannual recruitment fishery was a two-month closure starting in April (Figure 2b — marked with white cross). This closure produced a value 98% of the ideal value fishery. Biannual recruitment caused the value response surface

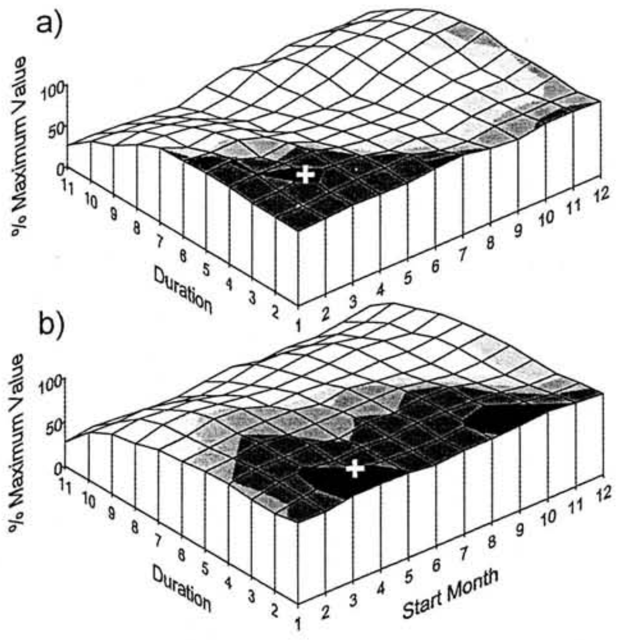

Fig. 2. Surface plot of percent maximum effort for seasonal closures of different durations and starting months for the (a) annual recruitment and (b) biannual recruitment fisheries. Black areas are those combinations resulting in annual catch values within 5% of the maximum from an ideal fishery and a white cross marks the best combination of duration and starting month.

to be smoother than for annual recruitment causing a wider range of seasonal closures to produce similar catch values (Fig. 2b — note the extent of shaded surfaces indicating closures producing values within 20% of the maximum produced by the ideal value fishery). Uncertainty in the timing of recruitment reduced value from this closure to 96%.

Yield

Although effort allocation was optimized to produce the maximum value not yield, the results from seasonal closure combinations are still instructive. For the annual recruitment fishery the maximum annual yield resulted from a two-month closure starting in March. This yield was 97% of that produced by the ideal value fishery and 3% more than the yield produced by the closure producing the highest value.

For the biannual recruitment fishery the maximum yield was produced by a three-month closure starting in March. This yield was 3% higher than that produced by the ideal value fishery and 6% higher than the closure which produced the highest value.

Eggs

As expected, any closure of the fishery generally improved egg production compared to a simulated fishery that operated year round. The three-month closure which produced the maximum value for the annual recruitment fishery increased annual egg production by 20% over that of the ideal value fishery and allowed 33% of the eggs production of an unfished stock.

The two-month closure maximizing value for the biannual recruitment fishery increased annual egg production by 7% over that of the ideal value fishery and allowed 35% of the egg production of an unfished stock.

Spatial closure

Value

Using a spatial closure width of 8 km, the value of the annual recruitment fishery reached 102% of that of the ideal value fishery, outperforming the best seasonal closure (Fig. 3). Changes to value introduced by uncertainty in recruitment timing were small, indicating that this variability has little or no impact on spatial closure performance.

The best spatial closure width for the biannual recruitment fishery was 7 km offshore and produced a value 104% of the ideal value fishery. Uncertainty in recruitment timing reduced value to 96%.

Yield

The spatial closure of the annual recruitment fishery which produced the maximum value (8 km offshore) produced the same yield as that of the best seasonal closure. The best spatial closure of the biannual recruitment fishery (7 km) produced 96% of the yield of the best seasonal closure.

Eggs

Egg production resulting from the best spatial closure of the annual recruitment fishery for value (8 km offshore) was 33% of the unfished egg production and 120% of the egg production

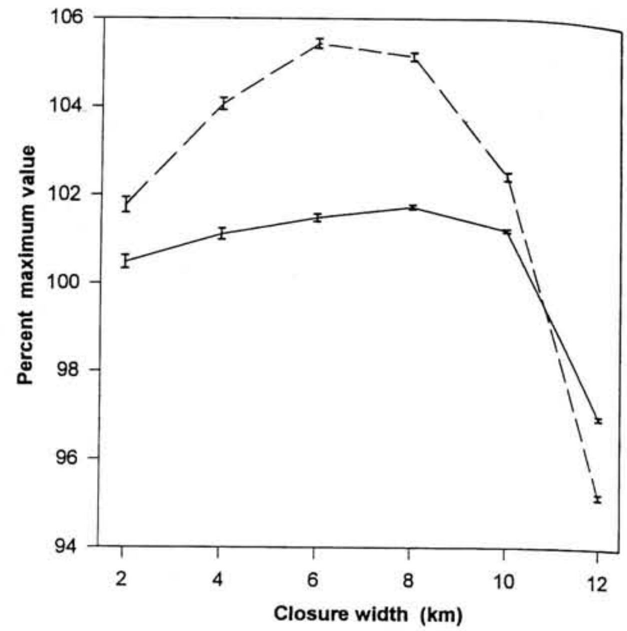

Fig. 3. Percent of maximum annual landed value resulting from simulated spatial closures extending to varying distances offshore for the annual recruitment (solid line) and biannual recruitment fisheries (dashed line) with 95% confidence limits. No concurrent seasonal closures were simulated.

associated with the ideal value fishery. For the biannual recruitment fishery there was 39% of the unfished egg production and 120% of that of the ideal value fishery.

Seasonal-spatial closure

Value

The best combination of seasonal and spatial closures of the annual recruitment fishery was a closure from April to July (inclusive) with a spatial closure width of 7 km offshore which produced 104% of the value of the ideal value fishery. This was the best single closure of this fishery and outperformed either the solely seasonal or spatial closures in the absence of uncertainty in recruitment timing. With the addition of uncertainty in the recruitment timing the value was reduced to 94% of that produced by the ideal no closure fishery which was less than that accomplished by spatial closures alone.

The best combined seasonal and spatial closure for the biannual recruitment fishery was a closure of June and July with a spatial closure width of 9 km which produced 116% of the ideal value fishery. This closure outperformed any single seasonal or spatial closure of this fishery. Uncertainty in recruitment timing reduced this considerably to 85%.

Yield

The yield for the best combined seasonal and spatial closure of the annual recruitment fishery was 86% of that of the ideal value fishery, while for the biannual recruitment fishery this was 96%.

Eggs

The egg production of the best combined seasonal and spatial closure of the annual recruitment fishery was 44% of the unfished level and 162% of the ideal value fishery. The best combined closure of the biannual recruitment fishery was 43% of the unfished level and 132% of the egg production from the ideal value fishery.

Closure strategies

A decision tree can be drawn up outlining the process of choosing a closure management strategy (Fig. 4). Ability to make these decisions would rely on accurate information and on suitable motivation. If fishers work in cooperation to achieve the global goal of maximizing the annual value of the catch (such as our ideal value fishery) there would clearly be no need to consider a closure. As this is seldom the case it becomes important to know whether stock migration or recruitment patterns allow effort to be targeted on individuals of the optimal size to maximize value of the fishery. Compulsory changes in fishing effort patterns might gain the benefits that would have been achieved through cooperation.

Migrating prawns can be managed through spatial closures; however, if prawns do not continue to migrate until they are at least the optimal harvest size then these spatial closures should be augmented by a seasonal closure. If the animals do not migrate then it becomes important to know whether recruitment patterns are simple, that is consisting of animals of a single size and value. If this is the case then seasonal closures can be effective in maximizing value, otherwise it may be difficult improve the value of the fishery through seasonal or spatial closures.

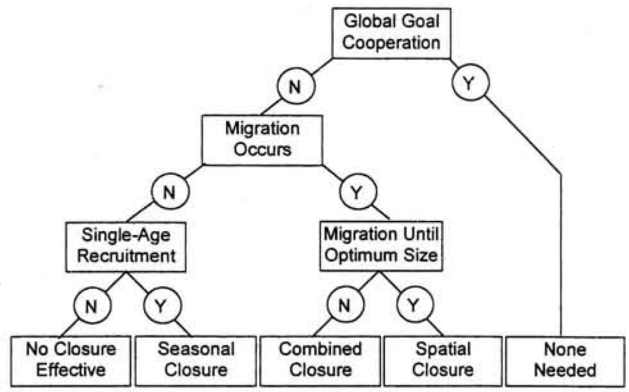

Fig. 4. Decision tree for choosing closure strategies to maximize annual catch value from a prawn fishery.

DISCUSSION

Seasonal closures were equally effective in maximizing harvest value in our two simulated fisheries, the annual and biannual recruitment fisheries, and were similar in their starting month and duration. It is likely that constraints on the maximum fishing effort which the optimization program could assign to any one month (11 000 hours) may have reduced the performance of seasonal closures particularly in the case of the annual recruitment fishery where all individuals reach the optimal size in the same month and can not all be harvested using the fishing effort allowed.

Spatial closures did better and outperformed the ideal value fishery which used the optimal distribution of monthly fishing effort but did not use a spatial closure. For the annual recruitment fishery the benefits of spatial closures were not eroded by uncertainty in recruitment timing like they were for seasonal closures but our investigations indicate that they are vulnerable to the equivalent, that is variation in migration timing and rates. Unlike the annual recruitment fishery, spatial closures of the biannual recruitment fishery were reduced by uncertainty in recruitment timing and this is likely to have been a consequence of the more complex recruitment pattern.

Combined seasonal and spatial closures outperformed any separate seasonal or spatial closure for both the annual and biannual recruitment fisheries. Combined closures produced higher catch values and higher egg production than either seasonal or spatial closures alone. Because combined closures include seasonal closures, their benefits were reduced by uncertainty in recruitment timing, particularly that of the biannual recruitment fishery. Improvements with the use of a combined closure *versus* either a seasonal or spatial closure alone were most evident for the biannual recruitment fishery. It should be noted, however, that the ideal value used as a benchmark for the biannual fishery was 88% of that for the annual recruitment fishery. Nevertheless it demonstrates how an appropriate closure can maximize the value produced by a fishery even if complex recruitment patterns make this difficult and restrict the maximum value obtainable.

Improvements to the process of optimizing the distribution of monthly fishing effort to maximize the landed value produced by our simulated closures must await work on new global optimization algorithms. These may include modifications of the simulated annealing method to better accommodate parameter constraints and achieve a true global optimum. With more efficient algorithms it may be possible to attempt a nested approach whereby the simulation program attempts to optimize fishery value by investigating different closures (combinations of starting month, duration, and distance offshore), and within each closure the monthly distribution of fishing effort is also optimized. Since the parameter values for closure starting month and duration are integer values, this would require a different approach to optimization than we have employed here.

Closures can be used by fisheries managers for many purposes. When the object is to maximize the value of annual landings then closures are used to modify the distribution of fishing effort in time and/or space in order to alter the mortality rates of selected components of the stock. These components typically are lower in their current landed value than the rest of the stock. In some fisheries it is easy to protect individuals until they reach an optimal value but in others it is not. This depends on the degree of spatial separation possible between stock components or cohorts of different values.

Changes to patterns of fishing effort in response to closures are not always predictable but they are the greatest determinant of their success as a management measure. Work by Allen and McGlade (1986); Die and Watson (1992b), and others has shown how differing strategies amongst fisheries can significantly influence the effects of management measures.

Many other factors may also influence closure effectiveness. Spatial closures are weakened by variable migration timing and rates, while seasonal closures are undermined by variable recruitment timing, multi-size or value recruitment, and by the persistence of individuals from one fishing season to the next. In Western Australia many prawn fisheries start the year by harvesting high value individuals which have survived from the previous year. These 'residuals' are soon harvested — often before 'new' recruits from the current year reach the optimal harvest size to maximize the value of the fishery. In these fisheries spatial closures must augment seasonal closures in order to prevent growth and recruitment overfishing.

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References

Allen, P, and McGlade, J M (1986). Dynamics of discovery and exploitation: the case of the Scotian shelf groundfish fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* **43**, 1187–200.

Carothers, P E, and Grant, W E (1987). Fishery management implications of recruitment seasonality: simulation of the Texas fishery for the brown shrimp, *Penaeus aztecus*. *Ecological Modelling* **36**, 239–68.

Cohen, M D, and Fishman, G S (1980). Modeling growth-time and weight and length-time relationships in a single year-class fishery with examples for North Carolina pink and brown shrimp. *Canadian Journal of Fisheries and Aquatic Sciences* **37**, 1000–11.

Die, J D, and Watson, R A(1992*a*). A per-recruit simulation model for evaluating spatial closures in an Australian penaeid fishery. *Aquatic Living Resources* **5**, 145–53.

Die, J D, and Watson, R A(1992*b*). Dissipation of spatial closure benefits as a result of non-compliance. *Mathematics and Computers in Simulation* **33**, 451–6.

Gallagher, K, and Sambridge, S (1994). Genetic algorithms: a powerful tool for large-scale nonlinear optimization problems. *Computers and Geosciences* **20**, 1229–36.

Gribble, N A, and Dredge, M C L (1994). Mixed-species yield-per-recruit simulation of the effect of seasonal closure of a central Queensland coastal prawn trawling ground. *Canadian Journal of Aquatic Sciences* **51**, 998–1011.

Kirkpatrick, S, Gelatt, D D, and Vecchi, M P (1983). Optimization by simulated annealing. *Science* **220**, 671–80.

Morgan, G R (1984). Recruitment and closed seasons for *Penaeus semisulcatus* in Kuwait. In: Final Report, Proceedings Third Shrimp and Fin Fisheries Management Workshop, Fin Fisheries Session, 4–5 Dec, 1982. pp. 173–80 (Ed C P Mathews).

Nichols, S (1982). Impacts on shrimp yields of the 1981 fishery conservation zone closure off Texas. *US National Marine Fisheries Service Marine Fisheries Review* **44**, 31–7.

Penn, J W, Watson, R A, Caputi, N, and Hall, N (1997). Protecting vulnerable stocks in a multi-species prawn fisheries. In 'Developing and Sustaining World Fisheries Resources: The State of Science and Management. Second World Fisheries Congress, Brisbane 1996'. (Eds D A Hancock, D C Smith, A Grant and J P Beumer) pp. 383–90 (CSIRO Publishing: Melbourne).

Restrepo, V R, and Watson, R A (1991). An approach to modeling crustacean egg-bearing fractions as a function of size and season. *Canadian Journal of Aquatic Sciences* **48**, 1431–6.

Somers, I F (1985). Maximising value per recruit in the fishery for banana prawns, *Penaeus merguiensis*, in the Gulf of Carpentaria. In: Second Australian National Prawn Seminar. (Eds P C Rothlisberg, B J Hill and D J Staples) pp. 185–91. Cleveland, Australia.

Sprott, J C (1991). 'Numerical recipes — routines and examples in Basic.' Cambridge University Press, Sydney. 398 pp.

Watson, R A, and Restrepo, V R (1994). Evaluating closed season options with simulation for a tropical shrimp fishery. *ICES Marine Science Symposia* **199**, 391–8.

Watson, R A, and Turnbull, C T (1993). Migration and growth of two tropical penaeid shrimps within Torres Strait, Northern Australia. *Fisheries Research* **17**, 353–68.

Watson, R A, Coles, R G, and Lee Long, W J (1993a). Simulation estimates of annual yield and landed value for commercial penaeid prawns from a tropical seagrass habitat, northern Queensland, Australia. *Australian Journal of Marine and Freshwater Research* **44**, 211–9.

Watson R A, Die, D J, and Restrepo, V R (1993*b*). Closed seasons and tropical penaeid fisheries: a simulation including fleet dynamics and uncertainty. *North American Journal of Fisheries Management* **13**, 326–36.

Watson, R A, Turnbull, C T, and Derbyshire, K J (1996). Identifying tropical penaeid recruitment patterns. *Australian Journal of Marine and Freshwater Research* **47**, 77–85.