Evaluating The Potential Implications Of The "Larval Subsidy Effect" For Management Of Reef Fish Populations On The Great Barrier Reef, Australia

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EXTENDED ABSTRACT

Closing areas of marine habitat to fishing ("no take" marine reserves) has been suggested as a strategy for enhancing harvested fish stocks possibly by providing a source of either emigrating adults (the spillover effect) or dispersive larvae (the larval subsidy effect). We have developed a spatially-structured simulation model of the population dynamics and harvest by line fishing of common coral trout (*Plectropomus leopardis*) on the Great Barrier Reef, in order to evaluate potential management strategies, including marine reserves.

The simulation model incorporates harvest by multiple sectors (commercial, charter and recreational) and a spatially structured sub-model of the full life-history of common coral trout, including larval dispersal and hence the possibility of a "larval subsidy effect". In this paper, we use this tool, the Effects of Line Fishing Simulator (ELFSim), to evaluate the conditions, extent and potential effects on the fishery that a "larval subsidy effect" might impart. Simulations were performed for different levels of larval settlement on the same reef to which they were spawned, for a range of spatial closures.

Results showed that under a constant effort scenario, as the amount of area closed to fishing increased, catch tended to decrease as the effort concentrated on a smaller proportion of the population. The spawning biomass increased however, as a larger proportion of the population was protected. The catch supported per unit of biomass was higher when there were area closures and when larvae were advected to reefs after being spawned. This occurred because the areas closed to fishing had biomass at near pre-exploitation levels, and thus subsidised the areas open to fishing with larval input.

When larvae were advected among reefs, closing small portions of habitat to fishing also enhanced catches over what would have been obtained had no areas been closed to fishing.

1. INTRODUCTION

When natural resource managers realised that compared to terrestrial systems, worldwide a very small amount of marine area has been set aside from commercial exploitation, a large amount of scientific interest was spawned. This interest has been directed towards determining the ecological and economic effects of setting aside marine habitat. Many studies have argued that closing marine habitat to fishing ('no take' marine reserves) generates conservation benefits (Hilborn et al. 2004). More controversial however is the claim that marine reserves generate fishery benefits (Smith 2004, McNeill & Fairweather 1993, Boersma & Parrish 1999; Côte, Mosquiera & Reynolds 2001). A fisheries benefit from a marine reserve would result if both catch and biomass increased as a result of saving a part of the population. The rationale behind the argument that marine reserves confer a fisheries benefit is that they provide a source of either emigrating adults (the spillover effect) or dispersive larvae (the larval subsidy effect) to the areas that are fished. The general conclusions that have been drawn are mixed, and depend on biological characteristics of the species of interest (Roberts & Sargant 2002) and the physical characteristics (Roberts 1997) of the habitat.

The Great Barrier Reef of Australia (GBR) extends over 15^o of latitude and includes over 3,000 individual coral reefs and shoals separated by deeper water, sand or muddy habitat. Most of the GBR was declared a multiple-use marine park in 1975. Fishing has occurred on the GBR for decades and is the principal extractive use on it. Fishing is of particular concern however, because of its potential to affect negatively the widely recognized heritage and ecological values for which the GBR is known. A wide range of fishing activities occur on the GBR, including prawn trawling, crabbing, netting and collection for aquarium fish, but perhaps the greatest potential effects on coral reef communities, as opposed to inter-reef habitat, arise from spear and line-fishing activities. Line fishing is of particular concern because it is widespread, and both a recreational and commercial activity, with greater potential to affect the targeted species than other activities. As a result, areas where fishing is prohibited (i.e. marine reserves) are currently implemented throughout the GBR as the principal conservation management tool for the Marine Park, most recently as part of a Representative Areas Program (Day 2002; Mapstone et al. 2004). Although these reserves have been implemented primarily to conserve biodiversity, and not specifically to manage fisheries, the primary effect of them is that they inhibit fishing.

Fishing on the GBR, however, is also an important social and economic contributor to the region. The Reef Line Fishery (RLF) consists of three main sectors: a commercial sector, a charter fishing sector and a private recreational sector. All sectors use similar gears, typically single baited hooks on heavy line with rod or hand reel. The fishery is multi-species in all sectors, but the primary targeted species is the common coral trout, *Plectropomus leopardus* Lacepède (Mapstone et al. 1996). Juvenile and adult coral trout are generally sedentary inhabitants of reefs (Davies 1995) linked only via dispersal of planktonic larval stages. A model that simulates the population dynamics and harvest of coral trout has been developed and used to evaluate options for conservation and harvest management. Similar to other models (e.g. Horwood et al. 1998), this model has three key components:

1. a (meta) population dynamics model of the species that captures the biology, including larval dispersal and hence the possibility of a “larval subsidy effect”,
2. a spatial effort allocation model that captures the exploitation pattern by the fishers, and
3. a management model that simulates the management measures.

In this paper, we use this model, the Effects of Line Fishing Simulator (ELFSim), to evaluate the conditions, extent and potential effects on the fishery under which a “larval subsidy effect” might affect the Reef Line Fishery.

2. METHODS

The software framework used for the model is the Effects of Line Fishing Simulator (ELFSim, Mapstone et al. 2004). ELFSim is a decision support tool designed to evaluate options for managing coral trout in the Reef Line Fishery on the GBR. It contains several components, including output visualisation and run management, but the most important components are a spatially-structured biological model of coral trout population dynamics, and a model of fishing behaviour. ELFSim operates at a monthly time scale, and each simulation consists of two parts. The first operates historically from 1965 to recent times (in this case 2000), using information from visual surveys, catch records, and the physical characteristics of the reefs to seed the population size on each reef. Using these conditions the second part projects the reef populations into the future (2001 and thereafter) subjecting them to simulated fishing pressure, which in turn is subjected to management measures imposed by the user of ELFSim. Thus, the user is able to evaluate the consequences of various management options by examining biological and economic performance indicators that are output from the model.

Some of the management options available allow the user to specify area closures, gear selectivity and minimum catch size. The user also specifies an annual amount of effort to be allocated over an area. Because ELFSim operates at a monthly time scale, annual effort allocated is converted to a monthly effort, based on the seasonal distribution of effort observed in the historical data. Effort therefore determines catch, which is in turn used by the biological model in projecting the coral trout populations forward in time.

In common with previous models of coral trout on the Great Barrier Reef (e.g. Mapstone et al. 1996; Campbell et al. 2001), the biological component of ELFSim is based on the assumption that the population of coral trout consists of many local populations, each associated with a single reef, linked through larval dispersal. The latter assumption is based on the lack of evidence for movement of animals age 1 and older (Davies 1995). Account is taken of the age, sex, and size-structure of the population on each reef. The number of animals settling each year is determined by the annual egg production, the assumed larval distribution pattern and density-dependence in first-year survival. The biological model also allows for variability in natural mortality and larval survival among different reefs and at different times, as well as monthly variation in the relationship between fishing effort and fishing mortality. Larval dispersal is controlled by reef to reef migration data, and a self-seeding parameter that specifies the proportion of larvae spawned on a reef that settle on it.

Fishing pressure is simulated in the projection period by spatially allocating fishing effort to reefs at each monthly time step. Effort allocation is determined by ranking reefs according to historical catch-per-unit effort (CPUE), and assigning to the highest ranked reef, the average amount of effort expended in it historically. This is repeated from the highest ranks until the total amount of effort to be allocated runs out.

ELFSim allows for both infringement into closed areas and displacement of effort away from them. This is done by assigning to closed areas a proportion of effort that would have been allocated to it had it been open, and the remaining effort is re-assigned to reefs with lower ranked CPUE. The proportion of effort allocated to closed reefs is set as a base level of infringement, which is then modified to account for spatial and temporal variability. This variability, specified by the ELFSim user, allows effort to infringe at the edges of closed areas, and the likelihood of infringement to increase with the amount of time an area is closed.

2.1. Scenarios Considered

Although ELFSim is capable of running with approximately 4000 reefs on the GBR, we selected a region in the south consisting of 324 reefs, in order to demonstrate the effects of self-seeding and different amounts of area closures on the resource, and resource users. Based on current knowledge of connectivity among coral reefs (Jones et al. 1999, James et al. 2002) and limited data, the reef to reef larval migration pattern was expressed as a function that decays with distance between reefs (Mapstone et al. 2004). The model ran for the historical period 1965 to 2000 followed by a projection period to 2050. Effort in the projection period was scaled to twice that logged in 1996. (This was the year immediately preceding the announcement of a review of the reef line fishery and a rapid increase in effort and catch, to impose relatively high fishing impacts as area closures increased.) Infringement into closed areas was not allowed in the simulations.

Because we were interested in larval subsidy of open areas by closing areas to fishing we considered seven different sizes of area closure (Table 1) under three different levels of reef self-seeding (0, 0.50 and 1.0). Because lower self-seeding implies greater importance of larval migration among reefs, we expected the subsidy effect to be more pronounced under lower self-seeding scenarios. The selection of closures was arbitrary and performed simply by extending the boundaries of polygons until the required percentage of habitat was contained within the closed boundary. Thus, we only examined a single arrangement or spatial configuration for each closure regime, (e.g. only a single spatial configuration of 20% closure was examined). Further, natural mortality and recruitment to the population were treated deterministically for this demonstration.

3. RESULTS

Under twice 1996 total effort, and no area closures, the spawning biomass (the biomass that is female and mature) was depleted to about 20% pre-exploitation level by 2050, and the catch was reduced to about 35% of what it was prior to the projection period (Figure 1). As the proportion of area closed increased, spawning biomass increased. Under self-seeding of 1.0 the total catch decreased with increasing amounts of area closed. Under self-seeding of 0, catch initially increased under Scenarios 2 and 3 from that with no closures (Scenario 1), but then decreased as areas closed to fishing increased. Under self-seeding 0.5, catch increased slightly in Scenario 2 over that of Scenario 1, but then decrease again as the amount of area closed increased.

Table 1 Proportion of total reef area and total reef perimeter closed for different run scenarios.

Scenario	Proportion Perimeter closed	Proportion Area closed
1	0	0
2	0.20	0.21
3	0.36	0.38
4	0.57	0.62
5	0.73	0.77
6	0.80	0.80
7	1	1

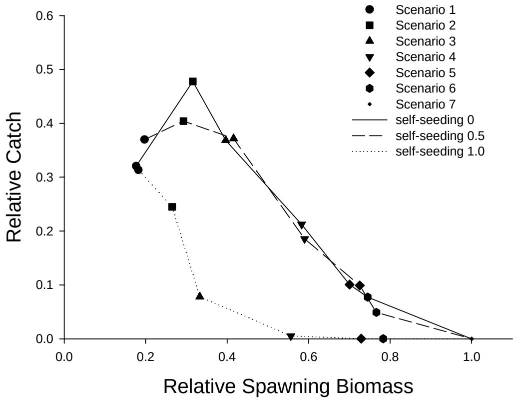

Figure 1 Average total catch 2010-2050 relative to start of projection (2000) plotted against average total spawning biomass 2010-2050 relative to pre-exploitation level (1965) for different levels of self –seeding and closure scenarios, subjected to 2.0 times 1996 effort and different closure scenarios.

At intermediate levels of area fishing closures (Scenarios 2-6), the catch that was supported by the biomass in the model was lowest when larvae settled only on reefs from which they was spawned (self-seeding 1.0).

Under the penultimate closure scenario 6, when self-seeding was 1.0, catch in the final year of the simulation was almost 0, but available biomass was about 80% of pre-exploitation (Figure 1). When the effort was confined to a relatively small area, as in this scenario, the small area open to fishing was depleted to almost extinct levels without any compensation or subsidy of biomass from the closed area (Figure 2). The larger closed area, however, independent of the depleted open area, recovered to its pre-exploitation level (Figure 2). The 80% biomass level of this scenario therefore corresponded to the amount of coral trout habitat closed to fishing (Figure 1).

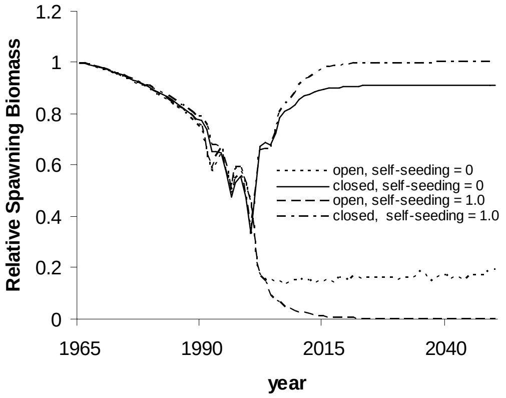

Figure 2 Time trajectory of total spawning biomass in open and closed areas relative to total pre-exploitation (1965) biomass for closure scenario 6, under two levels of self-seeding.

Figure 2 also shows the cost imposed on the closed area, when it subsidises the open area under self-seeding 0. Namely, the biomass on the closed reefs under self-seeding 0 was lower than under self-seeding of 1.0. The benefit however, was that the biomass and catch taken from the open reefs was higher (Figure 2 and 3) as the closed reefs were ‘subsidised’ by larvae exported from the relatively large closed areas.

Figure 1 also shows that when larvae are able to migrate and settle (self-seeding > 0), a fishery benefit occurs by closing areas to fishing. This benefit is manifest by the higher catches taken when a small amount of area is closed (Scenario 2) than when there are no areas closed (Scenario 1).

4. CONCLUSIONS

The Effects of Line Fishing Simulator captures the salient features of the coral tout (meta-) population on the Great Barrier Reef, including larval advection and settlement on reefs. Although work is beginning to show that coral reef fishes may not be dispersed passively among oceanic currents (Wolanski et al. 1997), less certain is the degree to which larvae settle on the same reef to which they are spawned. We have examined the effect of different biological self-seeding scenarios, and the potential effect they may have by increasing amount of fish habitat closed to fishing.

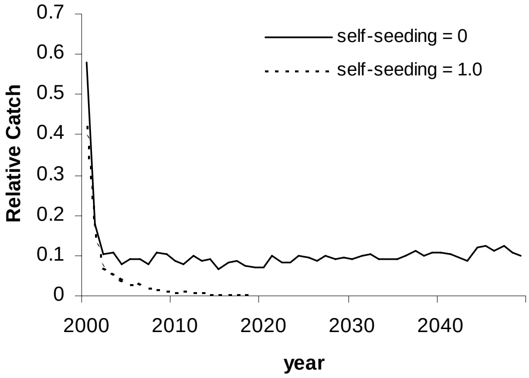

Figure 3 Time trajectory of total catch in the projection relative to 2000 catch level, for closure scenario 6, under two levels of self-seeding.

In the current simulation results higher catches were supported when larvae were able to migrate from the areas closed to fishing on which they were spawned and settle on reefs that were opened to fishing. The spawning biomass in the closed areas thus subsidised the reproductive potential removed from the open areas.

Fisheries benefits made by closing areas to fishing is controversial (Gell and Roberts 2003). In theory however, Polachek (1990) showed that closing areas can lead to higher catches than would occur with the closures, although his model allowed the movement of adults across the closure boundaries. The current results show that catches can be enhanced when just adults are sedentary and the larvae are able to migrate. The benefit to the fishery was inversely related to the proportion of larvae that settle on the same reef on which they were spawned. This benefit however was apparent under deterministic natural mortality and recruitment. The increased catch might be less discernible under more stochastic processes.

The current results occurred under relatively high levels of fishing mortality, of twice the 1996 level of effort. Under higher fishing pressure in the projection period, the catch and biomass will be pushed toward 0. A small closure that protects some of the spawning biomass will allow some of the larvae that are spawned by these fish to migrate and settle on open reefs (if the self-seeding factor is greater than 1). Once the fish in the area open to fishing are vulnerable to the fishing gear they will be harvested, and so the size distribution of the population in the open areas will be truncated close to the minimum legal size. Under lower levels of fishing mortality no such "subsidy effect" or fishery benefit has been witnessed in ELFSim (Little et al. 2005).

Other models of reef fisheries have shown marine reserves can benefit both conservation and fishery needs under high levels of fishing pressure (Man et al. 1995). Simulations using ELFSim have shown the possibility that fisheries benefits can result from closing areas to fishing, and the possible conditions under which such a benefit might occur. In populations that have relatively high amount dispersal, it is possible that within the protected area, where the spawning fish density or productivity is high, larvae can be exported providing additional biomass for harvest from open areas, compared to the biomass when no subsidy occurred. It is also possible that a small closure might result in catches that are higher than if no area was closed to fishing, although the population must already be subjected to relatively high fishing pressure.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Campbell, R.A., Mapstone, B.D. and Smith, A.D.M. (2001), Evaluating large-scale experimental designs for management of coral trout on the Great Barrier Reef. Ecological Applications 11:1763-1777.

Davies, C.R. (1995), Patterns of movement of three species of coral reef fish on the GBR. PhD thesis, Dept. Marine Biology, Jame Cook University, pp 212.

Day, J.C. (2002), Zoning-lessons from the Great Barrier Reef Marine Park. Ocean and Coastal Management 45:139-156.

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

Hilborn, R., Stokes, K., Maguire, J.-J., Smith, T., Botsford, L.W., Mangel, M. Orsensanz, J., Parma, A., Rice, J. Bell, J., Cochrane, K.L., Garcia, S., Hall, S.J., Kirkwood, G.P., Sainsbury, K., Stefansson, G., Walters, C. (2004), When can marine reserves improve fisheries management? Ocean and Coastal Management 47:197-205.

Horwood J.W., Nichols J.H. & Milligan S. (1998), Evaluation of closed areas for fish stock conservation. Journal of Applied Ecology 35: 893–903.

James, M.K., Armsworth, P.R., Mason, L.B., Bode, L. (2002), The structure of reef fish metapopulations: modelling larval dispersal and retention patterns. Proceedings of the Royal Society of London, Series B 269: 2079 – 2086.

Jones, G.P., Milicich, M.I., Emslie, M.J. and Lunow, C. (1999), Self-recruitment in a coral reef fish population. Nature 402: 802-804.

Little, L.R., Smith, A.D.M., McDonald, A.D., Punt, A.E., Mapstone, B.D., Pantus, F., and Davies, C.R. (2005), Effects of size and fragmentation and fisher infringement on the catch and biomass of coral trout, *Plectropomus leopardus*, on the Great Barrier Reef, Australia, Fisheries Management and Ecology 12: 177-188.

Man, A., Law, R. and Polunin, N.V.C. (1995) Role of marine reserves in recruitment to reef fisheries: A metapopulation model. Biological Conservation, 71: 197-204.

Mapstone, B.D., Campbell, R.A. and Smith, A.D.M. (1996), Design of experimental investigations of the effects of line and spear fishing on the Great Barrier Reef. CRC Reef Research Centre, Technical Report No. 7, CRC Reef Research Centre, Townsville, Queensland, 86 pp.

Mapstone, B.D., Davies, C.R., Little, L.R., Punt, A.E., Smith, A.D.M., Pantus, F., Lou, D.C., Williams, A.J. , Jones, A., Russ, G.R. and McDonald, A.D. (2004), The effects of line fishing on the Great Barrier Reef and evaluations of alternative potential management strategies. CRC Reef Research Centre, Technical Report No. 52, CRC Reef Research Centre, Townsville, Queensland, 205 pp.

Polacheck, T. (1990) Year round closed areas as a management tool. Natural Resource Modeling 4: 327-353.

Smith, M.D. (2004), Fishing yield, curvature and spatial behaviour: Implications for modeling marine reserves. Natural Resource Modeling, 17: 273-298.

Wolanski, E., Doherty, P., and Carleton, J. (1997), Directional swimming of fish larvae determines connectivity of fish populations on the Great Barrier Reef. Naturwissenschaften 84: 262-268.