Ecosystem Modelling Of The Great Barrier Reef: A Balanced Trophic Biomass Approach.

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EXTENDED ABSTRACT

By its charter the Great Barrier Reef Marine Park Authority (GBRMPA), must balance the needs of indigenous traditional owners, commercial and recreational fishing interests, and the conservation requirements of the Great Barrier Reef (GBR) marine park's World Heritage Area status. Under both Commonwealth and State legislation, as well as through international obligations of the World Heritage Area listing, management of the marine park is committed to the ecologically sustainable development of fisheries, and most importantly, conservation of their supporting ecosystems. In the current study the basic Gribble (2000) "GBR prawn" ECOPATH trophic model was expanded into a "linked-ecosystems" model, which considered the biodiversity and connecting biomass flows within and between (1) mangrove, (2) lagoon-seagrass, and (3) coral reef systems.

The GBR linked-ecosystem model is an equilibrium trophic hierarchy, with the biomass flows balanced such that there are not more predators than prey to feed them, nor conversely are there "wasted" prey with insufficient predators to exploit the available resource. Thirty-two trophic guilds were modelled, including 25 from the original "GBR prawn" model (Gribble, 2003), plus inshore finfish species groupings and juvenile life-history stages. This spectrum represents a generalised food-web that attempts to capture the major biomass dynamics and flows within the component GBR systems. The model was implemented by means of ECOPATH EwE (version 5 beta) software using the ECOSIM and ECOSPACE routines for temporal and spatial simulations respectively.

The particular application for the model was to identify the effects of the major fisheries in each of the component systems, and the possible confounding effects of independently developed fisheries management plans. Accordingly, long-term temporal simulations of the GBR linked ecosystem model explored the interactions across the line, gillnet and trawl fisheries, and highlighted a number of issues. In both the Sea turtle and Barramundi trophic guilds there were significant interactions between fisheries that are important to the management of these stocks. It appears that there is not a simple intuitive link between fishing pressure and biomass of some targeted species, but a more complex "food-web" effect.

Targeting of fish or prawn aggregations by commercial fishers reduces the efficacy of logbook catch-per-unit-effort (CPUE) as an index of abundance or biomass because the reported catch rate reflects only the densities of fish or prawns within the aggregation or school, not the unbiased estimate of abundance obtained if the population was randomly sampled. Therefore it would be expected that the biomass trajectory predicted by the ecosystem model and by the logbook data would show a reasonably poor fit, as was evident in this study. This result has implications for the reliability of traditional single-species "surplus-production" stock assessment models that use CPUE to model the maximum sustainable yield of a fishery.

Fisheries management plans are currently formulated as stand-alone initiatives that concentrate on the sustainable harvest of target species (usually derived from single-species models), and have little regard for other fisheries that may be directly affected or for indirect ecosystem effects. At present, techniques are lacking to determine the cumulative ecosystem effects of these separate plans or to identify synergies or antagonisms between plans. Consequently the ultimate aim of this study was to produce an "environmental audit" tool for assessing and integrating proposed fisheries management plans for this critical "World Heritage" ecosystem.

1. Introduction.

The Australian Great Barrier Reef Marine Park (GBRMP) covers 325,848 sq km of tropical reef, islands, inter-reef areas and lagoon environments and is a designated "multi-use" World Heritage Area. By its charter the Great Barrier Reef Marine Park Authority (GBRMPA), must balance the needs of indigenous traditional owners, the existing commercial and recreational fishing interests, and the conservation requirements of the park's world heritage area status. Management of fishing, in all its forms, is seen as a major challenge as the harvest, bycatch and collateral damage due to large-scale fisheries are likely to have the greatest anthropogenic impacts on the highly complex and diverse ecosystem of the park (Gribble and Robertson, 1998).

As of January 2005, a fleet of up to 450 commercial prawn trawlers were licensed to operate within the GBRMP World Heritage Area, as were potentially 1,400 inshore gillnet licences (≈ 300 boats), 200 line and over 1,000 pot licences (≈ 300-400 fishers). On average 450 trawler operators and 641 other commercial fishers derive a large proportion of annual income from the GBR World Heritage Area (Lew Williams, QDPI&F Senior Fisheries Economist, pers com. 2005).

Individual commercial fishers are usually multi-endorsed across a number of fisheries, which can reduce the total number of operators fishing in individual fisheries at any one time. Recreational fishers tend to be concentrated around the major population centres but the charter-boat fishing industry can extend the recreational harvest over the entire GBR. A combination of local and tourist sectors exceeds 10,000 recreational fishers annually (Jim Higgs QDPI&F Fisheries pers com. 2005). The GBRMP was designated as a "multi-use" World Heritage Area, which means these fisheries must be accommodated but that their activities must also conform to the conservation obligations of a designated World Heritage Area.

Current management of fishing activity within the GBRMP is two-tiered involving both Commonwealth and State agencies. The Commonwealth GBRMPA controls usage within the park via broad spatial zoning; ranging from general purpose (Open or Blue zones) to fully protected no-take (Closed or Green zones). This zoning is imposed over the top of regulatory Fisheries Management Plans, which are the responsibility of the state via the Queensland Department of Primary Industries and Fisheries (QDPI&F). Management plans include size and bag limits for species taken by the commercial and recreational fishery, and seasonal closures, gear restrictions, and species/size limits (i.e., input controls) for the limited entry commercial fisheries. Neither GBRMPA zoning nor State legislation cover indigenous fishing, so long as the harvest is for traditional use and not for commercial purposes.

Gribble (2000) developed a trophic mass-balance ecosystem model of the northern GBR, which concentrated on predator-prey and dominance relationships of the mainly inter-reefal assemblages. As noted by Tyler (1999) the assemblage is a more tractable level for monitoring and managing an ecosystem, in terms of stress applied by fishing effort. The Gribble (2000) GBR model focussed on impacts of the industrial prawn trawl fleet but considered the activity of a second fishing "fleet", comprised of commercial line fishing with a component of indigenous subsistence fishing.

In the current study the basic Gribble (2000) model has been expanded into a "linked-ecosystems" model, looking at the biodiversity and biomass flows within and between mangrove, lagoon-seagrass, and coral reef systems. The particular application of the model was to identify the effects of the major fisheries in these systems, and the possible confounding effects of the individual fisheries management plans.

Management plans are currently formulated as stand-alone initiatives that concentrate on the sustainable harvest of target species, having little regard for other fisheries that may be directly affected or for indirect ecosystem effects. Currently there is no way to determine the cumulative ecosystem effects of these separate plans nor to identify synergies or antagonisms between plans. While the ecosystem modelling approach can give an "over-view" perspective, the estimation of specific management targets and performance criteria requires a more focussed model. The compromise attempted in this study was to use the ecosystem model to set up the priors for single-species Bayesian stock assessment models (eg. Meyer and Millar, 1999), so allowing the ecosystem insights gained to flow through to setting management criteria.

The ultimate aim of this study was to produce an "environmental audit" tool for assessing and integrating proposed fisheries management plans for the GBR World Heritage ecosystem.

2. Methods

2.1 Main characteristics of the ECOPATH model

The ecosystem simulations of the Great Barrier Reef World Heritage Area were implemented by means of ECOPATH EwE (version 5 beta) software (Christensen et al 2000) using the ECOSIM and ECOSPACE routines for temporal and spatial simulations respectively (Christensen et al., 2000) More detail on the structure and underlying equations of ECOPATH, and of the base "GBR-prawn" model, are presented on the ECOPATH website www.ecopath.org, and in Christensen et al (2000), and Gribble (2000, 2003) respectively.

2.2 Trophic structure of the GBR linked ecosystem model.

The base ecosystem model is an equilibrium trophic hierarchy, with the biomass flows balanced such that there are not more predators than prey to feed them, nor conversely are there "wasted" prey with insufficient predators to exploit the resource. There are 32 trophic guilds, including 25 from the original "GBRprawn" model (Gribble, 2000, 2003), plus inshore finfish species groupings and juvenile life-history stages. The linkage of the component habitat predator-prey systems is via:

- Linked "pools" of inshore juveniles and offshore adults of the same species
- Diet of each component depends on other guilds within that habitat, effectively separating the habitats to a degree; eg, reef species feed mainly on other reef species.

ECOSIM and ECOSPACE simulations allow preferred habitats to be allocated for each guild, with some overlap provided. Pelagic trophic guilds such as "sharks and rays" can feed across all component systems providing food chain linkages.

2.3 Data sources/parameter estimates.

Estimates of species composition and biomass of the major avian, reptile, fish, mollusc, and crustacean assemblages (including the harvested species and discards), as well as diet, consumption and production were calculated from:

- two annual cross-shelf prawn-trawl surveys in the 10,000 sq km far-northern GBR study area (see Pioner et al. 1998). Biomass of fish and non-fish taxa were based on parallel fish-trawling and benthic dredge samples taken at the time of the prawn surveys, (Poiner *et al,* 1998).
- Literature on prawn predation (Brewer *et al*., 1991; eg. Salini *et al.*, 1998; Haywood *et a1*., 1998; Randall *et al*., 1990; Roman *et al,* 1990).
- Diet and life-history information in FISHBASE 99 (Froese and Pauly, 1999) fish database.
- Previously published Ecopath models; (a) the trophic interactions in Caribbean coral reefs, (Opitz, 1993, 1996), (b) for the shrimp fishery in the Southwest Gulf of Mexico (Sherry Manickchand-Heileman, University British Columbia Fisheries Centre, 1999, pers com), and, (c) dynamics of the mangrove forest of Darwin Harbour, Northern Australia, (Julie Martin, Northern Territory University, pers com 2002).
- Additional information on the species composition and biomass of inshore estuarine/mangrove associated biota (see fig 1) gathered by field survey in the far northern GBR in 2000 (Sheppard *et al.* 2002). This habitat had not been sampled extensively in the original surveys of the GBR lagoon, inter-reef and reef areas (see Poiner *et al*., 1998). Fisheries data for the coastal gillnet fishery that operates in this habitat came from the QFISH compulsory logbook database.

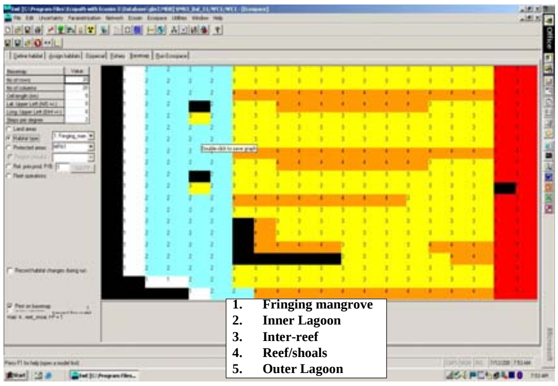

Figure 1. Map (virtual) of the Great Barrier Reef World Heritage Area cross-shelf.

All data not derived from the GBR-WHA surveys, were taken from tropical prawn trawl grounds with similar general characteristics. The expanded "GBR linked ecosystem" model deals mainly with the inner lagoon and inter-reef trawl grounds as this habitat complex represents 80-90% of the World Heritage Area, (Pioner *et al,* 1998). The coral-reef proper was included, as was the reef line fishery, but the model represents a simplification and generalisation of the fractal-like complexity of this ecosystem. Similarly only a simplification of the full mangrove forest/swamp ecosystem, along with the coastal gillnet fishery, was included in the linked ecosystem model.

Combined with the original parameter estimates in Gribble (2000), the new survey data increased the species used to estimate trophic guilds to over 1000 fish and non-fish taxa**.** New trophic guilds of “inshore finfish” and “Dugong” (a protected inshore species) were added. The species mix of “small schooling fish” and “small fish omnivores” trophic guilds changed from Gribble (2000) due to the addition of the mangrove and estuary species, hence the proportion of these guilds taken as trawl bycatch also changed because of a reduction in vulnerability to capture by the trawl fishery in the inshore mangrove areas. The biomass estimates for both guilds were also increased appropriately; in line with the combined survey estimates

Figure 2. Linked ecosystem model of the Great Barrier Reef World Heritage Area cross-shelf. Boxes indicate the fishery that impacts a particular habitat/ecosystem; loops indicate the linkage of habitat/ecosystems to the greater reef-wide ecosystem.

The cross-shelf connectivity or linkage between component ecosystems (see Figure 2) was introduced via the split-pool facility within ECOPATH where juveniles with a particular diet, can be linked with adults of the same species whose diet has significantly changed (see Table 2 part a & b). For example, herbivorous plankton feeding in juveniles of the “small schooling fish” trophic guild, change to a more carnivorous diet in adults. This guild includes species commonly referred to as “baitfish”, which are commercially harvested from inshore shallow waters, as well as being significant prey items for mid-shelf and offshore demersal and pelagic fish species. The latter are high value targets for commercial reef-line and gill-net fisheries. The “small schooling fish’ trophic guild is also a component of the lagoon and inter-reef bycatch from prawn trawlers and, partly as a consequence of this, is a component of the diet of seabirds.

Estimates of biomass, consumption, production, and diet matrices (see also Gribble, 2000) represent the underlying assumptions of the model and a different set of assumptions may also produce a balanced model. As with all models the aim was to capture the major biomass dynamics and flows of the much more complex, "real" system.

Note: Heuristic validation of the basic model using historic logbook data has been reported separately in Gribble (2000) and Gribble (2003).

2.4 Spatial simulations and speed of movement.

The “GBR linked ecosystem” model was made spatially explicit by mapping five broad habitat types, (fringing mangrove swamp, inner reef lagoon, mid-shelf reef/shoals, mid-shelf inter-reef, and outer reef lagoon, see Figure 1) onto a virtual landscape and moving the trophic guilds across them. The land and islands were mapped as “no-movement areas” and the trophic guilds distributed around rather than across them. Movement rates were set at biologically reasonable speeds for typical species within each guild.

2.5 Fishery parameter estimates.

The fishery parameter estimation for the model was divided into three commercial fishing fleets, with the recreational fishery harvest not treated separately but included as a component of each:

- The inshore gillnet fishery, which tends to take large predatory coastal fish, or through the baitfish fishery, to take small schooling fish. Bycatch for this fishery is mainly small omnivorous fish species. There was also a very small bycatch of the inshore seagrass herbivores, Dugong and Green turtles (Gribble *et al*, 1998).
- The reef line fishery for large reef/inter-reef carnivores, both schooling and non-schooling fish, which was combined with the Indigenous harvest of turtles; and
- The prawn trawl fishery for penaeid prawns, which produces the highest proportion of discarded bycatch, mainly small fish (small fish omnivores), conservatively estimated at a ratio of 6: 1 by weight of bycatch to retained catch (Poiner *et al,* 1998).

The recreational fishery estimates were derived from two overlapping sources; a national survey of non-commercial fishing in 2001 (Anne Coleman NT Fisheries pers com; Henry and Lyle, 2003), and, the Queensland RFISH database which is based on telephone and logbook surveys carried in 1999, 2001, 2003 (Jim Higgs, QFS RFISH program, pers com 2005).

The inshore commercial gillnet fishery was restricted to the fringing mangroves and inshore lagoon. The trawl fleet could fish in both the inshore lagoon and the inter-reef but the cost of fishing increased proportionately further offshore into the inter-reef habitat. The reef line fishery fleet was restricted to the more accessible reef-shoal and inter-reef habitats. Again it was made slightly more "costly" to line fish in the less-accessible offshore sections of these habitats. The rationale for these increasing costs was the increased fuel required to travel further offshore, increasing loss of fishing gear in the rougher terrain, and an increased risk of boat damage in the poorly charted offshore reef-shoal zone.

Further out, the offshore lagoon habitat was not fished in this simulation because of its exposed position, very rough ocean floor (extensive plate coral), and to provide a refugia for turtles and seabirds around nest-site islands and shoals. This scenario broadly matched the known fishing behaviour of trawlers and line fishers in the far northern GBR (Gribble and Robertson, 1998; Poiner *et al,* 1998).

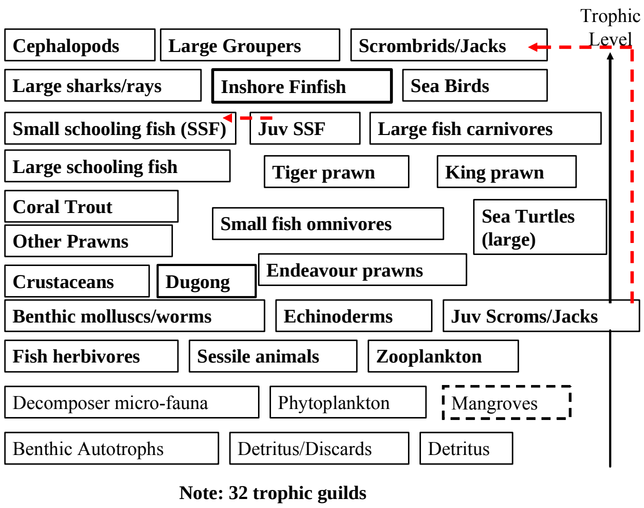

Figure 3. Diagram of the 32 trophic guilds used in the ECOPTH EwE, GBR ecosystem model.

3. Simulations

A series of 100 year ECOSIM time-series simulations of the GBR model were run with a simple but compounding scenario. After equilibrium was established at the current levels of fishing pressure, the relative fishing effort was reduced to 50% of the current levels for:

- The reef line fishery.
- The reef line fishery + the inshore gillnet fishery
- The reef line fishery + the inshore gillnet fishery + the inter-reef/lagoon prawn trawl fishery.

The ecosystem effect of the reduced fishing pressure and the cumulative effects of such a reduction in each fishery are presented in Figures 4, and 5.

4. Results

Simulation scenario(s): As fisheries were successively added to the base scenario of a 50% reduction in fishing effort, interactions between fisheries became apparent. The reduction of effort in the Reef Line Fishery showed a long-term increase in the relative biomass of the primary target “guilds”; Coral trout, adult Mangrove jack, large Sharks/Rays, and large Groupers (see Figure 4).

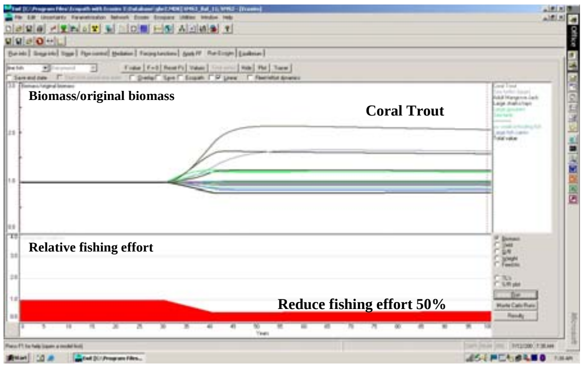

Figure 4. ECOSIM temporal simulation output panel from ECOPTH EwE, GBR ecosystem model, for a 50% reduction in fishing effort in the Reef line fishery. Lower box shows time-series of relative fishing effort (and effort scenario being modelled); upper box shows trajectories of relative biomass for all trophic guilds; right-hand box lists guilds that increase (above the dotted line) and guilds that decrease (below the dotted line) in relative biomass.

Trophic guilds that decreased in relative biomass were primarily prey species “juvenile schooling fish” or the competing “large fish carnivores” that logically would be impacted by the increased biomass of the previously targeted top predators.

Reduction of fishing effort in both the Reef Line Fishery and the inshore/estuary gillnet fishery showed a similar long-term increase in the relative biomass of the primary target “guilds” of the line fishery but with an interaction between the fisheries indicated by the rise in the relative biomass of the Sea turtles (compare Figure 4 and 5).

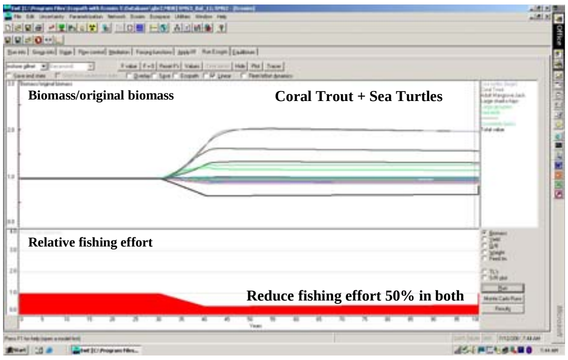

Figure 5. ECOSIM temporal simulation output panel from ECOPTH EwE, GBR ecosystem model, for a 50% reduction in fishing effort in the Reef line fishery and the inshore Gillnet fishery.

Similar but more pronounced impacts were seen when fishing effort was reduced in the combined Reef Line Fishery, inshore/estuary gillnet, and trawl fisheries.

5. Discussion.

One of the main insights drawn from this expanded modelling of the GBR ecosystem has been the effect of scale. By increasing the number trophic guilds and area/type of habitats simulated, the fine detail in prawn behaviour noted in Gribble (2000, 2003) has been effectively "blurred". In ECOPATH the biomass of a given species must to be averaged over the whole area simulated, therefore small areas or habitats where high definition data has been collected tend to be averaged out in the larger model. In particular, the biomass of the "small omnivorous fish" guild increased significantly with the addition of the mangrove habitat. The vulnerability of this guild to the trawl fishery was therefore reduced and the number of predators on this guild increased across the multiple habitats.

A second unforseen effect was that with more complex models, any personal involvement in collection of data-sets was necessarily reduced, with the result that the intuitive feel for how a certain population or assemblage would behave was lost. In this case the question "is a predicted response biologically reasonable" becomes less useful as a heuristic test of the model's output. Balancing the biomass flows in the overall model required more difficult compromises in adjusting parameter estimates, not only because of the extra complexity but also because of the need to link habitat "sub-systems" (see methods).

Temporal simulations of the GBR linked ecosystem model explored the interactions across the line, gillnet and trawl fisheries, and highlighted a number of issues. The most obvious was the apparent negative impact of fishing on the Sea turtle trophic guild. All species of sea turtles are protected in Queensland hence this issue is of major concern to managers. The *Fisheries (East Coast Trawl) Management Plan 1999* addressed the issue by making turtle excluding devices (TEDs) mandatory on all trawl nets in Queensland, with the exception of small river beam trawls. An obvious future scenario simulation for the model is to include the impact of TEDs on the Sea turtle guild.

Less tractable are the catches of Sea turtles made by the Reef line and inshore gillnet fisheries. These catches are made up of a small bycatch by the commercial fishers but also include the relatively large catches made by indigenous fishers who take sea turtles as traditional food (Henry and Lyle, 2003). Indigenous traditional fishing is not controlled under any of the current Queensland fishery management plans.

The comparison of the model output with the "catch per unit effort" index of abundance/biomass provided by the commercial catch and effort logbook data also highlighted issues. One problem with using CPUE as the index of fish population abundance or biomass is the underlying assumption that catch per unit of fishing effort will reliably estimate some consistent proportion of the true abundance or biomass. Targeting of fish or prawn aggregations by fishers reduces the efficacy of CPUE as an index because the reported catch rate reflects only the densities of fish or prawns within the aggregation or school, not an unbiased estimate of abundance or biomass.

6. Conclusions

1. The ecosystem modelling approach to fisheries management can provide insights into the interactions and cumulative impacts of various control initiatives of commercial and recreational/indigenous fishing. The approach also meets the current legislative imperative in Queensland and goes a long way towards addressing international concerns for ecologically sustainable management of the GBR World Heritage area.
2. The ecosystem modelling approach to fisheries management can also provide insight into the impact of fishing on non-target species, which are not normally recorded in commercial logbooks and therefore cannot be monitored except by fisheries-independent means.
3. Linked ecosystem modelling of an ecosystem such as the GBR can predict biomass trajectories that vary significantly from that of fisheries dependent indices of biomass (i.e., CPUE), due to the aggregating behaviour of some target species and the consequent non-random behaviour of fishers.

7. Acknowledgment.

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