Supporting Information

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SI Methods

Integrated Management Strategy Evaluation Framework. We developed a management strategy evaluation (MSE) methodology (Fig. 2) that substantially expands on previous approaches globally to holistically compare social, economic, and biological trade-offs anticipated under a range of proposed alternative management strategies (Table S1), as well as the sensitivity to related external factors, such as the government Community Development Employment Projects (CDEP) program that funds part-time community work by Islanders. The MSE framework we used links together a diverse mix of biological, economic, and sociocultural analysis tools (Table S2). At its core is a spatial and age-structured bio-economic operating model of the Torres Strait Rock Lobster (TRL) resource and fishery, simulating linked lobster sub-populations in each of 16 model spatial areas (Fig. S1). The TRL is extremely fast growing (1) and the successful recruit-based fishery is characterized by high interannual variability. Full details of the bio-economic model are provided in Plagányi et al. (2).

As well as developing a bio-economic model framework to define and estimate economic benefits per sector/subfleet that include the basic elements of revenue streams and cost structures, the overall analysis included a range of other methods that either fed into or used the results from these structures. These methods included a production function and frontier analysis (3), a data envelopment analysis (DEA) [to estimate which nonindigenous (TVH, transferable vessel holder) vessels might exit the fishery with lower quota levels], and evaluated the flow-on effects by including aspects of the supply chain (2). Hence, our framework includes consideration of economic benefits beyond the direct benefits to the fishery by integrating a supply-chain model with a bio-economic model to predict an additional performance indicator (Value Added) to the fleet profit (Fig. 3). The model predicted magnitude of Value Added (year 2011) is considerable ($3.2 million AUD) compared with summed profit (and returns to owner-operator labor) over the fishing fleets of $6.5 million AUD (Table S3).

One of the biggest challenges in attempting to simulate the outcomes of different management systems was the need to quantify how participation by each fisher subgroup would change. To estimate participation rate changes for the indigenous (TIB, traditional inhabitant boat) sector, which depends on social as well as economic drivers, a Bayesian Network (BN) analysis was used to partition the TIB fleet into subfleets based on a typology of activity and alternative licensing arrangements (as well as technical and economic factors) and facilitated prediction of the changes in participation under alternative scenarios (4). Integrating the social dimension in our analysis was only possible because of the extensive stakeholder consultation. Using structured approaches we were able to convert, to the extent possible, social information into quantitative metrics that could serve as inputs to a quantitative bio-economic model. Moreover, we recognized the value of qualitative social information and incorporated this in our modeling framework by using a common currency (i.e., qualitative indicators that show whether the effect being tested is positive, negative, or neutral) to present our results and highlight biological, economic, and sociocultural trade-offs associated with different scenarios.

Details of current Islander motivations for fishing TRL, current fishing strategies, and barriers to increased effort and participation from the perspectives of Torres Strait indigenous fishers was included in the BN and the probabilities of full-time, part-time, and casual participation can thus be estimated. The BN results suggest there are three primary drivers that apply to both active part-time and casual Islander fishers (ease of catch, tradition and culture, and incidental household payments). The primary driver of full-time Islander fishers is "returns from fishing," which is not significantly different to drivers of nonindigenous fishers. The feedback of some of the social indices on system dynamics can be estimated through participation of the different types of indigenous fishers (full time, active part time, and casual fishers).

Because the lobster resource is currently above the B_{MSY} level (MSY, maximum sustainable yield), we ran additional sensitivities that assumed fishing mortality is much higher (multiplier added up to a factor of 5 for the Torres Strait and up to 20 for East Coast) to compare which spatial areas are most affected and which strategies perform best from a biological perspective. The most sensitive spatial area, in other words the first area to show a substantial decrease or crash was Papua New Guinea, suggesting that this region cannot sustain even moderately higher catches. This result is corroborated by previous stock assessments in Papua New Guinea waters by Commonwealth Scientific and Industrial Research Organisation in 1998 and 2003, which suggested that ~60% of the Papua New Guinea stock is exploited annually. The next most sensitive area identified was Thursday Island, which started to show a decrease under a range of higher fishing mortality simulations. This finding is not too surprising given the concentration of fishing and fishers in the vicinity of Thursday Island, which is predicted to increase further if future changes in participation occur along the lines suggested by the alternative management strategies and scenarios. Changing the numbers participating in different sectors (TVH and TIB) or subsectors (TIB full-time commercial and part-time) shifts the relative spatial concentrations of fishing effort, and hence the need to explore potential localized depletion effects (Table S3).

We focused predominantly on evaluating trade-offs between alternative strategies comprising various derivatives of the introduction of an output control system in the form of individual transferable quota (ITQ) per Islander fishing license, a community-based system, or an Olympic-type competitive system for the whole sector or part thereof (Fig. S2). In an Olympic system, a global total quota is set at the beginning of the season for this sector and the fishing season is open until the sector catch equals quota. Hybrid versions imply future operational management systems that include some form of ITQ system for a subset of the Islander licenses (the commercial operators) and an Olympic-type system for the rest of the Islander sector (alternative management strategy A3, A6, and A9) (Table S1).

Selected results for the management strategies and scenarios as listed in Table S1 are presented in Table S3. We use green to represent "good" (i.e., a positive effect or improvement on the current situation), red for "bad" (i.e., negative or poor outcome), and blue for "neutral" (i.e., no change). Thus, strategies with mostly green are preferred to those with mostly red. There are always trade-offs between different aspects so that no one strategy will ever be the perfect "green" overall. Furthermore, the aim of this research is not to make a decision or express which strategy the researchers prefer. Rather, the aim is a method to objectively show side-by-side the trade-off among the different strategies so that this can assist stakeholders when making decisions.

Our list of indicators contains three types of social indicators (Table S4): (*i*) dynamic continuous variables (those linked to the biological and economic model through the BN); (*ii*) second-order discrete variables (based on BN calculated size and redistribution of fisher numbers between the three fisher groups); and (*iii*) nondynamic discrete variables (directly related to the type of management system and indigenous allocation proportion).

The nondynamic variables were based on information obtained during the consultation process. The discrete value of these variables is directly related to the different management system or allocation amount. An indication of the positive or negative direction of the effect was obtained from indigenous fisher consultation participants. The variables emerged unprompted and were appropriately labeled by the researchers. There is no explicit feedback from these nondynamic variables on the system dynamics, but an iterative process was nonetheless used to revisit and verify the scoring of these variables in light of the final biological and economic results obtained under alternative scenarios.

Stakeholder Consultation and Indigenous Information Gathering. Extensive consultations were conducted with a broad range of stakeholders, including the TRL Resource Assessment Group, Australian Fisheries Management Authority (AFMA), TIB/TVH fishers and processors. Several research visits were conducted to the Torres Straits and Cairns, including by three researchers, an AFMA manager and TSRA (Torres Strait Regional Authority) representative in August 2010, to Thursday Island, Badu, Mabuiag and Iama communities, and separately to Cairns. A follow-up meeting, attended by three researchers (together with TSRA and AFMA) was held on Thursday Island during November 2010 to gather further information on aspirations and concerns from the significant Thursday Island, Hammond Island, Prince of Wales (Muralug) Island, and Horn Island-based fisher sector. The establishment of key contacts in the TRL fishery allowed the research team to collect further data via e-mail. A large stakeholder workshop was held in Brisbane, Australia, November 2011 (2).

Structured Indigenous fisher workshops were held on Thursday Island, Badu Island, and Yam Island in the Torres Straits in March 2011, with location coverage of the workshops and interviews accounting for three-quarters of the TRL catch. The first part of the workshop sessions provided both qualitative and quantitative information that underpinned the development of the BN. Workshop participants were asked to discuss, outline, and agree on a hierarchy of reasons for going fishing, thus developing a model of different behavioral drivers. The pertinence of a fisher typology to a number of the behavioral drivers was also detailed. The main categories under which the behavioral drivers were categorized were culture, need for personal money, community use and income, and food.

The second part of the workshop provided qualitative information for the traffic lights. The property ownership characteristics of the three different systems (competitive, community, and hybrid ITQ management system) were explained to the workshop participants (5). In the discussion sessions that followed, workshop participants identified a series of positive and negative aspects associated with each of the management systems. On the basis of the issues raised, qualitative information was brought into the quantitative decision-making tool by allocating red (green) traffic light colors to occasions where negative (positive) impacts were identified for each of the three management systems under consideration. If workshop participants indicated there was unlikely to be a change observed as a consequence of introducing the different management system, a neutral effect, or blue color was allocated. If the issue was not raised for a particular management system, this was also noted. Workshop participants were also asked to discuss the impact of the availability of the CDEP on fishing behavior.

Additional informal face-to-face interviews were carried out after the workshops to provide further clarification and to seek inputs from additional indigenous fishers and processors. In total, 50 indigenous fishers and community members participated in the interviews and workshops. Preliminary research results were presented to indigenous and nonindigenous members of the fishery co-management group, and feedback and initial validation of the results, and refinement of the indicator categories, were thus received.

Although all proper avenues and protocols were followed, some potentially unavoidable communication difficulties may have occurred at the time of consultation, for example, because of initial misclassification of researchers as government officials. Moreover, results presented may be affected by the political climate at the time, which was tense because of the Islander's full ownership desires. When interpreting the results of this study, these issues have to be kept in mind.

Hybrid Systems. Hybrid management plans or partial rights allocation (often a common feature of international cross jurisdictional boundaries) can result in negative impacts on the stock (6, 7). The amount that any ITQ system would be undermined and the magnitude of rent dissipation (profit loss) depends on the availability of good catch rates at the beginning of the season across fishing grounds. In a system with partially allocated rights (ITQs for some and an Olympic system for others), the incentive exists for fishers in either group to harvest stock before others do (8). This incentive essentially creates the equivalent of an Olympic system with a fishery-wide "race to fish." Not only would profit be reduced in the short-run as fishers race to fish in areas of high productivity at the beginning of the season, the value of any traded quota would be negligible. Moreover, the equity in the initial allocation of quota to only some fishers who become the ITQ holders may be questioned (7). Awarding weakly delineated rights to some may not accurately reflect their investment in the fishery. Moreover, those fishers who have an ITQ may find that its value is minimal and cannot be used as collateral for further investment. Given that it also potentially restricts their activity, those allocated an individual quota are more likely to attempt to opt out of the system in favor of the competitive quota.

The rent dissipation effect provides a partial explanation as to why there was minimal difference in the overall profit computed in our model under an Olympic strategy compared with the hybrid or partial allocation strategy (Fig. 3). There was also minimal difference in the predicted participation in the fishery between the Olympic and hybrid strategy (but with a slight increase in participation with greater allocation to the whole TIB sector), as estimated by the BN. In general, we based parameterization of participation under each strategy and scenario on the outputs of the BN and recognized that it is difficult to extrapolate our analyses across multiple dimensions (changing strategies, allocations, and externalities), especially those that differ substantially from the current situation. Nonetheless, to test the effect of a tightly controlled hybrid system with ITQ operational (e.g., a system in which the Olympic component makes up only a very small proportion of the total allowable catch and the ITQ owners catch the vast majority of the catch so that it closely resembles a true ITQ), we ran an additional sensitivity. We considered one of the most extreme scenarios, namely a well-controlled ITQ strategy with a 70% TIB, 30% TVH allocation (A9) and no-CDEP (scenario S1), such that there would be increased incentives for greater participation in the commercial subsector for TIB fishers. The net effect predicted is an increase in overall profits of the fishery from $3.7 million AUD to $4.8 million AUD (Fig. S3).

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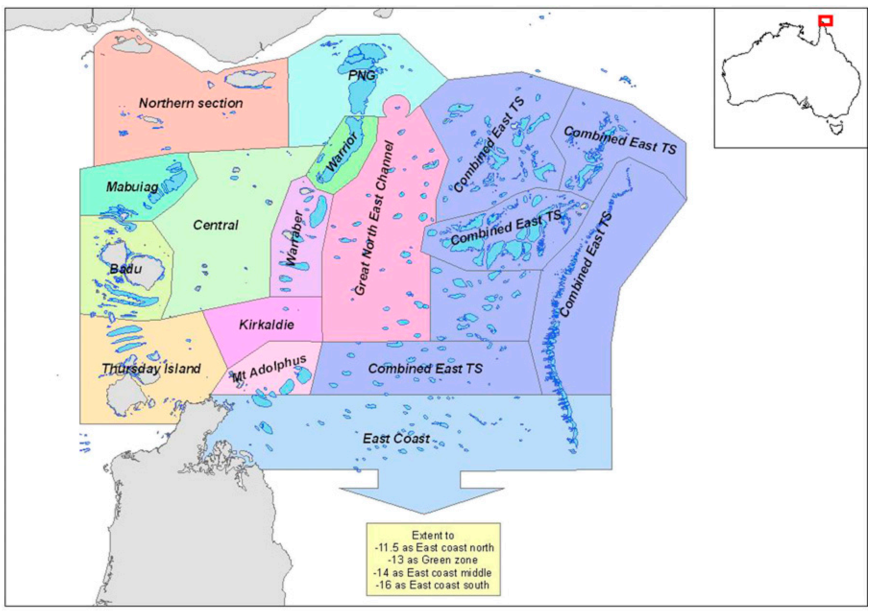

Fig. S1. Map showing 16 spatial areas used in study. Note that several Eastern areas have been lumped together to form a combined East Torres Strait spatial region in the model. The East Coast box extends southwards to include all East Coast lobster catches, and is in turn subdivided into four spatial areas: northern, central, southern, and green zones, which are not shown explicitly in this plot.

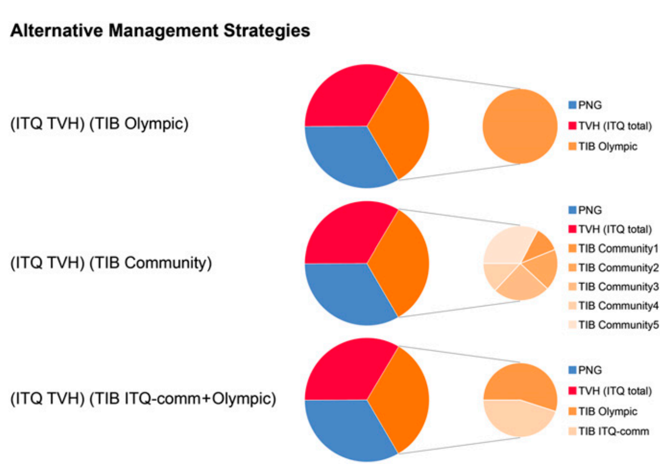

Fig. S2. Comparison of three alternative management strategies.

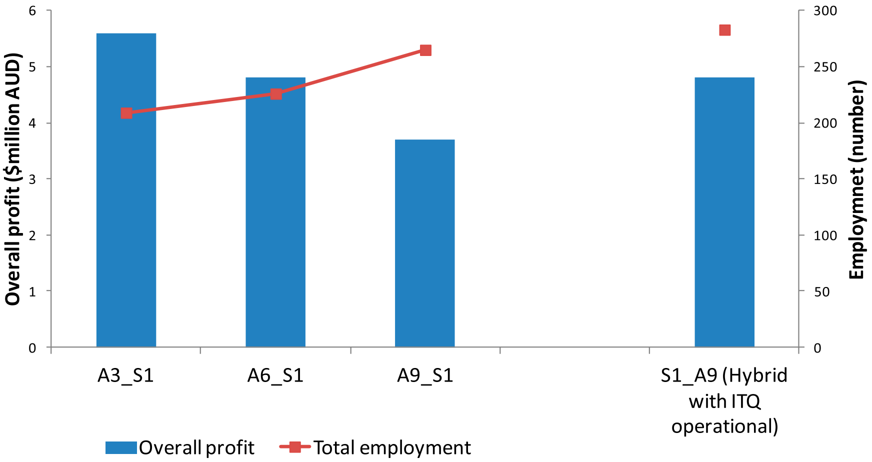

Fig. S3. Results of sensitivity analysis comparing the performance of a hybrid strategy at different levels of TIB allocation (A3–53%; A6–60%; A9–70%) with a strategy that assumes a 70%:30% TIB:TVH allocation ratio and in which implementation of the ITQ is not compromised by an Olympic system (as the quota to this sector is small or set aside for them only). The examples shown assume no-CDEP (scenario S1).

Other Supporting Information Files

Table S1 (DOCX)
Table S2 (DOCX)
Table S3 (DOCX)
Table S4 (DOCX)