Contributed Paper

Complementarity of No-Take Marine Reserves and Individual Transferable Catch Quotas for Managing the Line Fishery of the Great Barrier Reef

L. R. LITTLE,*†§ R.Q. GRAFTON,† T. KOMPAS,† A. D. M. SMITH,* A. E. PUNT,*‡ AND B. D. MAPSTONE*

*CSIRO Marine and Atmospheric Research and CSIRO Wealth from Oceans Flagship, GPO Box 1538, Hobart, Tasmania 7001, Australia

†Crawford School of Economics and Government (Building 132), Lennox Crossing, Australian National University, Canberra, ACT 0200, Australia

‡School of Aquatic and Fishery Sciences, University of Washington, Box 305520, Seattle, WA 98195, U.S.A.

Abstract: *Changes in the management of the fin fish fishery of the Great Barrier Reef motivated us to investigate the combined effects on economic returns and fish biomass of no-take areas and regulated total allowable catch allocated in the form of individual transferable quotas (such quotas apportion the total allowable catch as fishing rights and permits the buying and selling of these rights among fishers). We built a spatially explicit biological and economic model of the fishery to analyze the trade-offs between maintaining given levels of fish biomass and the net financial returns from fishing under different management regimes. Results of the scenarios we modeled suggested that a decrease in total allowable catch at high levels of harvest either increased net returns or lowered them only slightly, but increased biomass by up to 10% for a wide range of reserve sizes and an increase in the reserve area from none to 16% did not greatly change net returns at any catch level. Thus, catch shares and no-take reserves can be complementary and when these methods are used jointly they promote lower total allowable catches when harvest is relatively high and encourage larger no-take areas when they are small.*

Keywords: computer-simulation modeling, fisheries management, ITQ, management strategy evaluation, marine protected areas

Complementariedad de Reservas Marinas Sin Captura y Cuotas de Captura Individuales Transferibles para el Manejo de la Pesca con Anzuelo en la Gran Barrera Arrecifal

Resumen: *Los cambios en el manejo de la pesquería de peces en la Gran Barrera Arrecifal nos motivaron a investigar los efectos combinados de los retornos económicos y la biomasa de peces en áreas sin captura y la captura total permisible asignada como cuotas individuales transferibles (tales cuotas reparten la captura total permisible como derechos de pesca y permiten la compraventa de estos derechos entre pescadores). Desarrollamos un modelo biológico y económico espacialmente explícito de la pesquería para analizar los pros y contras de mantener determinados niveles de biomasa de peces y de los rendimientos económicos netos obtenidos de la pesca bajo regímenes diferentes. Los resultados de los escenarios que modelamos sugieren que el decremento en la captura permisible total en niveles de cosecha altos incrementó los rendimientos económicos o los disminuyó ligeramente, pero incrementó la biomasa hasta en 10% en un amplio rango de tamaños de reserva, y el incremento en la superficie de la reserva desde ninguno hasta 16% no cambió los rendimientos económicos significativamente en ningún nivel de captura. Por lo tanto, las cuotas de captura y las reservas sin captura pueden ser complementarias y cuando estos métodos son usados conjuntamente*

§*email: rich.little@csiro.au*
Paper submitted November 18, 2009; revised manuscript accepted June 4, 2010.

Conservation Biology, Volume 25, No. 2, 333–340

DOI: 10.1111/j.1523-1739.2010.01590.x

promueven menores capturas totales permisibles cuando la cosecha es relativamente alta e impulsan mayores áreas sin captura cuando es pequeña.

Palabras Clave: áreas marinas protegidas, CIT, evaluación de estrategias de manejo, manejo de pesquerías, modelo de simulación en computadora

Introduction

Many fishes have been harvested intensively in the wild. Although the abundance and biomass of some species have increased in response to management, the biomass of many fished species are low relative to historical levels (Worm et al. 2009). Collaborative partnerships among industry, government, and nongovernmental organizations may result in increased abundance and biomass of fishes (Gleason et al. 2009), but economic goals of some stakeholders can compete with the conservation goals of others (Mapstone et al. 2008). Two approaches, which are typically implemented independently, are believed to increase both the probability of achieving conservation goals and the economic sustainability of fisheries (Jones 2007): spatial no-take areas (Gell & Roberts 2003) and rights-based catch shares (Grafton et al. 2006*a*) that guarantee a portion of a total allowable catch (TAC) either to individuals, communities, or specific locations (territorial user rights).

No-take areas mitigate uncertainty in ecological knowledge, environmental variability (Mangel 2000; Grafton et al. 2006*b*), and uncertainties in measurements and control of fishing effort and catch (Lauck et al. 1998). Additionally, spillover of larvae or adult fish from areas closed to fishing may lead to increased catches in fished areas (Gell & Roberts 2003). Rights-based catch shares decrease the probability of fisheries collapse provided there is adequate monitoring and enforcement to ensure individual catch shares are not exceeded (Costello et al. 2008). Nevertheless, detrimental effects on the ecosystem can still result, such as incidental catches of other species and continued fishing when quota is met in order to increase the value of the catch (Branch 2009; Smith et al. 2009*b*; Essington 2010). Transferability of rights-based catch shares in the form of an individual transferable quota (ITQ) can also increase economic returns and reduce fishing effort (Dupont et al. 2005; Grafton et al. 2006*a*). Transferability allows fishers with higher net financial returns per unit of fish landed to harvest a greater proportion of the TAC by buying extra shares from fishers with lower returns, who can then still derive a profit.

Establishment of both large no-take areas and ITQs together has occurred in relatively few fisheries. An exception is the coral reef fin fish fishery of the Great Barrier Reef (Australia), in which the primary fisheries-management measure is ITQs and the primary conservation measure is no-take areas. We examined the effect on fish biomass and economic returns to the fishery of the two approaches, even though the no-take areas are not used explicitly to manage the fishery.

The Great Barrier Reef Marine Park (hereafter, park) encompasses one of the largest coral reef ecosystems in the world and contains of one Australia's most valuable fisheries (annual commercial value about US$40 million). The park has three fishing sectors: commercial; charter, which caters to tourists; and private recreational. Over 125 species are taken, but most of the catch consists of common coral trout (*Plectropomus leopardus*). The Queensland Department of Primary Industries and Fisheries manages the fishery with seasonal closures during spawning times, size and hook limits for all sectors, limited entry to the fishery regulated through licensing of the commercial and charter sectors, and limits to the amount of catch a person can take in a day for the recreational and charter sectors. An ITQ system was implemented in 2004 to manage the commercial fishery, and the TAC for coral trout was 1280 t, on the basis of historical catches, distributed among 411 individual share holders.

Management of the coral reef fin fish fishery is complicated because the region is under jurisdiction of the federal Great Barrier Reef Marine Park Authority (hereafter, authority). The authority manages the park for conservation of biological diversity primarily through zoning to restrict fishing (no-take areas), the primary extractive activity in the park. A major rezoning program, implemented in 2004, increased the area of the no-take zones from about 4.5–33% of the entire park (Fernandes et al. 2005) and from 16% to 32% of coral trout habitat (Little et al. 2008). The effects of this zoning have been variable, but there have been indications that fish abundances are recovering. In some cases there has been a 2-fold increase in biomass of some species, such as coral trout, in closed areas that were historically heavily fished (McCook et al. 2010).

Since implementation of ITQs and rezoning, the number of active commercial fishing vessels has decreased from over 600 to less than 240, and the catch per unit effort in the commercial fishery has increased by about 30% (Queensland Primary Industries and Fisheries 2008, 2009; CRC Reef Research Centre 2005). We explored the effects of harvest-management systems in the form of ITQs and no-take areas on economic returns and biomass of coral trout with a model that simulates the metapopulation dynamics of coral trout and its harvest (Mapstone et al. 2004; Little et al. 2007).

Methods

We used the Effects of Line Fishing Simulator (simulator) (Mapstone et al. 2004, 2008; Little et al. 2007, 2009*b*) to show the effects of ITQs and no-take areas on biomass and economic returns. The simulator models the population dynamics, harvest, and management of a line fishery. It operates stochastically at monthly time steps. Each simulation has two parts: initialization and projection. Initialization operates temporally from the assumed time at which harvest began, in our case 1965. We built the model with data on historical commercial, charter, and recreational catches; selectivity of the gear in catching fish of different sizes; biological characteristics of the two species of interest, coral trout and red throat emperor (*Lethrinus miniatus*); and physical characteristics of the reefs. Initialization was used to derive a credible distribution of age structure and biomass of the species after several decades of historical harvest on more than 3000 individual reefs within the Great Barrier Reef. The populations were then projected into the future to 2025 by simulating harvest of each population. Levels of harvest were affected by user-specified management strategies that include no-take areas, minimum fish size, gear limits, and either effort limits or catch controls implemented with or without ITQs.

Effects of Line Fishing Simulator

The biological component of the simulator is a spatially explicit metapopulation model of the species of primary interest, here common coral trout, and the secondary target species, here red throat emperor in over 3000 reefs of the park. This model represents growth, reproduction, and natural and fishing mortality and accounts for the protogynous life cycle of species that begin life as females and become males as they grow. The model allows for larval migration and settlement among reefs, which are based on hydrodynamic data when they are available. A full description of the biological component of the simulator and a summary of its parameterization is in Mapstone et al. (2004) and Little et al. (2007, 2009*a*).

The simulator captured the spatial allocation of fishing effort in the three fishing sectors. Recreational fishing effort was assumed to be static and was modeled on the basis of past spatial distribution of recreational fishing effort. Recreational fishing has occurred in inshore areas historically, whereas commercial fishing has occurred more often in offshore areas, which results in little or no interaction between these fishing sectors. The spatial distribution of charter-fishing effort was determined from historical catch rates and was responsive to localized reduction in abundance of the species on reefs.

The behavior of the commercial fleet was captured in an agent-based model that simulated the movement, reef-selection processes, and fishing activities of 411 fishing vessels, the number of vessels initially allocated shares in the coral trout fishery (Little et al. 2009*b*). Consistent with previous work on fishing-effort dynamics, the behavior of the commercial fleet was based on a random utility model, (Smith & Wilen 2003), which was specified with an objective function constructed from analyses of historical data on catch and effort (Little et al. 2008). Fishers were assumed to select fishing locations to maximize fishing returns. A decision was made by operators of each vessel on where to fish on each day within each month. This decision includes whether to stay on a currently occupied reef or move to another reef. Whether a vessel stayed was related to the size of the reef on which the vessel was located and the biomass of fish taken from that reef during its stay. If a vessel moved to another reef, the key elements for selecting the next reef were travel time, bearing to the candidate reef relative to the general direction of travel within the current trip, size of the candidate reef, and expected catch from the candidate reef on the basis of prior experience.

No-take areas of different sizes were combined in the model with different input and output control schemes. The input control scheme consisted of controls on total fishing effort (i.e., effort control), whereas the output control scheme consisted of different total harvest levels (TACs) under either ITQs, in which individual quota restrictions applied, or a competitive TAC, in which there were no individual restrictions on the amount of TAC that could be landed.

The ITQ model captured the behavior of commercial fishers as they bought and sold catch shares. This behavior affects the seasonal allocation of effort because fishers attempt to maximize profit on the basis of fish prices, catch rates, and operating costs. In the model, trading of ITQs for each vessel depended on the relation between the expected marginal profit of catching fish and the cost of acquiring more shares (Lanfersieck & Squires 1992; Little et al. 2009*b*).

Model Scenarios

We compared simulation results of no-take areas with ITQs and results of no-take areas with effort control and a competitive TAC. Effort controls were modeled by keeping the aggregate fishing effort at the average annual fishing level for 1994–2003.

Under the competitive TAC scenario, in which there were no individual restrictions on the amount of TAC that could be landed, we used historical data for 1994–2003 to capture fishing vessel effort and applied it to the model until the TAC was reached. Competitive TACs have not been used in the park, so we assumed, without data on fisher behavior, that there was no explicit competition among fishers to secure the highest portion of TAC. Competition among fishers for a share of the TAC was therefore implicit and depended on the fishing efficiency of the vessel and historical fishing patterns. No fishers left the fishery as a result of inefficiency relative to the other competing fishers.

We examined four spatially explicit no-take extents: an extent consistent with that from the mid-1980s to mid-2004 (approximately 16% of coral trout habitat in the park); an extent implemented during rezoning in 2004 (32%); a hypothetical extent of 50% (Little et al. 2009*a*); and a hypothetical extent of 0%.

We examined four levels of TAC of coral trout for the output control scenarios: 750 t, 1000 t, 1250 t, and 1500 t. For comparison, the catches derived from the effort-control scenario varied over the projected period from about 1500 t to about 1320 t. We held the TAC for red throat emperor constant at its current level, 630 t, because this TAC does not restrict fishing activity (Little et al. 2009*b*). The actual TAC of coral trout in 2009 was approximately 1280 t, so the modeled scenario of a 1250 t TAC subjected to ITQ and 32% no-take area most closely resembled the conditions in the fishery at the time we completed this work.

In the simulations we specified that the biomass of coral trout and red throat emperor available to the fishery at the start of the projection period in 2003 was approximately 30% and 50% of preharvest levels, respectively. The value for red throat emperor is consistent with a previous estimation (Leigh et al. 2006). There has been no formal estimation of the abundance of coral trout because the species has a metapopulation structure, but we considered the modeled biomass value reasonable because the commercial and noncommercial value of the species is high and historical quantities of biomass harvested were more than twice that of red throat emperor (CRC Reef Research Centre 2005; Queensland Primary Industries and Fisheries 2008, 2009). We ran 100 projections of the model from 2003 to 2025 under each scenario.

Results

Negative net returns were generated at high levels of TAC (1250 t and 1500 t) with a competitive TAC because the model assumed fishers continue fishing until the TAC is filled. In reality, fishers would likely respond to negative returns by exiting the fishery, so the estimated difference between ITQs and a competitive TAC when TAC is high would be less than our model indicated. Biomass of fish available to the fishery decreased as TAC increased (Fig. 1) in all scenarios.

Spatial closures had a small effect on net returns (Fig. 1). When catch was prohibited across 32% of the reef, net returns were higher than when catch was prohibited across 16% of the reef at the highest TAC (1500 t) and with a competitive TAC. By contrast, net returns were higher when catch was prohibited across 16% compared with 32% of the reef at the same TAC when ITQs were applied.

When take was prohibited across 16% or 32% of reefs in the park, ITQs generated substantially higher net returns than a competitive TAC at all except the lowest TAC. The difference in net returns between the ITQ and competitive TAC scenarios was greater than among spatial closure scenarios. This difference in returns between ITQ and competitive TAC scenarios increased as the TAC increased (Fig. 1). This shows that fishers under a competitive TAC exerted effort until the TAC was filled, so economically inefficient fishers incurred higher fishing costs than efficient fishers. Under ITQs, by contrast, economically inefficient fishers sold their shares to more

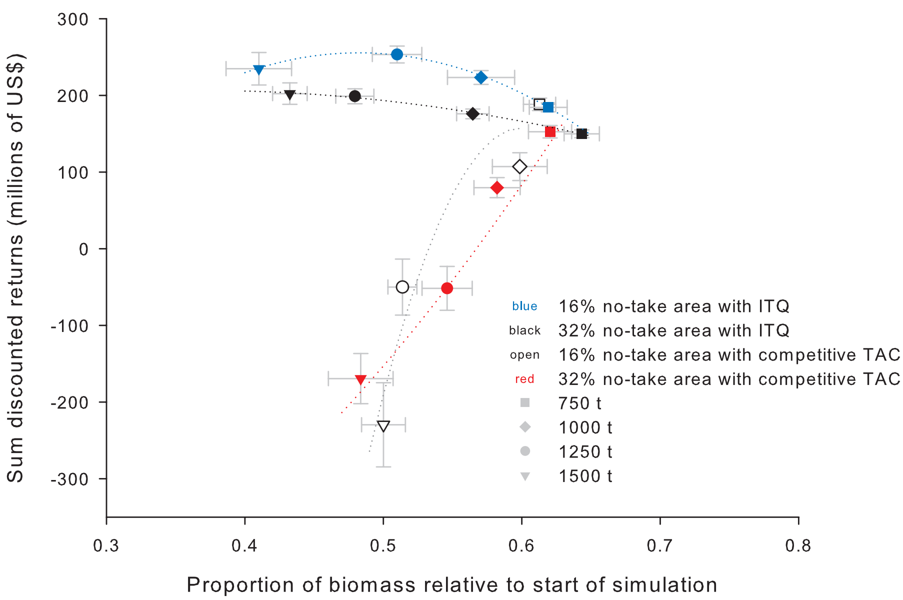

Figure 1. The mean (SE), simulated, total, discounted net return (future net returns discounted to present value by 5%/year) 2003–2025 plotted against fish biomass available to the fishery at the end of the simulation under current (32%) and pre-2004 (16%) no-take area combined with competitive and individual transferable fishing quota (ITQ) at different levels of total allowable catch (TAC) (dotted lines, quadratic fit).

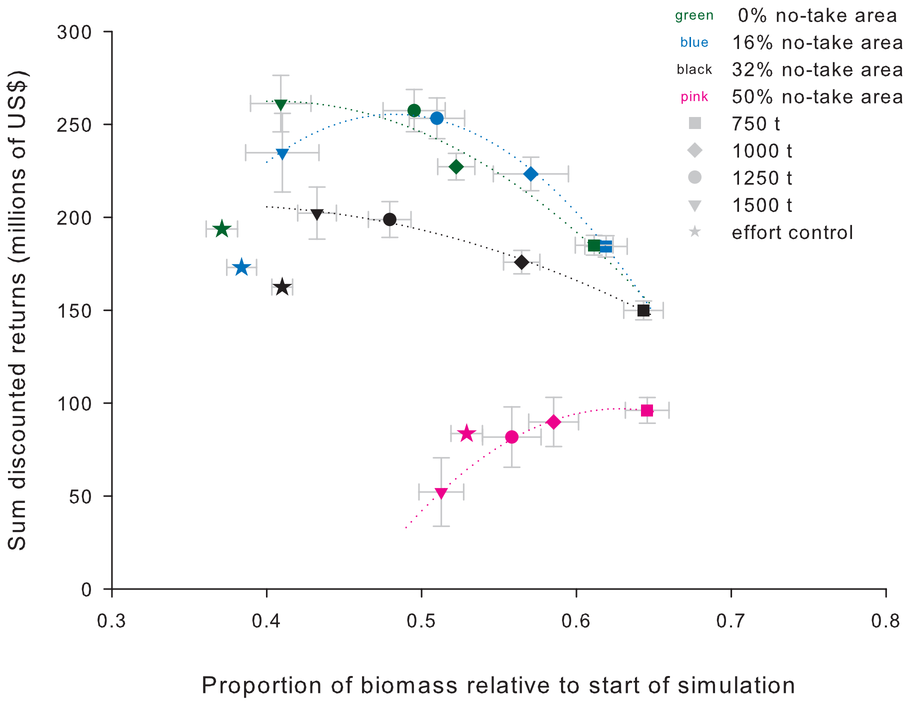

Figure 2. The mean (SE) simulated total discounted net return from 2003 to 2025 (future returns discounted to present value by 5%/year) for the coral reef fin fish fishery plotted against the fish biomass available to the fishery at the end of the simulation for combinations of total allowable catch with individual transferable quotas and no-take area (dotted lines, quadratic fit).

efficient fishers and thus avoided continued economic losses.

Maintaining controls on fishing effort and increasing the no-take area from 16% to 32% (Fig. 2) led to slightly smaller net returns and a small increase in biomass. Increasing the no-take area to 50% decreased returns further but increased biomass to about 50% of preharvest levels (Fig. 2). Maintaining controls on fishing effort but eliminating no-take areas increased returns and slightly decreased biomass (Fig. 2).The economic effect of eliminating no-take areas and keeping the previous controls on fishing effort (Fig. 2) was equivalent to the economic effect of 1250 t TAC under ITQs and 32% no-take area, but this scenario reduced biomass (Fig. 2).

In general, establishment of ITQs increased net returns and biomass more than the pre-2004 effort controls with a no-take area of 16% or 32% except at the lowest catch level (Fig. 2). When the no-take area was 32%, net returns at the lowest catch level were only slightly lower than under the 2004 fishing-effort controls, but the catch was 40% less (CRC Reef Research Centre 2005) and biomass was 50% more. Thus, ITQs when combined with the use of no-take areas maintained net returns from commercial fishing and increased biomass levels more than effort controls.

The difference in net returns across different percentages of no-take area increased as the size of the TAC increased (Fig. 2). For instance, the difference in net returns with no-take areas of 0% and 50% with ITQs was about US$200 million at a TAC of 1500 t but the difference was about US$50 million at a TAC of 750 t. The extent to which no-take areas limited returns increased as the TAC increased. The difference in biomass associated with increasing the size of a no-take area, however, also increased as the level of harvest increased. For instance, the difference in biomass between 50% and 0% of no-take area was greater when the TAC was 1500 t than when it was 750 t. This suggests that the trade-off between net financial returns and biomass for different percentages of no-take area increased as overall catch increased.

Within the range of TACs examined, ITQs and the percentage of no-take area interacted to affect net financial returns and biomass (Fig. 2). For example, as TAC increased net financial return increased in the absence of no-take areas, but at a diminishing rate (Fig. 2), whereas as TACs increased net financial returns given 50% no-take area decreased (Fig. 2). Net returns decreased as TAC increased given 50% no-take area, mainly because more protected areas meant less of the stock was accessible to fishing, and more fishing effort in the areas open to fishing resulted in decreased biomass, catch rates, and return per unit of catch from those areas. Lower returns in this scenario were also heightened because fishers did not leave the fishery but fished until they filled any quota they had not sold, even if it was not profitable. Therefore, reducing a large TAC decreased net returns slightly when no-take area was relatively small and may increase net returns if no-take area is large.

Decreasing the TAC from 1500 t to 1250 t changed net returns only slightly when ITQs were combined with no-take areas of 0–32% (Fig. 2) and increased biomass by approximately 10%. Similarly, for any TAC, increasing no-take area from 0% to 16% did not affect net returns or biomass. Increasing no-take area further, however, particularly for higher TACs (1500 t, Fig. 2), tended to decrease net returns more substantially and increase biomass. Alternatively, if the TAC was large (1500 t), a small reduction in TAC had little effect on net returns but increased biomass over a range of percentages of no-take area.

Discussion

There are many ways other than ITQs to use catch shares and incentive-based techniques for managing fisheries. Usually catch shares grant access to harvesters with the intention of making harvest of a species more economically sustainable. Spatially allocated no-take areas restrict access to the fishery with the intent of making human use of the resource more ecologically sustainable. Spatially allocated catch shares, seen as territorial user rights (Cancino et al. 2007), may complement marine reserves if access to certain areas is prohibited. Additionally, marine reserves may protect and thus increase fish stocks (McCook et al. 2010) and, in some cases, increase catches (Sanchirico & Wilen 2001; Gell & Roberts 2003; Grafton et al. 2005). Nevertheless, the ability of marine reserves to increase both the economic and ecological sustainability of fisheries is uncertain and depends on largely stochastic processes, including fish dispersal (Little et al. 2007; Le Quesne & Codling 2009; Little et al. 2009*a*; Smith et al. 2009*a*) and fishing behavior (Smith et al. 2009*a*). Some of the ecological effects of marine reserves may not have been captured directly in our model. Babcock et al. (2010), for example, documented the indirect effects of trophic cascades associated with protection of species of higher trophic level where there were no-take marine reserves.

The simultaneous use of no-take areas and ITQs in our model resulted in higher biomass and net economic returns compared with effort controls and no-take areas. This result shows that not only the commercial fishing industry benefits by increasing future discounted returns (Fig. 2), but the tourism industry (including charter fishing), which relies on high biomass and catch rates and relatively undisturbed habitat (Kragt et al. 2009) also benefits. Recreational fishing, which generates about US$190 million/year (Hand 2003), was captured in the simulator, but we lacked economic data with which to calculate future expected returns of this activity in the model.

Increasing the overall harvest through the competitive TAC scenario within the range of TACs we considered reduced net returns and biomass. By introducing ITQs, however, as TAC increased returns increased and stock biomass decreased. As the amount of no-take area increased, however, especially at the highest TAC, returns decreased and biomass increased. Thus, we suggest that both ITQs (via TACs) and marine reserves may increase the probability of achieving both conservation and economic objectives for the fishery.

Biomass levels at all TAC values were higher than those under 16% no-take area with effort controls because catches under effort controls were determined on the basis of relatively high historical effort since 1989, which resulted in catches between 1500 t and 2000 t (Mapstone et al. 2004, Little et al. 2007, 2009*b*). The TAC levels in our simulations were lower than that, which allowed stocks to rebuild. The economic returns under ITQs were higher than under effort controls, despite a lower TAC, because higher stock sizes lead to higher catch rates and lower per unit harvesting costs. Moreover, less-profitable operators generated higher returns by selling or leasing their catch share to more economically efficient fishers, thereby increasing overall net returns from fishing (Little et al. 2009*b*). These results apply for harvested species that are relatively sedentary (e.g., Smith et al. 2008), no-take areas that are effectively enforced, and a sufficiently large and effective quota-trading market (e.g., Anderson 1991). Where the quota-trading market is not effective or transfers of quota are not allowed, the biomass and economic returns will be intermediate to those defined by the ITQ and competitive TAC scenarios in Fig. 1. Similarly, when marine reserves do not protect fish from fishing because the species is highly mobile (e.g., Le Quesne & Codling 2009; Little et al. 2009*a*), the relation between economic returns and biomass will be similar to the relation between economic returns and biomass where none of the reef is no-take (Fig. 2).

No-take areas are generally applied for conservation purposes (Allison et al. 1998), not to increase catch or economic returns (Hilborn et al. 2006). They can benefit a fishery economically and ecologically; however, if establishment of no-take areas is combined with ITQs (Degnbol et al. 2006). Increasing TACs in an ITQ system tended to increase economic returns when harvests were low and no-take areas were 0–32% of the reef. This, however, led to decreased biomass. Increasing the no-take area from 0% to 50% was associated with an increase in biomass and a decrease in net returns, particularly at high TACs (1500 t). Thus, TACs could be marginally lowered and result in increased biomass and economic returns if no-take area is large. Conversely, no-take area could be marginally increased, with little effect on economic returns, if no-take area is small or nonexistent. Net financial returns tended to be lower in the absence of ITQs. These results suggest that integration of no-take areas with rights-based catch shares may promote both marine conservation and economically sustainable fish harvest.

Acknowledgments

The work was supported by the Australian Research Council, CSIRO Wealth from Oceans National Flagship, CSIRO Division of Marine and Atmospheric Research, and Commonwealth Environmental Research Facility (Environmental Economics Hub). We thank B. Hatfield for his help in completing the simulations, E. Fleishman, and two reviewers for their insightful comments.

Literature Cited

Allison, G. W., J. Lubchenco, and M. H. Carr. 1998. Marine reserves are necessary but not sufficient for marine conservation. Ecological Applications **8:**S79–S92.

Anderson, L. G. 1991. A note of market power in ITQ fisheries. Journal of Environmental Economics and Management **21:**291–296.

Babcock, R. C., N. T. Shears, A. C. Alcala, N. S. Barrett, G. J. Edgar, K. D. Lafferty, T. R. McClanahan, and G. R. Russ. 2010. Decadal trends in marine reserves reveal differential rates of change in direct and indirect effects. Proceedings of the National Academy of Sciences DOI:10.1073/pnas.0908012107.

Branch, T. A. 2009. How do individual transferable quotas affect marine ecosystems? Fish and Fisheries **10:**39–57.

Cancino, J. P., H. Uchida, and J. E. Wilen. 2007. TURFs and ITQs: collective vs. individual decision making. Marine Resource Economics **22:**391–406.

Costello, C., S. D. Gaines, and J. Lynam. 2008. Can catch shares prevent fisheries collapse? Science **321:**1678–1681.

CRC Reef Research Centre. 2005. Queensland's east coast reef line fishery. CRC Reef Research Centre, Townsville, Australia. Available from http://www.reef.crc.org.au/research/fishing_fisheries/statusfisheries/statusline.htm (accessed August 2010).

Degnbol, P., H. Gislason, S. Hanna, S. Jentoft, J.-R. Nielsen, S. Sverdrup-Jensen, and D. C. Wilson. 2006. Painting the floor with a hammer: technical fixes in fisheries management. Marine Policy **30:**534–543.

Dupont, D. P., K. J. Fox, D. V. Gordon, and R. Q. Grafton. 2005. Profit and price effects of multi-species individual transferable quotas. Journal of Agricultural Economics **56:**31–57.

Essington, T. E. 2010. Ecological indicators display reduced variation in North American catch share fisheries. Proceedings of the National Academy of Sciences **107:**754–759.

Fernandes, L., et al. 2005. Establishing representative no-take areas in the Great Barrier Reef: large-scale implementation of theory on marine protected areas. Conservation Biology **19:**1733–1744.

Gell, F. R., and C. M. Roberts. 2003. Benefits beyond boundaries: the fishery effects of marine reserves. Trends in Ecology & Evolution **18:**448–455.

Gleason, M., C. Chook, M. Bell, and E. Feller. 2009. Are we missing the Boat? Collaborative Solutions for North American Fish Wars. Conservation Biology **23:**1065–1067.

Grafton, R. Q., T. Kompas, and D. Lindenmayer. 2005. Marine reserves with ecological uncertainty. Bulletin of Mathematical Biology **67:**957–971.

Grafton, R. Q., et al. 2006a. Incentive-based approaches to sustainable fisheries. Canadian Journal of Fisheries and Aquatic Sciences **63:**699–710.

Grafton, R. Q., T. Kompas, and P. Van Ha. 2006b. The economic payoffs from marine reserves: resource rents in a stochastic environment. The Economic Record **82:**469–480.

Hand, T. 2003. An economic and social evaluation of implementing the Representative Areas Program by rezoning the Great Barrier Reef Marine Park. Report on the revised zoning plan. PDP Australia Pty, Sydney.

Hilborn, R., F. Micheli, and G. A. De Leo. 2006. Integrating marine protected areas with catch regulation. Canadian Journal of Fisheries and Aquatic Sciences **63:**642–649.

Jones, P. J. S. 2007. Point-of-view: Arguments for conventional fisheries management and against no-take marine protected areas: only half the story? Reviews in Fish Biology and Fisheries **17:**31–43.

Kragt, M. E., P. C. Roebeling, and A. Ruijs. 2009. Effects of Great Barrier Reef degradation on recreational reef-trip demand: a contingent behaviour approach. Australian Journal of Agricultural and Resource Economics **53:**213–229.

Lanfersieck, J., and D. Squires. 1992. Planning models for individual transferable quota programs. Canadian Journal of Fisheries and Aquatic Sciences **49:** 2313–2321.

Lauck, T., C. W. Clark, M. Mangel, and G. R. Munro. 1998. Implementing the precautionary principle in fisheries management through marine reserves. Ecological Applications **8:**S72–S78.

Leigh, G. M., A. J. Williams, G. A. Begg, N. A. Gribble, and O. J. Whybird. 2006. Stock assessment of the Queensland east coast red throat emperor (*Lethrinus miniatus*) fishery. State of Queensland, Department of Primary Industries and Fisheries, Brisbane.

Le Quesne, W. J. F., and E. A. Codling. 2009. Managing mobile species with MPAs: the effects of mobility, larval dispersal, and fishing mortality on closure size. ICES Journal of Marine Science **66:**122–131.

Little, L. R., A. E. Punt, B. D. Mapstone, F. Pantus, A. D. M. Smith, C. R. Davies, and A. D. McDonald 2007. ELFSim—A model for evaluating management options for spatially structured reef fish populations: an illustration of the "larval subsidy" effect. Ecological Modelling **205:**381–396.

Little, L. R., G. A. Begg, B. Goldman, N. Ellis, B. D. Mapstone, A. E. Punt, A. Jones, S. Sutton, and A. Williams. 2008. Modelling multi-species targeting of fishing effort in the Queensland coral reef fin fish fishery. Report. Project 01/20. Fisheries Research and Development Corporation, Townsville, Queensland.

Little, L. R., A. E. Punt, B. D. Mapstone, G. A. Begg, B. Goldman, and N. Ellis. 2009a. Different responses to area closures and effort controls for sedentary and migratory harvested species in a multispecies coral reef line fishery. ICES Journal of Marine Science **66:**1931–1941.

Little, L. R., A. E. Punt, B. D. Mapstone, G. A. Begg, B. Goldman, and A. J. Williams. 2009b. An agent-based model for simulating trading of multi-species fishery quota. Ecological Modelling **20:**3404–3412.

Mangel, M. 2000. Irreducible uncertainties, sustainable fisheries, and marine reserves. Evolutionary Ecology Research **2:**547–557.

Mapstone, B. D., et al. 2004. The effects of line fishing on the Great Barrier Reef and evaluation of alternative potential management strategies. Technical report 52. CRC Reef Research Centre, Townsville, Queensland.

Mapstone, B. D., L. R. Little, A. E. Punt, C. R. Davies, A. D. M. Smith, F. Pantus, A. D. McDonald, A. J. Williams, and A. Jones. 2008. Management strategy evaluations for line fishing in the Great Barrier Reef: Balancing conservation and multi-sector fishery objectives. Fisheries Research **94:**315–329.

McCook, L., et al. 2010. Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. Proceedings of the National Academy of Sciences DOI: 10.1073/pnas.0909335107.

Queensland Primary Industries and Fisheries. 2008. Annual status report 2007 coral reef fin fish fishery. State of Queensland, Department of Employment, Economic Development and Innovation, Brisbane.

Queensland Primary Industries and Fisheries. 2009. Annual status report 2008 coral reef fin fish fishery. State of Queensland, Department of Employment, Economic Development and Innovation, Brisbane.

Sanchirico, J. N., and J. E. Wilen. 2001. A bioeconomic model of marine reserve creation. Journal of Environmental Economics and Management **42:**257–276.

Smith, A. D. M., et al. 2008. Experience in implementing harvest strategies in Australia's south-eastern fisheries. Fisheries Research **94:**373–379.

Smith, M. D., J. E. Wilen, and J. N. Sanchirico. 2009a. The economics of spatial-dynamic processes: Applications to renewable resources. Journal of Environmental Economics and Management **57:**104–121.

Smith, M. D., and J. E. Wilen. 2003. Economic impacts of marine reserves: the importance of spatial behaviour. Journal of Environmental Economics and Management **46:**183–206.

Smith, T., M.Gibbs, and D. Smith. 2009*b*. Fishing for more effective incentives. Science **203:**337–338.

Worm, B., et al. 2009. Rebuilding global fisheries. Science **325:**578–585.