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A Case Study in Successful Management of a Data-Poor Fishery Using Simple Decision Rules: the Queensland Spanner Crab Fishery

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Abstract.—The Queensland spanner crab *Ranina ranina* is the target of a relatively data-poor, low-value fishery that has been managed for the last decade by using total allowable catches (TACs) in an individual transferable quota system. Despite the fact that this management system is usually applied to data-rich fisheries, it has been successfully used on this data-poor fishery. The key factor has been the use of harvest strategies that consisted only of simple decision rules that were appropriate given the size of the fishery and knowledge of the resource. These strategies were tested in a management strategy evaluation framework; however, it was not traditional in that (1) the operating model (or "true" resource to be managed) was not conditioned to data but rather was set to parameter ranges seen as appropriate for the resource and (2) the TAC was not set by using a stock assessment model, so the magnitude of the stock biomass was unknown. The important test was whether one could develop harvest strategies that were robust to this large uncertainty in knowledge by using only commercial catch rates. The management system had to be adaptive over time as more was learned about the biology of the species and how the harvest strategies affected the management of the fishery. This meant that the TAC was almost always set using the harvest strategies, but modifications to the decision rules were made on several occasions as more was learned about the fishery. The transparency and simplicity of the rules mean that the industry was empowered to make significant contributions to fine tuning the harvest strategies. As a result, the process does not rely solely on scientific advances but on the pooled knowledge of scientists, industry, and managers in a cooperative environment.

Spanner crabs *Ranina ranina*, also known as red frog crabs in Asia and kona crabs in the United States, inhabit sandy substrates in shelf waters throughout the tropical and subtropical Indo-Pacific region from the western Indian Ocean (de Moussac and de San 1987) to the northcentral Pacific Ocean (Onizuka 1972; Brown et al. 1999). These large, edible crabs are the subject of distinct but relatively small fisheries throughout this region, including the Seychelles (Boullé 1995), Japan (Sakai et al. 1983), Philippines (Tahil 1983), Hawaii (Onizuka 1972; Brown 1984; J. P. Vansant, University of Hawaii, unpublished data), and Australia (Brown et al. 1999). Information on how, and indeed whether, many of these fisheries are managed is scant. Apart from Queensland, Australia, where output controls have been introduced, input controls on fishing apparatus are believed to be the norm where controls exist.

In Australia, adult spanner crabs are targeted by using simple, inexpensive baited tangle nets (dillies) placed on the sea floor. The nets are typically about 1 m^2 in area, baited with Australian sardine *Sardinops neopilchardus*, and deployed on a set of groundlines for periods ranging from 30 min to 2–3 h. The spanner crabs' broad, flattened appendages and elongated body shape enable them to burrow rapidly and swim efficiently (Vicente et al. 1986) but also render them susceptible to this method of fishing. The spanner crabs' mobility allows them to be attracted to bait from considerable distances of up to 70 m (Hill and Wassenberg 1999), and the terminal segments of their legs easily become enmeshed in the tangle nets (Kirkwood and Brown 1998). This fishing apparatus is surprisingly size selective; it is unusual to catch a spanner crab smaller than 50–60 mm rostral carapace length (RCL; Brown et al. 1999; Kirkwood et al. 2005).

While the species has a wide depth distribution from the intertidal to at least 100 m, the commercial catch is

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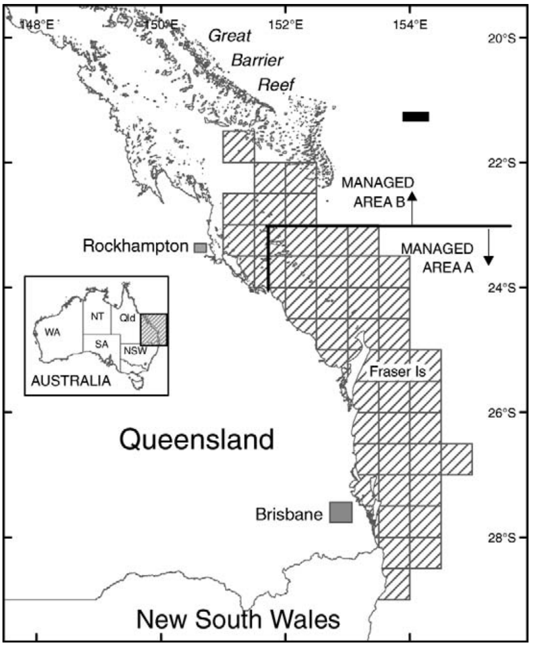

FIGURE 1.—Principal spanner crab fishing grounds in Queensland, Australia (hatched grids), showing the boundary between managed area A (total allowable catch [TAC] regulated) and managed area B (no TAC). Grids where less than 20 fishing days have been logged since 1988 are not shown; fishing areas further south in New South Wales (NSW) are not shown.

taken principally from depths between about 30 and 80 m. There is a marked sexual disparity in size, with male spanner crabs reaching 150 mm RCL while females rarely exceed 120 mm RCL (Brown et al. 1999). Although certain aspects of the species' life cycle, biology, and behavior are well documented, critical elements of their population dynamics (e.g., growth rates, age at maturity, longevity, and recruitment) are poorly known (Chen and Kennelly 1999; Kirkwood et al. 2005).

History of the Australian Fishery

The Queensland component of the fishery is of relatively recent origin (Figure 1), having developed initially in coastal waters off Moreton Island in the 1970s following a fortuitous catch of spanner crabs by a commercial offshore line-fisher using the inverted dillies ("witches' hats") normally used at that time in the estuarine fishery for blue swimmer crabs *Portunus pelagicus* (R. Freeman, fisherman of the Queensland spanner crab fishery, personal communication). During the subsequent decade, more fishers became interested in spanner crabbing as a sideline to other fishing activities, and increasing quantities of product were marketed through the Queensland Fish Board.

However, when local processors identified export markets in Asia and elsewhere, a spectacular increase in activity followed, with fishing effort expanding from 2,200 boat-days in 1990 to 14,900 boat-days in 1994. This expansion was accompanied by an increase in landings over the same period from about 470 metric tons to over 3,000 metric tons, at which point the fishery became the largest in Queensland in terms of total catch of an individual species (Williams 1997). During this period, the fishery also expanded northward and southward in response to the discovery of new fishing grounds, some stock reduction in close inshore grounds, and the development of an export market for live product.

The total catch declined from its 1994 peak as a result of reduced fishing effort in 1995 and stringent management restrictions on the fishery that were introduced in 1996. Under the total allowable catch (TAC)/individual transferable quota (ITQ) arrangement, the fishery is currently producing around 1,300 metric tons (in Queensland) and 200 metric tons (in New South Wales). Most of this is exported live to Asian markets, but a small proportion is sold domestically.

Development of Management Arrangements

A chronological summary of the fishery's development and management (Table 1) shows the classic initial expansion of the fishery followed by a tightening of management controls and subsequent reduction in total catch to more sustainable levels.

Data Collection Arrangements

Daily commercial catch and effort data have been collected since 1988 by way of a statewide compulsory logbook reporting program (Figure 2). This data source provides daily effort (as net-lifts) and catch (as weight in kilograms), as well as fishing location data. Initially, the precision of the location data was low (at the $0.5° \times 0.5°$ resolution of the logbook grid), but more recently, with the uptake of Global Positioning System units and plotters, spatial reporting resolution has increased to the level of geographical coordinates. Since the advent of the ITQ system, all crabbers are required to notify the fishery compliance authorities of their estimated catch and intended landing time and location at least 1 h prior to landing their product; this notification is made by mobile phone via an interactive voice response system. The notification requirement provides compliance staff with the capacity to carry out random checks for quota and minimum legal size infringements. Fishers also have online access to the Queens-

TABLE 1.—Key dates in the development and history of the spanner crab fishery in Queensland, Australia, and the management or fishery change that occurred.

Year	Development
1970s	Small-scale exploratory fishing begins after the identification of the spanner crab resource off Moreton Bay.
1980s	Fishery develops, mostly small operators with outboard-powered vessels. Fishery expands south into northern New South Wales waters and north to Hervey Bay. Interim Crab Management Advisory Committee (MAC) introduces minimum legal size (10 cm carapace length, primarily for marketing reasons) and some gear restrictions.
1988	Queensland Department of Primary Industries (DPI) establishes a compulsory logbook program for reporting daily catch and effort statistics in all Queensland commercial fisheries.
1994	Investment warning is issued. A Queensland DPI researcher highlights an exponential increase in spanner crab fishing effort since 1992, resulting in Interim Crab MAC's recommendation for the introduction of output-based management arrangement to constrain further expansion. Management options discussion paper is released; public meetings are held.
1995	Crab MAC is appointed. Interim management arrangements are introduced based on limited entry. Fishery is divided into managed areas A (known fishing grounds; 244 entitlements) and B (exploratory grounds; 306 entitlements; Figure 1).
1996	Annual (competitive) total allowable catch (TAC) for 1996–1997 is set at 2,000 metric tons allocated quarterly, with a daily catch quota of 300 kg/vessel. Quota year is changed to 1 July–30 June (fiscal year), and TAC is increased by 600 metric tons.
1997	Daily catch limit is reduced to 200 kg/vessel, later changed to eight baskets (~25 kg/basket); weekend closure is extended by 24 h, resulting in a 4-d fishing week. Draft management plan is released for public discussion. Independent consultation and Future Management Options Group are established to evaluate possible changes. Crab MAC recommends the introduction of an individual quota system to counter problems with competitive TAC.
1998	Independent Assessment Advisory Committee is established to review quota allocation arrangements. Revised draft management plan and regulatory impact statement are released.
1999	Management plan is released, setting initial TAC at 2,800 metric tons to take effect on 1 June 1999 (TAC year now 1 June–31 May). Spanner Crab Stock Assessment Group (SAG) is established to develop "scientific method" for evaluating the status of the fishery and appropriate decision rules for setting the TAC.
2000	The SAG keeps TAC for 2000–2001 at 2,800 metric tons based on accepted methodology, including decision rules. Annual fishery-independent spanner crab survey is established by DPI with dedicated industry funding.
2001–2005	The SAG sets TAC for 2001–2002 at 2,208 metric tons. The SAG is directed to carry out a second management strategy evaluation (MSE; 2002), after which the assessment period is changed from 5 to 6 years and the TAC year is changed from 1 to 2 years to promote stability in the fishery. The TAC for 2002–2003 set at 1,727 metric tons and remains unchanged during 2003–2004 and 2004–2005.
2006–2007	The TAC is increased to 1,923 metric tons for 2006–2008. The model prediction, on the basis of increasing fishery-dependent and independent catch rates, is considerably higher than this. However, industry believes that such a large increase would not be in its best interests and strongly supports a far more modest rise. The SAG is instructed to revise the assessment and TAC-setting rules to prevent possible adverse impacts resulting from an expected reduction in relative stock abundance indices (from currently high to long-term average levels). Queensland DPI carries out a spanner crab fleet survey to identify potential undocumented sources of increasing fishing power. The DPI and SAG undertake a third model-based MSE to revise the assessment and TAC-setting procedures. New methods and rules, formally incorporating the fishery-independent survey data, are accepted in preparation for the 2008–2010 TAC period.
2008	The SAG sets TAC for 2008–2010 at 1,923 metric tons using revised methodology.

land Department of Primary Industries and Fisheries quota tracking system that provides instant updates of their expended and available portions of quota, as well as an environment for quota trading.

Weather frequently constrains the operation of smaller vessels in the fleet, and many crabbers who do not catch their quota (because of other income-earning activities) choose not to lease or sell the unused portion. This accounts for the annual catch being consistently less than the TAC.

The fishery-independent spanner crab survey protocol was developed as a result of recommendations from the 1998 Stock Assessment Review Workshop (Dichmont et al. 1999) and was expanded recently to include northern New South Wales waters (Brown et al. 2008). All six regions of the main part of the fishery are surveyed during May of each year by chartered commercial and research vessels. Within each region (a single region spans a block of coastal waters from 30 to 90 nautical miles wide), five fixed, 6- × 6-min subgrids are sampled. Each subgrid is divided notionally into a 10 × 10 matrix, giving 100 possible sampling points or sites from which 15 are chosen randomly each year. At each site, a line or string of 10 standard commercial tangle nets baited with Australian sardine and spaced 50 m apart is deployed for a minimum of 40 min. The 10-net set is the sampling unit as individual net catches are not enumerated separately, but all spanner crabs are measured (RCL; mm) and sexed.

Management Strategy Evaluations, Assessment, and Decision Rules

The initial objective of moving from an input control system to ITQs was to maintain a sustainable resource while having catch stability in a noncompetitive fishing environment. Under input controls, the fleet exhibited strong "race to fish" behavior that seriously eroded their profitability. However, the initial TAC was competitive and set too high—contrary to scientific

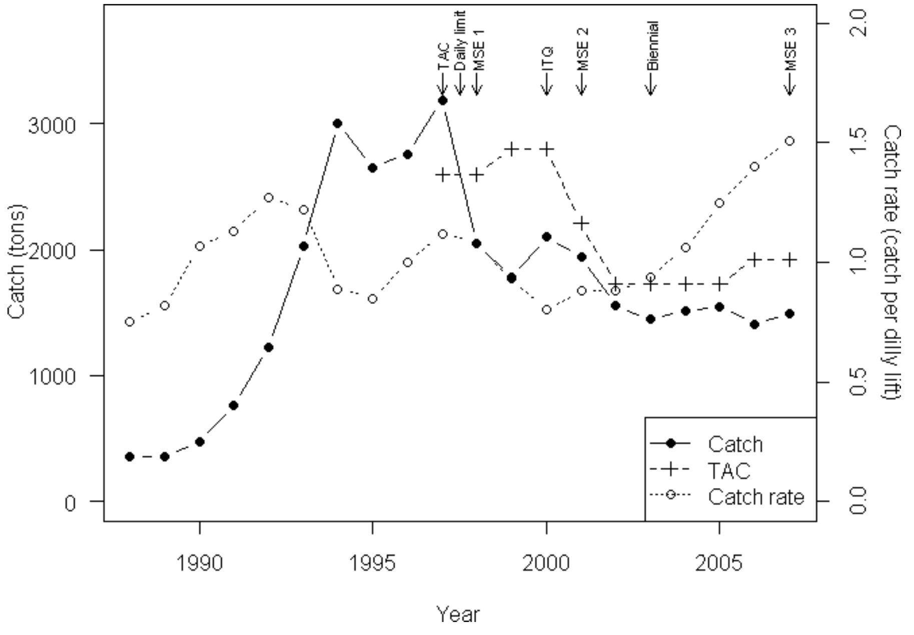

FIGURE 2.—Spanner crab catch (metric tons), total allowable catch (TAC; metric tons), and catch rates (catch/dilly-lift) over time since the 1988 commencement of the logbook program in Queensland, Australia. Key management changes are highlighted at the top of the figure (TAC = moving to TAC; daily limit = implementing a daily catch limit; MSE 1 = undertaking the first management strategy evaluation [MSE]; ITQ = moving to individual transferable quotas; MSE 2 = undertaking the second MSE; biennial = moving to biennial assessments; MSE 3 = undertaking the third MSE).

advice—and this caused some issues. Several years of very high catches led to a decline in the stock, which resulted in subsequent restrictive TAC levels. Furthermore, the competitive TAC meant that fishers caught their quota very quickly—a situation later mitigated by the introduction of daily catch limits. Thus, many of the benefits of the TAC system were realized only when the fishery moved to ITQs.

The Queensland Spanner Crab Stock Assessment Group (SAG) believed that clear rules for setting the TAC in an ITQ system would be preferable to a flexible system in which TACs are set by agreement—a system that may lead to argument, distrust, and political interference. To aid in the development of these rules, three separate and distinct management

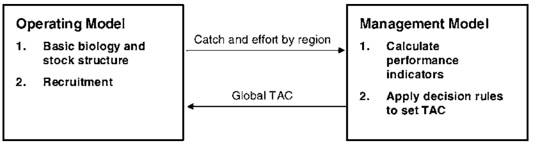

FIGURE 3.—Schematic describing the relationship between the operating model and the management model in the spanner crab management strategy evaluation (TAC = total allowable catch).

strategy evaluation (MSE) exercises have been undertaken since 1996.

The MSE is a simulation framework that models the whole management system and can be used to compare and evaluate the relative performances of different management strategies. The framework consists of an operating model and a management model (Figure 3).

The operating model can be considered a virtual resource representing the underlying dynamics of the resource and the fishery and includes methods for generating the types of data typically collected from the fishery—in this case, catch and effort by region. There is also an assessment procedure that analyses the fishery and/or monitoring data generated by the operating model (but remains "ignorant" of other "truths" included in the operating model) and a set of decision rules that interprets the results of the assessment procedure and leads to the modeled management advice. Here, abundance indicators were based on the slope of a linear regression of the previous 5 years' catch rates against time for each region. A global weighted abundance indicator was also calculated (see Appendix 1).

The management or harvest model comprises the monitoring program, the applied assessment-related analysis method, and the decision rules used to set the

TAC. The MSE is used to compare a set of alternative management strategies. The outcome from the management strategy (e.g., the level of catch to be applied in the next year) is fed back to the operating model and is used to simulate the dynamics of the "true" situation being managed.

The overall performance of a management strategy is summarized by using performance measures that are derived from predetermined management objectives. In the spanner crab MSE, the biomass relative to the start of the simulation, the total catch, and the regional catch rates over time and the interannual catch variability were used to assess the performance of each management strategy. These performance measures are similar to those used, for example, by Punt and Smith (1999). The performance measure values are based on the "true" resource as encapsulated by the operating model.

It is essential for the complete range of uncertainties (e.g., those related to biology, stock structure, and how management decisions are implemented) to be identified and modeled so that their effects can be quantified. Most of the uncertainty was associated with recruitment, growth, and stock structure.

The operating model is almost always more detailed than the models underlying the stock assessment. For example, it may explicitly include multiple stocks even though the stock assessment is based on the assumption of a single homogeneous stock. This mismatch between the operating model and the assessment procedures within each management strategy is one of the strengths of the MSE approach as it allows the impact of differences between the assessment procedure assumptions and reality to be quantified.

This means that the MSE approach allows the tradeoffs among the (preagreed and prespecified) management objectives achieved by different management strategies to be evaluated, taking account of various sources of uncertainty (e.g., uncertainty in the assessment, implementation error, etc.). The MSE approach has been applied to several single and multispecies fisheries (Punt 1992; De la Mare 1996; Butterworth et al. 1997; Punt and Smith 1999; Smith et al. 1999; Punt et al. 2002; Dichmont et al. 2006) and at the ecosystem level (Sainsbury et al. 2000; Fulton et al. 2007).

The First Management Strategy Evaluation and Decision Rules

The first MSE for the spanner crab fishery (Appendix 1) was undertaken in 1998, when little was known about the species' population dynamics. It was used to create decision rules to set a TAC aimed at stabilizing the annual catch while keeping the resource sustainable, with the intent of providing (1) economic stability, especially through reducing competition between fishers, and (2) overall sustainability but not at the expense of any one region.

At that time, the only available index of abundance was based on fishery-dependent catch per unit effort (CPUE) data. The decision rules that needed to be tested were iteratively developed by the Queensland Spanner Crab SAG and the modeling team. A key factor here (typical of data-poor fisheries) was a lack of knowledge about the likely magnitude of the sustainable harvest since no estimate of total biomass was available. Given the lack of information about key processes, such as growth and recruitment dynamics, the objective was to develop a set of simple, robust decision rules based only on trends in CPUE while taking into account a number of sources of uncertainty and error, including (1) highly variable and unknown recruitment patterns; (2) inaccurate estimates of catch rates (i.e., large observation errors); (3) inappropriate management regions with respect to the actual stock structure; and (4) the possibility that the catch rates are not directly proportional to biomass. These were tested individually and also in combination.

As a result, the management model assumed that catch rates were proportional to biomass, whereas in reality (in the operating model), catch rates were proportional to biomass only at low density, remaining relatively constant at increasing densities (i.e., a situation of hyperstability).

Although the operating model parameters were not tuned to data (as is usually the case), only parameter values that could be realistically applied to this specific resource were used based on tagging and survey data and experience elsewhere. The strategy used to test the decision rules was to develop an operating model of a hypothetical population that describes the biology of the local spanner crab resource and then to sample this resource to provide regionally explicit catch and effort data (Dichmont et al. 1999).

The management decision rules were then applied to observed regional catch rate data generated by the operating model, and the resulting global TAC was fed back into the operating model for another year's fishing activity. The rules were tested in an annual adaptive cycle over a 25-year period, reflecting characteristics of the species' biology and also the time horizon of the management agency and industry. As the operating model was not tuned to actual data, the objective was to develop management decision rules that were robust to uncertainty about the true status of the stock. A major reference source to make the input parameters (and therefore outputs) realistic was the work reported by Dichmont et al. (1999), wherein growth, natural mortality, and other parameters were estimated from survey and tagging data. The resultant harvest or management strategy used from 1999 to 2001 (Appendix 1, Final Harvest Strategy) consisted of abundance indicators based on regional catch rates over the previous 5 years, which were then applied to a series of simple hierarchical rules to set the TAC.

Several scenarios were tested, including a single stock, several biological stocks, and a mismatch between biological and management stocks. The latter applied a single management process to several distinct biological stocks. Despite uncertainty in these and other biological inputs as tested in the MSE, this harvest strategy was robust because the strategy tended to adapt the TAC to catch rate changes over time. If the TAC was set too high and the resource declined, then so too would the catch rates, resulting in lower TACs being set after a short time lag.

It is important to note that an initial TAC for the spanner crab fishery had to be set. This initial TAC (1,990 metric tons) had been determined previously by extrapolating the catch per unit area in the southern part of the fishery to the total area in which the fishery was known to be operating at the time. The initial TAC was later increased to 2,600 metric tons as a result of industry pressure and an expansion of the known fishing grounds. Thereafter, the TAC was determined by the management decision rules, and the system was self sustaining. This system was very simple and inexpensive to operate: it did not require advanced analytical skills and was transparent to all, including the industry and managers.

Although reductions in the TAC extended by the full amount of the pooled index, increases in the TAC were limited to half the amount of the index. This "half up, full down" policy was initially implemented to provide an additional degree of precaution at a time when stock status was uncertain.

The Second Management Strategy Evaluation and Decision Rules

The second MSE (Appendix 2) was in response to evidence of a possible environmental signal producing a 5–7-year cycle in catch rates. The end result was that the original 1999 rules caused too many unnecessary adjustments, some quite large, at considerable cost to the industry. It was also demonstrated that under a cyclical recruitment scenario, the "half up, full down" rules would progressively drive the TAC down even if, on average, stock biomass remained constant.

The new size- and age-structured operating model tested more variables than previously (e.g., alternative catch rate measures, bias in catch rate indices, and variation in the length of the catch data time-series used in the analysis). However, the most important part was the investigation of potential effects of cyclic recruitment. After much more extensive testing of different scenarios, three major changes were made: (1) the abundance indicators were changed from using the previous 5 years' catch rate data to using the previous 6 years' catch rate data; (2) the "half up, full down" policy was changed to "full up, full down"; and (3) the TAC was changed every second year rather than annually. It was recommended that in years between TAC-setting years, a precautionary assessment should be undertaken to detect any early evidence of major stock problems.

In the 2007 assessment, however, the "exceptional circumstances" clause in the decision rules was invoked in setting the TAC. This was necessary because catch rates had been increasing steadily over several years, and the substantial projected TAC increase was considered not to be in the best interests of the fishery. The reasons were twofold. Firstly, there would very likely be an influx of more boats, which would later need to be removed as the TAC declined. Secondly, catch rates would inevitably decrease to what is now still considered a sustainable level, but in the process the earlier decision rules might require closure of the fishery. Thus, for this particular year, a negotiated TAC was set (well below that projected by the management model), and the SAG was directed to review the method and rules to account for what seemed to be a significantly greater degree of variability in recruitment success than had been factored into the previous rules.

The Third Management Strategy Evaluation and Decision Rules

Since it was clear that the fundamentals of the harvest strategy needed to be changed to a more constant catch rule and an upper catch limit, a new MSE was developed. A further important change was that industry and government had co-invested in a program of fishery-independent annual surveys. This survey time-series was now long enough to be incorporated into the harvest strategy.

The new harvest strategy (Appendix 3) was somewhat different from its predecessor. It incorporated the concept of a base TAC such that the TAC would remain at a fixed level unless some significant change was called for. Both the catch rate and survey data are weighted equally as stock abundance indicators, as there is no a priori reason to consider one data set more accurate than the other in reflecting changes in stock abundance. An initial set of decision rules is applied to the stock abundance indicators to determine whether the TAC is to be re-set to the base TAC or to a different point, regardless of the value of the current TAC.

If the proposed (new) TAC is above or below the base TAC, then a subsidiary decision rule is invoked to determine whether the new value is sufficiently different from the current TAC (i.e., more than ±5% different) to warrant a change. This is designed to avoid making trivial changes to the TAC.

These decision rules contain the following four precautionary elements:

(1) The TAC is increased above the base TAC only if both abundance indices are positive (i.e., they are both higher than their respective base catch rates);
(2) The trigger for an increase above the base TAC is further restricted by the need for both of the indices to exceed +10% (i.e., for both to be more than 10% higher than their respective base catch rates);
(3) When a decrease below the base TAC is indicated, the amount of the reduction is equal to the full amount of the pooled index, but when an increase above the base TAC is indicated, the amount of the increase is limited to half the pooled index; and
(4) When an increase above the base TAC is indicated, the amount of the increase is further restricted by the TAC cap of 2,000 metric tons.

Although the cost of this new harvest strategy has increased due to the inclusion of a survey index, the actual calculations still remain simple and cost effective. The inclusion of the survey index gives a great amount of confidence to the overall harvest strategy as it is not subject to major problems associated with fishery-dependent indices of abundance, such as changes in fishing power.

Role of Co-management

In Australia, the agency responsible for the management of a fishery is determined by the Offshore Constitutional Settlement Agreement (Brayford and Lyon 1995). As a result, the management of the Queensland spanner crab falls to the Queensland state government, which, through promotion of co-management, has established a number of management advisory committees (MACs) with expertise from key stakeholder areas (industry, management, compliance, research, etc.). The subsidiary Spanner Crab SAG advises the Queensland Spanner Crab MAC on technical issues and has been instrumental in developing the spanner crab TAC-setting process. The real success story of this system has been the relationship developed within the SAG. Since 1996, the group has essentially had the same membership. Of particular importance are two fishers (one of whom has been fishing for spanner crabs since the start of the fishery) and a scientist who has had a long involvement in research into the fishery. In addition, there was good communication between industry, modeling, and research personnel. This created an excellent environment for MSE model development and iterative testing and allowed broad input into the subsequent harvest strategies. Also, during periods of controversy, the independent chair encouraged constructive discussion and input from all sectors.

The economic circumstances of the fishery were frequently considered but not formally factored into the MSE. However, one of the MSE's objectives was to create stability in the fishery, avoiding periodic surges of effort (i.e., influxes of new boats), product gluts and associated marketing issues, and costly, "trivial" changes to the TAC. This information was obtained and discussed in the SAG so as to inform the decision rules.

Over the last decade, this SAG has been extremely constructive and rewarding for its members. The result is that fishers have been highly influential in the development of and subsequent adjustments to the assessment methodology and decision rules. For example, it was an industry member who identified that (given natural catch rate cycles) the existing rules could have deleterious long-term consequences on the TAC and who more recently suggested adjusting the TAC from a base reference point rather than from the previous TAC. Subsequent modeling has shown this to be appropriate.

Advantages and Disadvantages of Rules

Advantages

The harvest strategy is simple, easy to understand, transparent, inexpensive, and quick to produce. It does not require complex stock assessment models, which are often data hungry, resource intensive, and difficult for laypersons to comprehend. Given the relatively low value of this fishery, the cost of this method has been more than appropriate. Furthermore, and perhaps more importantly, the transparency of this method has meant that it has been easy for all sectors to (1) contribute to the development of and changes to the system and (2) pool their knowledge in a data-poor environment.

The move to ITQs has meant that the spanner crab fishers can now apply business principles more objectively in deciding when and where they fish. There is no longer a need to try to catch the quota as soon as possible after the start of the TAC season, as was the case under the competitive TAC. The value of the quota has increased from around AU$3.50–4.00 per kilogram (when the ITQ system was introduced) to today's price of $13.00 per kilogram. It would therefore take about 3 years for an investor to start seeing a return as a result of buying into the fishery at the present time. Changes in the TAC appear to have had little influence on the value of the quota, which has always been priced by the kilogram rather than by the quota unit. Contrary to initial expectations, the beach price has increased only marginally to the present $5 per kilogram, which is low for a live-marketed product.

Since the TAC is set by well-defined rules, there is clarity for fishers. Since the introduction of ITQs, there has never been a difference between the TAC advice and the actual TAC that was finally set by the relevant minister. The responsible state government department can take a good deal of credit for this, having implemented the legislation with a sufficient degree of flexibility. While the Spanner Crab Management Plan specified the TAC-setting policy (in terms of the need for a decision-rule-based system), it left the responsibility for developing the technical details of that policy to the co-management process via the Spanner Crab MAC and its SAG. The key to the success of this method was that the rules could be fine-tuned for technical reasons (e.g., as the result of a better information base) but the TAC could not be changed arbitrarily. It is impossible initially to be sure that any harvest strategy is entirely appropriate, so provision for a learning component over time is essential.

Catch rates are now the highest they have been since the commencement of the logbook program, and there are no signs that the method is unsustainable. The good catch rates in the present environment of high fuel costs will also benefit profitability. In the absence of a reliable estimate of stock biomass, sustainability can never be assured; however, in data-poor fisheries such as this, the lack of knowledge about absolute stock status does not preclude active and effective management of the resource.

Disadvantages

One of the major drawbacks of this management system is that because absolute stock status is not known, there is a need for greater precaution in harvest strategies, as was exemplified by the "half up, full down" clauses in the initial decision rules. The combination of these particular rules with natural cycles in catch rates would eventually have driven the TAC down to a point where the fishery was seriously impacted regardless of the status of the stock. Arguably, the level of precaution in these rules can only be inferred from the output from the MSE models, but because the system is based on indices of relative rather than absolute abundance, the true status of the stock is essentially unknown.

The TACs over time have been quite volatile, necessitating substantial adjustments that, in a quota trading environment, have been a cost to the industry. A management system needs to be responsive when change is required, but there have been instances of large changes where this urgency was evidently not warranted. As a result, the 2008 rules are much more likely to tend towards constant catches. It would not have been possible to implement these rules initially, as only after a decade or more is the sustainable level of spanner crab catch becoming clearer.

Important Lessons and Conclusions

The difficulty with managing this resource is that it is a relatively small, low-value fishery managed by ITQs. The ITQs have allowed fishers to concentrate on spreading their catch over a longer period than was the case under the initial competitive TAC arrangement; spreading the catch over a longer period allows fishers to focus their effort on the more valuable live trade. At the start of the ITQ system, the TAC was set at such a high level that a constant TAC policy could have been biologically disastrous. However, little is known about some important elements of this species' population dynamics. Inconsistent results from different studies into spanner crab growth rates, for example, mean that this important process is known only within probability bounds (Kirkwood et al. 2005). The MSEs developed over time have operating models that are not conditioned to catch rate data or other data—they are entirely simulation based. However, they are capable of using a large set of biological parameters and a range of potential population sizes (given that some priors for this species are known) to test whether it is possible to develop an inexpensive but robust set of stock abundance indicators and decision rules. From our experience, the answer appears to be "yes."

While this system suggests that the resource is not overexploited, it cannot determine the extent of possible underexploitation. However, the industry is quite prepared to trade some loss of production for greater confidence in sustainability. The continued increase in both fishery-dependent and fishery-independent indices over the last several years is encouraging, as is the industry's strong desire for an upper cap on the TAC.

In short, there are three simple conclusions: (1) "simple" does not mean bad—simple means easy to interpret and cost-effective; (2) adaptability is essential—alter rules when there is good justification, but adhere to the overall principles; (3) in terms of co-management, an industry that contributes constructively is important, as is having a good working relationship between managers, the industry, and scientists. All this makes for a productive SAG.

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Appendix 1. First Management Strategy Evaluation: Harvest Strategies in 1999–2001

The basic structure of the management strategy evaluation (MSE) is described in Figure 3 in the main text of the article.

Operating Model

The system was modeled to have four management regions (all within managed area A) and four spanner crab stocks. The management areas did not align with the biological stocks: stocks 1 and 2 were regarded as constituting a single management area; stock 3 was regarded as two separate management areas; and stock 4 was correctly identified as a single management area. Although the actual stock regions relative to the management areas are unknown, the theory is to develop decision rules that are robust to errors in the alignment of the stock areas relative to the regions.

A first-order difference model was used to describe the dynamics of the resource from one year to the next:

$$B_{t+1,s} = \rho e^{-M} B_{t,s} - C_{t,s} + \frac{e^{\text{rand}\sigma_r} \alpha B_{t,s}}{\left(\beta + \frac{B_{t,s}}{K_s}\right)}, \tag{1}$$

where $B_{t,s}$ is the biomass of stock s at time t, ρ is a proportional constant, M is natural mortality, $C_{t,s}$ is the catch taken from stock s at time t, K_s is the stock carrying capacity, rand is a random normal deviate (Z), σ_r is recruitment variance, α is a stock–recruit parameter, and β is a stock–recruit parameter that is calculated as follows:

$$\beta = \frac{(1-\delta)0.2}{(\delta - 0.2)}, \tag{2}$$

where δ is the steepness of the recruitment relationship.

The stocks were assumed to be independent of each other (i.e., there was no migration between stocks). A tagging study by I. W. Brown (unpublished data) showed no evidence that spanner crabs migrate significant distances over periods of months and years.

Catch rates in each management area were defined as:

$$\text{CPUE} = B_{t,z}^{\gamma} e^{\text{rand}\sigma_q}, \tag{3}$$

where $B_{t,z}$ is the biomass at time t for management zone z, γ is the index of hyperstability, rand is a random normal deviate (Z), and σ_q is the variance of the catchability coefficient q.

The effects of different degrees of hyperstability (γ) were tested.

Since only a global total allowable catch (TAC) is set by the decision rules, within the operating model a rule was applied to divide the catch taken from each stock:

$$C_{t,s} = \frac{B_{t,s} e^{\text{rand}\sigma_U} \text{TAC}_t}{\sum_s B_{t,s} e^{\text{rand}\sigma_U}}, \tag{4}$$

where TAC_t is the TAC that was set for year t; σ_U is the variance of fisher knowledge; and $B_{t,s}$ is the biomass of biological stock s at time t.

This implies that the fishery takes the greatest yield from the areas with the highest levels of biomass (despite the incomplete knowledge of the biomass level). The initial stock biomass in each area was defined as an input parameter. The final MSE therefore had 21 input parameters, all based on the best available knowledge (Dichmont et al. 1999). In this report, growth and mortality rates were estimated from tagging, survey, and other data. Note that in this simulation, the management stock z does not necessarily overlap with the biological stock s.

Testing the Decision Rules

Several scenarios were tested. In one case, a seriously depleted resource was simulated. In this case, the decision rules performed extremely well. They did not allow the stocks to go extinct, and they reversed the downward trend of population biomass.

A second scenario described a resource in which one of the four stocks (1) was severely depleted relative to the other stocks, (2) had a much smaller carrying capacity than the other stocks, or (3) exhibited both of these characteristics. The decision rules saved the other stocks but were unable to prevent the extinction of the seriously depleted stock.

A further case described the resource being extremely large and the TAC being well below sustainable levels. In this case, the decision rule did not respond well at all and was unable to take advantage of the good resource biomass and production characteristics.

The simulation model indicated that the final tested set of catch-rate-based decision rules were very conservative, precautionary, and risk averse. They were likely to perform extremely well in a declining fishery but were likely to underutilize the resource when it was in good condition.

Final Harvest Strategy

The harvest (or management) strategies consisted of calculating stock abundance indices and decision rules.

Abundance indices

The abundance indices to which the review rules apply are indices of change in relative stock abundance over the period of the assessment data time-series. The annual assessment (for the period 21 December in the previous year to 20 December in the current year) produced (1) an index of change in each of the five assessment regions; and (2) a pooled index reflecting changes throughout the stock in the total area.

The catch per unit effort (CPUE; kg/net-lift) for the entire fleet was calculated for each of the five assessment regions and for each of the previous six assessment years, t_1 to t_6, where t_1 is the first year and t_6 is the final year in the series. Only records with positive nonzero values in the effort (net-lifts) field were used. These may include records where a zero catch was reported.

The regression parameters for CPUE on year (from t_1 to t_6 and for each assessment region separately) were estimated. From these estimates, the percentage change in the fitted CPUEs between the first and last years of the assessment period was calculated.

The weighted average pooled index for all regions was then calculated. This was the primary index of proportional change in relative stock abundance throughout the fishery. The regional indices were weighted by effort (net-lifts) so that a region with little fishing effort could not unduly influence the overall value, as shown by:

$$P = \frac{\sum_r D_r E_r}{\sum_r E_r}, \qquad (5)$$

where P_r is the pooled index (%), D_r is the difference between the first and last assessment years' estimated CPUEs (obtained from the linear regression of the annual observed CPUE by region against year), and E_r is the total effort expended in assessment region r.

The assessment took into consideration changes in abundance index within individual regions to ensure that potentially significant spatial trends were not overlooked.

Total allowable catch decision rules

The TAC decision rules are as follows:

(1) If the pooled index is −50% or less, the TAC is set to zero (i.e., the fishery is closed); or
(2) If the pooled index is between −10% and −50%, the TAC for the forthcoming year is to be less than its value in the previous year by the amount of the index; or
(3) If the pooled index is +10% or more, the TAC for the forthcoming year is to be more than that in the previous year by *half* the amount of the index.
(4) Notwithstanding rule 3, if the index for any individual assessment region is between −25% and −15%, the TAC for the forthcoming year is to be 5% less than it was in the previous year.
(5) Notwithstanding rules 3 and 4, if the index for any individual assessment region is −50% or less, the TAC for the forthcoming year is to be at least 10% less than that in the previous year.
(6) If the pooled index is between 0% and −10% in each of the three most recent consecutive years, the TAC for the forthcoming year must be reviewed.
(7) If and when any new information becomes available indicating that the assessment and quota-setting arrangements are not consistent with the sustainable management of the fishery, the scientific method and review rules must be reviewed and, if appropriate, the reference points must be adjusted.

Appendix 2. Second Management Strategy Evaluation:

Harvest Strategies in 2002–2007

The biological operating model was changed from a delay difference model to a classic length-structured model (e.g., Sainsbury 1982) with male and female components of the spanner crab resource modeled separately because of their apparently different growth characteristics. The basic population dynamics in terms of length were as follows:

$$N_{t+1,g} = \mathbf{X}_g S_{t,g} N_{t,g} - C_{t,g} + 0.5\underline{R}_t, \qquad (6)$$

where $N_{t,g,l}$ is the number of spanner crabs of sex g in length-class l that were alive at the start of year t, $\mathbf{X}_g$ is the growth matrix (the probability of an animal of sex g in size-class i growing into size-class j) during a week, $S_{t,g}$ is the survival matrix (a diagonal matrix with $e^{-M_{y,w,l}}$ on the diagonal, where M is the natural mortality rate and is a constant over all lengths), $\underline{R}_t$ is the recruitment to the population during year t assuming an equal sex ratio, $C_{t,g,l}$ is the catch of animals in length-class l at the end of year t, and R_t is the recruitment during year t.

TABLE 1A.—Growth and Ricker stock–recruitment parameter values for the operating model of the second management strategy evaluation of the spanner crab fishery, Queensland, Australia. Ricker stock–recruit parameters are defined in Appendix 2. Growth parameters are asymptotic length (L_∞), growth coefficient (K), and theoretical age at zero length (t_0).

		Slow-growth option		Fast-growth option	
Type	Parameter	Male	Female	Male	Female
Growth	L_∞ (mm)	14.0	11.5	14.5	12.0
	K (per year)	0.24	0.26	0.50	0.45
	t_0	−0.1	−0.1	−0.1	−0.1
Ricker stock-recruitment	A	225	225	69.5	69.5
	B	4×10^{-8}	4×10^{-8}	4×10^{-8}	4×10^{-8}

A Ricker equation describes the stock–recruitment relationship:

$$R_{t+1} = AS_t e^{-BS_t} e^{\phi} P_t,$$

where A and B are the Ricker input parameters, S_t is the spawning stock size in year t, ϕ is a lognormally distributed random number with a mean of 1 and a coefficient of variation of 0.15, and P is a periodic recruitment term (described below).

The conversion from total allowable catch (TAC) to catch is similar to the first management strategy evaluation (MSE; equations 3 and 4) because it includes a length-based selectivity function and weight-at-length parameters, but it does not include gamma hyperstability (Dichmont et al. 1999; Brown, unpublished data). The second MSE also differs from the first MSE in that it does not include stock or management levels as components.

However, in this model, unlike the traditional approach, no parameters are estimated. For example, the growth transition matrix is calculated from von Bertalanffy growth curve parameters obtained from Dichmont et al. (1999) and Kirkwood et al. (2005; Table 1A). The input parameters used to define a particular prefishery model in the operating model included (1) population size relative to virgin stock size, (2) growth rate (fast or slow; Table 1A), (3) total survival rate (0.2, 0.3, or 0.4 per year), (4) stock–recruitment parameters linked to slow or fast growth rates (Table 1A), (5) recruitment variance, and (6) alternative environmental cyclical recruitment models (sinusoidal, intermittent, or absent). The sinusoidal and periodic recruitment model amplitude was 0.1 and the period was set at 6 years based on the historical catch rate series. Also, different levels of catch-per-unit-effort (CPUE) observation error were added, with the coefficient of variation equal to 0.1, 0.2, or 0.3.

Although managed area A of the fishery is divided into five assessment regions, which are used separately in the current assessment and decision rule process, the model was spatially aggregated.

The assessment submodel defines what happens when there is fishing taking place and the fishery is assessed periodically. Its parameters included initial TAC as a proportion of fishable stock, number of consecutive years of data used in the assessment and TAC-setting process, catchability coefficient, degree of stochasticity in computing CPUE from catchable biomass, annual or biennial assessments, and TAC increase fraction.

In the assessment model, unlike in the first MSE, the annual CPUE for each region was weighted in the following manner: a linear weighting scale was set to unity for the final (most recent) year of the assessment period, followed by a value decreasing by 0.1 for each preceding year back to a weighting value of 0.5 for the first year of the 6-year assessment period. This system was introduced to emphasize the most recent year's data, ensuring that the system was more responsive to recent changes than to past changes.

These tests did not change the basic harvest strategies described in Appendix 1 (Final Harvest Strategy), other than (1) changing the catch rate data set from the previous 5–6 years, (2) changing from the "half up, full down" rules to "full up, full down," (3) undertaking biennial assessments, and (4) undertaking a weighted linear regression of catch rates against year.

Appendix 3. Third Management Strategy Evaluation:

Harvest Strategies from 2008 to Present

The third MSE operating model was similar to that in the first MSE, but the assessment process was substantially different. The main changes were related to the inclusion of the survey index and a major revision of the decision rules. As a result, the spanner crab total allowable catch (TAC) is kept at a constant value (base TAC) unless the abundance indices (base commercial catch rate and base survey index) change significantly.

The base TAC was calculated as the arithmetic mean annual spanner crab catch in managed area A over the period 2000–2007; this base TAC remains fixed. A generalized linear model (GLM) was used to standardize catch rates from the natural log-transformed catch and effort over the above period and adjusted for the factors of year, month, vessel, region, and grid, with two components of moon phase (azimuth and elevation; Geoscience Australia; www.ga.gov.au/geodesy/astro/moonrise.jsp) used as covariates. Skipper experience had been identified from a recent fleet survey as an important component of vessel fishing power and was estimated to make an overall contribution of about 2% per annum to undocumented effort. A schedule of annual offsets was therefore included in the model to account for the effect of this increase in fishing power on catch rates. The base commercial catch rate was then calculated as the bias-corrected (Beauchamp and Olson 1973), back-transformed standardized mean catch rate over the period 2000–2007 (Brown 2008; M. O'Neill, Department of Employment, Economic Development, and Innovation, Queensland Primary Industries and Fisheries, unpublished data).

The base survey catch rate was calculated as the average catch rate (number of spanner crabs [all sizes and both sexes] per 10-net string) obtained during the annual spanner crab survey over the period 2000–2007. Catch rate was standardized by location, year, and fishing effort (net-hours) by using a simple GLM (Brown 2008; M. O'Neill, unpublished data).

Stock abundance indicators are routinely calculated for each assessment by using the same GLM specifications but are of course updated with a new annual data set. The pooled index is derived as the simple arithmetic mean of the commercial and survey indices, which were given equal weight as there was no evidence that one was a better indicator of stock abundance than the other.

Decision (Review) Rules

The revised decision rules below were expressed as much as possible using terminology and structure similar to those of the decision rules they replaced in order to maximize process continuity and minimize confusion.

(A) Prior to 28 February of each year in which the biennial quota cycle commences, the status of the spanner crab stock is assessed and the TAC is set for each of the two forthcoming years in managed area A (regions 2–6).

(B) This assessment is based on an analysis of changes in relative stock abundance as represented by the fishery-dependent and fishery-independent catch and effort data.

(C) Notwithstanding the biennial nature of the TAC-setting cycle, the fishery is assessed each year (as described in rule B above). In the event of evidence of a sudden and catastrophic collapse of the stock, immediate remedial action using emergency powers provided under the Queensland Fisheries Act of 1994 will be instituted.

(D) In determining the TAC, the following decision rules are used:

(1) If the pooled index is -50% or less, the TAC is nil (fishery is closed); or

(2) If the commercial index and the survey index are both greater than $+10\%$, the TAC is equal to the base TAC increased by half the amount of the pooled index, with the provisos that (1) if the new value lies within $\pm 5\%$ of the current TAC, then the new TAC will be equal to the current TAC; and (2) notwithstanding any of the above, the new TAC is not to exceed 2,000 metric tons; or

(3) If one index is less than -10% and the other is between 0% and -10%, the TAC is equal to the base TAC reduced by the full amount of the absolute (unsigned) pooled index, with the proviso that if the new value lies within $\pm 5\%$ of the current TAC, then the new TAC will be set equal to the current TAC; or

(4) If the commercial and survey indices are both less than -10%, the TAC is equal to the base TAC reduced by the full amount of the absolute (unsigned) pooled index, with the proviso that if the new value lies within $\pm 5\%$ of the current TAC, then the new TAC will be set equal to the current TAC; or

(5) The TAC is equal to the base TAC.

(6) If and when any new information becomes available indicating that the assessment and quota-setting arrangements are not consistent with the sustainable management of the fishery, the scientific method and review rules are to be reviewed and, if appropriate, the reference points must be adjusted accordingly.