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MODELLING MULTI-SPECIES TARGETING OF FISHING EFFORT IN THE QUEENSLAND CORAL REEF FIN FISH FISHERY

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Non Technical Summary

FRDC 2001-020	Modelling multi-species targeting of fishing effort in the Queensland Coral Reef Fin Fish Fishery

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Objectives:

1. Develop dynamic computer simulation models that predict the spatial distribution of effort by commercial line fishers in response to the harvest of multiple species in the Queensland Coral Reef Fin Fish Fishery.
2. Formally evaluate alternative harvest and conservation management strategies for Coral Trout and Red Throat Emperor for the Queensland Coral Reef Fin Fish Fishery, given models of changes in fishing strategy related to the harvest of multiple species, either through target switching or retention of significant by-product.

Non Technical Summary:

Multi-species targeting is a common feature of tropical coastal fisheries and is particularly prevalent in coral reef fisheries such as the Coral Reef Fin Fish Fishery (CRFFF) of the Great Barrier Reef, Queensland, Australia. Predicting the distribution and effects of fishing effort in multi-species fisheries is difficult, and must be factored into management strategies so that all targeted species are adequately protected. In this project, we simulate the targeting behaviour, vessel dynamics and effort distribution in the CRFFF and evaluate alternative management strategies for the sustainable harvest and conservation of the major target species, common Coral Trout (*Plectropomus leopardus*) and Red Throat Emperor (*Lethrinus miniatus*). We build on the single species population and effort dynamics models developed for common Coral Trout as part of the previous CRC Reef Research Centre's Effects of Line Fishing (ELF) Project, and extend them to include Red Throat Emperor, the second major target species of the CRFFF, thereby incorporating the multi-species nature of the fishery. We also add an individual-based vessel dynamics model to simulate individual vessel behaviours associated with harvesting the two species. We evaluate simulated outcomes from a range of stakeholder identified management strategies against a range of stakeholder identified management objectives.

Results showed that, of the strategies considered, reducing fishing effort is the most effective way of maximizing conservation and stock objectives for both Coral Trout and Red Throat Emperor. Reducing effort increased the biomass of spawning fish on closed reefs and also increased the total biomass of fish available to the fishery on open reefs. The management strategy that best maximised the harvest objective depended on the species. Reducing the minimum legal size limit (MLS), combined with increasing fishing effort and the amount of area open to fishing achieved the highest harvest of Coral Trout, while for Red Throat Emperor, reducing the selectivity of the gear combined with changing the MLS led to the largest harvests. The highest CPUE (catch per unit effort) of Coral Trout was obtained by reducing fishing effort and the highest catches rates of Red Throat Emperor were obtained by reducing the selectivity of the gear combined with changing the MLS. The best strategies for the recreational fishers who wished to catch a big fish (over 50 cm total length) each trip

also involved reducing total fishing effort. (The reduction in fishing effort however implies that those benefits are conferred only to the fishers choosing to remain in the fishery.)

Area closures tended to have mainly conservation benefits, particularly with the more sedentary Coral Trout. The results of varying area closed, however, were less effective on Red Throat Emperor than they were for Coral Trout. This difference can be attributed to the species' different population dynamics: Coral Trout are assumed to distribute spatially in the larval stage only, and when they settle do not move among reefs; Red Throat Emperor, however, are assumed to disperse as larvae, settle on reefs and then migrate among reefs with greater likelihood as they age. It is widely recognised that the effects of marine reserves and area closures on migratory stocks such as Red Throat Emperor are less effective than on more sedentary species such as Coral Trout.

A major issue addressed with this research concerns the effect of the seasonal spawning closures. Although the importance of seasonal spawning closures is increased if the catchability of Coral Trout and Red Throat Emperor increased during spawning periods, previous unpublished research indicates that catchability does not increase during the spawning season for Coral Trout, and for Red Throat Emperor any increase is at best marginal. In general, similar to the other effort reduction strategies, a three month closure that effectively decreased total fishing effort for the year had conservation and stock benefits, but tended to reduce the ability to satisfy management objectives related to harvest (specifically, to meet catch quotas). The absence of seasonal spawning closures had an effect similar to increasing effort, although the effect was somewhat “muted” compared to the effects of higher effort levels applied in other management strategies.

Finally, we also addressed the implications of changing the size restrictions for Coral Trout and Red Throat Emperor. Results showed that reducing the MLS of either species had an effect similar to increasing fishing effort. In general, such management options increased the total harvest but led to lower levels of spawning and available biomass. The management strategy that involved a reduction in MLS from 38 cm to 35 cm total length had a marginal effect if no change in gear selectivity was invoked, but coupling the reduced MLS with a change in gear to target the smaller fish exaggerated the effect substantially. The management strategies that evaluated introduction of a maximum legal size were based on the premise that large individuals contribute a disproportionate amount of spawning potential to the population. Coupled with a reduced MLS of 28 cm, this strategy led to less chance of achieving the conservation objectives.

The results emphasise a difference in the effectiveness of management strategies on the different species considered (i.e., Coral Trout and Red Throat Emperor). This highlights the importance that fishery managers and stakeholders should not judge the effectiveness of a management strategy on only a single species, like Coral Trout, alone. In a multi-species fishery such as the CRFFF, impacts of fishing and performance of fisheries are likely to vary with species harvested by the fishery.

We have highlighted the consequences of different management options for the CRFFF. These have been laid out in a manner that is comparative rather than prescriptive, stressing the trade-offs among alternative strategies when assessed against the diverse objectives held for the fishery. Such a process aids in decision-making, in a frank and transparent manner by all who value the Great Barrier Reef.

Keywords:
Coral Trout, *Plectropomus leopardus*, Red Throat Emperor, *Lethrinus miniatus*, multi-species targeting, reef line fishery, management strategy evaluation, Great Barrier Reef.

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1. Introduction

1.1. Background

Multi-species targeting is a common feature of tropical coastal fisheries and is particularly prevalent in coral reef fisheries. Targeting behaviour is influenced by a multitude of factors including market demands, life-style considerations, and seasonal abundances of target species (Allen and McGlade 1986, Pradhan and Leung 2004). Predicting the distribution and effects of fishing effort is difficult in multi-species fisheries in which costs and catch expectations differ among target species, fishing grounds, times of year and individual fishers (Holland and Sutinen 1999). However, multi-species targeting behaviour and associated vessel dynamics and fishing effort need to be considered when formulating management strategies so that the flexibility in fishing operations is taken into account and that all targeted species are adequately protected. Although there is a growing acceptance for the need to understand fisher behaviour and incorporate it into management (e.g., Hilborn 1985, Holland and Sutinen 1999, Little et al. 2004, Salas and Gaertner 2004), relatively little is known about the effects of targeting behaviour or vessel dynamics on either the patterns of fishing or the sustainability of the underlying fish stocks upon which the fisheries depend. In this project we examine the targeting behaviour, vessel dynamics and resultant effort distribution in the Queensland Coral Reef Fin Fish Fishery (CRFFF) and evaluate alternative management strategies for the sustainable harvest and conservation of the two major target species, common Coral Trout (*Plectropomus leopardus*) and Red Throat Emperor (*Lethrinus miniatus*).

Fisheries management has come under intense scrutiny in the past decade with over 70% of the world fisheries either fully- or over-exploited (Garcia and de Leiva Moreno 2003), despite significant investments in understanding key biological aspects of targeted fish stocks. Most of the problems in fisheries management can partly be attributable to the failure to understand and incorporate fishers' behaviours and motivations in the assessment and decision-making processes (Hilborn 1985). Management strategies typically have focused on biological aspects of targeted stocks and either ignored or made simplistic assumptions about the responses of fishers to changes in stock sizes, market fluctuations and management regulations (Hilborn and Walters 1992, Salas and Gaertner 2004). These short-comings have been recognised in recent years with a growing recognition of the need to understand fisher behaviour to accurately predict the response of fishers to management strategies (Hutton et al. 2004, Little et al. 2004, Salas et al. 2004).

Fisher behaviour is complex and multi-faceted (Hilborn 1985) but where and how fishers allocate their fishing effort is critical to evaluating the effects, and likely success or failure, of potential management strategies (Little et al. 2004). For example, understanding fishers' responses to the implementation of spatial and temporal fishing closures will assist in predicting the effects of effort displacement to new fishing grounds and target species. Consequently, it is important to evaluate the basic processes that determine fisher behaviour, and in turn the fleet-wide vessel dynamics of a fishery. An understanding of vessel dynamics can provide insights into the spatial dynamics of fishing effort, fisher behaviour and the flexibility of fishers to adapt to new and changing circumstances, and the relationships between fisheries and the resources on which they depend (Hilborn 1985, Gillis 2003, Salas and Gaertner 2004). Few studies, however, have examined the factors that influence fisher behaviour, and models of vessel dynamics and effort allocation are poorly developed (Hilborn and Walters 1987). As effort allocation involves when, where and what to fish, development of such models is fundamental for predicting responses of fishers to management strategies, particularly in multi-species fisheries where fishers can adjust fishing strategy to target different species or in response to catches of different species.

Multi-species targeting of fishing effort is a characteristic of the CRFFF, which operates predominantly in the Great Barrier Reef World Heritage Area (GBRWHA) of Australia (Fig. 1.1). The Great Barrier Reef (GBR) is one of the largest coral reef ecosystems in the world, with over 2900 gazetted individual coral reefs. The Great Barrier Reef Marine Park (GBRMP) was established in 1975 to facilitate conservation management of most of the GBR and an area including the GBRMP was inscribed on the World Heritage list as the GBRWHA in 1981. The GBRMP contains a number of no-take zones or those areas where extractive activities such as fishing are prohibited, with the best known and most widespread being the Marine National Park Zones (locally referred to as “green” zones). The legislation for the GBRMP sets broad objectives of zoning, which require both conservation and protection of biodiversity, whilst also allowing multiple uses, including fishing, in some areas. Until recently, no-take zones accounted for about 5% of the total area of the GBRMP and approximately 24% of the area of the mapped coral reef habitat in the Marine Park. A major rezoning program, called the Representative Areas Program (RAP), was undertaken in the late 1990s by the Great Barrier Reef Marine Park Authority (GBRMPA) resulting in a more comprehensive, adequate and representative zoning network encompassing all habitats, being declared in July 2004. Coverage of no-take zones increased to 33% of the entire Marine Park under the RAP zoning (GBRMPA 2004, Fig. 1.1).

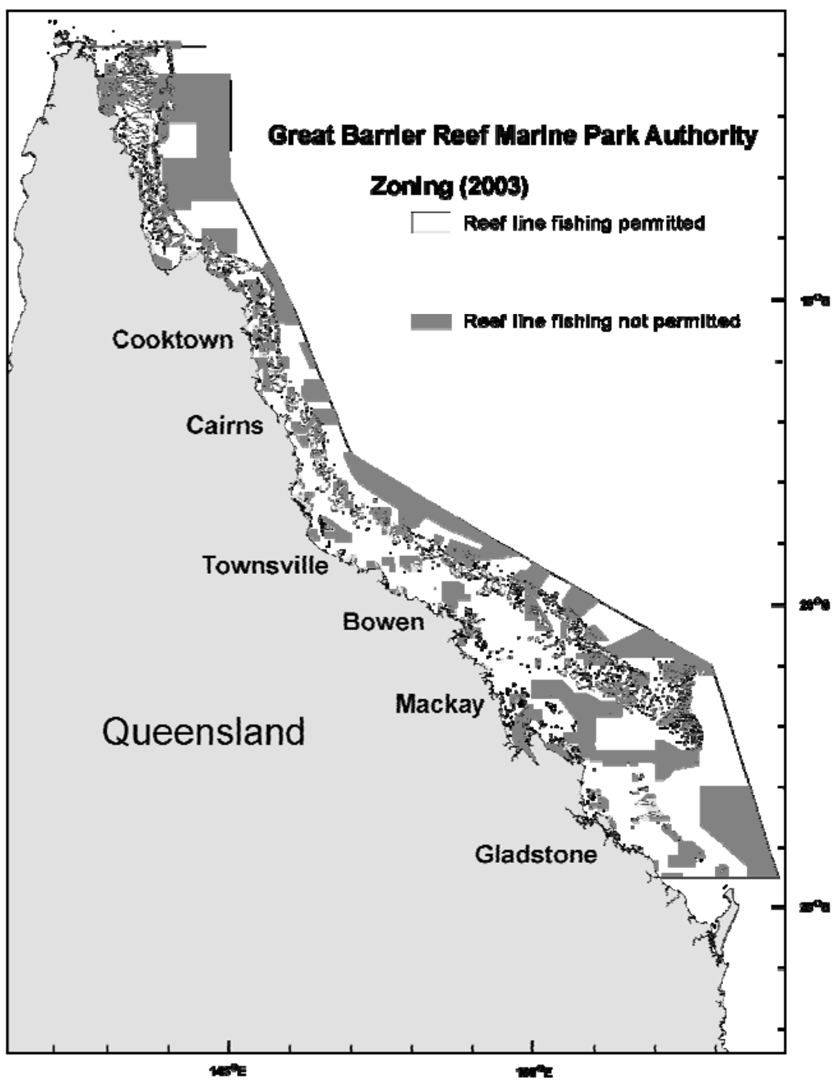


Fig. 1.1. Map of Great Barrier Reef and area accessible to reef line fishing under the GBRMPA RAP zoning provisions of 2004.

Fishing is the major extractive resource use on the GBR, with zoning determining the locations in which different activities can occur. The CRFFF is one of a variety of commercial fisheries supported by the GBR, with an annual economic value of about AU$60-100 million (Williams 2002). This diverse and valuable line fishery comprises commercial, recreational, charter and traditional fishing sectors, all of which target a range of demersal reef fish species, while providing substantial economic and recreational benefits to the community (Mapstone et al. 2004). The commercial sector harvests 3000-4000 t annually from the multi-species reef line fishery of the GBR, while significant quantities are also harvested by the recreational (~2000 t) and charter boat (~300 t) sectors (Williams 2002). Common Coral Trout and Red Throat Emperor are the two major target species of the reef line fishery for all sectors in most regions of the GBRWHA, comprising nearly 50% of the total catch (Higgs 1996; Mapstone et al. 1996b; 2004). However, over 125 species groups have been recorded in the compulsory logbook system managed by the Queensland Department of Primary Industries and Fisheries (DPI&F) for the commercial sector (Mapstone et al. 1996b). The reef line fishery is managed by the state of Queensland (Queensland Fishery Act 1994) and current management strategies for the fishery include seasonal spawning closures and size limits for all sectors, limited entry and an Individual Transferable catch Quota (ITQ) system for the commercial sector and hook and bag limits for the recreational and charter sectors.

This project builds on the single species population and effort dynamics models developed for common Coral Trout as part of the CRC Reef Research Centre's Effects of Line Fishing (ELF) Project (FRDC 1997-124; Mapstone et al. 2004), and extends them to include Red Throat Emperor, the second major target species of the CRFFF. The project is directly relevant to the management of tropical line fisheries and the conservation management of the GBRWHA, and builds on previous model development, data collection and analyses conducted as part of the ELF Project and FRDC Projects 1996-138, 1997-124 and 1998-131 (Mapstone et al. 2001, 2004, Davies et al. 2006). In doing so, the project extends the generality of the single species and coarse effort allocation models developed previously to include vessel-specific allocation of effort between the two major target species (common Coral Trout and Red Throat Emperor) and the resultant effect on the effort distribution in the fishery and effects on both primary harvest species.

1.2. Need

The CRFFF is a high-valued, multi-sector, multi-species line fishery operating in the GBRWHA, where, until recently, there were substantial gaps in our knowledge of the biology of the major target species and considerable uncertainty about the effects of current harvest levels. However, the CRC Reef ELF Project and other related FRDC Projects have provided an improved understanding of: 1) the biology of the major target and by-product species with a particular focus on common Coral Trout and Red Throat Emperor; and 2) the characteristics and fishing practices of the different sectors of the fishery.

Furthermore, one of the main tools for delivery of the outcomes of the ELF Project has been the development of the Effects of Line Fishery Simulator (ELFSim); a set of models that can be used to evaluate alternative management strategies relative to specific stakeholder objectives for common Coral Trout (Mapstone et al. 2004). Given the multi-species nature of the fishery, however, there was a need to address the implications for the effectiveness of alternative management strategies of fishers harvesting species with different distributions and biology. Multiple species could be harvested either by targeting or as a significant by-product when targeting Coral Trout and there was particular interest in the effect of such harvest on the second major species taken in the fishery, Red Throat Emperor (*Lethrinus miniatus*). Assessing the effects of fishing on different species is especially relevant on the GBR where many species have different spatial distributions and population dynamics and prominent conservation and fishery management strategies include area and spawning closures that directly affect the spatial and temporal distribution of fishing effort. Despite considerable previous work, the potential effects of closures and other management strategies on the harvest, spatial distribution of effort and effects on stocks of fish other than common Coral Trout were largely unknown. This project, therefore, provided a formal context in which to evaluate a range of management strategies related to the harvest and conservation of both common Coral Trout and Red Throat Emperor, the two major target species of the CRFFF.

Our capacity to address the multi-species nature of the fishery previously was limited by a paucity of information for target species and fishing practices, and the lack of a formal management strategy evaluation (MSE) framework that included more than one species. This project is a step towards explicitly incorporating the multi-species nature of the fishery when evaluating alternative management strategies for line fishing on the GBR, focusing on both common Coral Trout and Red Throat Emperor as the primary and secondary harvest species respectively. While this project focused on the CRFFF, the tools developed provide the basis for extension to include other species of the fishery and application to other multi-species fisheries as relevant data are collected. The project directly addressed concerns of QFIRAC (Queensland Fishing Industry Research Advisory Committee), ReefMAC (Reef Line Fishery Management Advisory Committee) and GBRMPA related to management of the diversity of effects of the fishery on species other than common Coral Trout.

1.3. ELF Project

The Effects of Line Fishing (ELF) Project is a multi-faceted research project designed to understand the effects of line fishing on the productivity and conservation status of key target and by-product species of the GBR. The ELF Project commenced in 1993 to provide information directly relevant to management on the CRFFF and its effects on the GBR (Mapstone et al. 2004). The ELF Project involves six main research areas related to the CRFFF, including: 1) documentation of historical catch and effort patterns; 2) monitoring by fishery-dependent and -independent methods; 3) determination of vital biological characteristics of key target, by-product and by-catch species; 4) manipulation of fishing pressure and subsequent responses of target stocks and their prey; 5) evaluation of alternative management strategies; and 6) liaison and extension of research results to stakeholders (Mapstone et al. 2004). The current project on multi-species targeting arose as part of the broader ELF research project. Outcomes of research investigating the effects of the live reef fish trade, the ELF Experiment, management strategy evaluation of common Coral Trout, and stock structure and population dynamics of Red Throat Emperor and other target species are reported elsewhere (Mapstone et al. 2001, 2004, Davies et al. 2006).

1.4. ELF Experiment

The Effects of Line Fishing (ELF) Experiment is a fundamental component of the ELF Project, designed to monitor the responses of target fish stocks to various levels of fishing pressure (Davies et al. 1998; Mapstone et al. 2004). The large-scale manipulative spatial and temporal design of the ELF Experiment is unique and of global interest, particularly with respect to monitoring the effects of no-take zones in marine protected areas (Begg et al. 2005). The ELF Experiment involved monitoring reef fish populations from clusters of six adjacent reefs in four geographic regions that covered a broad expanse of the GBR (Fig. 1.2). Four of the six reefs in each region had been closed to all forms of fishing for 10-12 years prior to the commencement of fieldwork for the Experiment in 1995. The remaining two reefs in each cluster were historically open to fishing, and provided the necessary “effect” treatment against which the performance of the no-take zones (i.e., “green” reefs) could be assessed. In addition, two of the closed reefs in each region were opened to fishing for one year, while the historically open reefs were subject to increased “pulse” fishing for one year prior to being closed for five years (Mapstone et al. 2004).

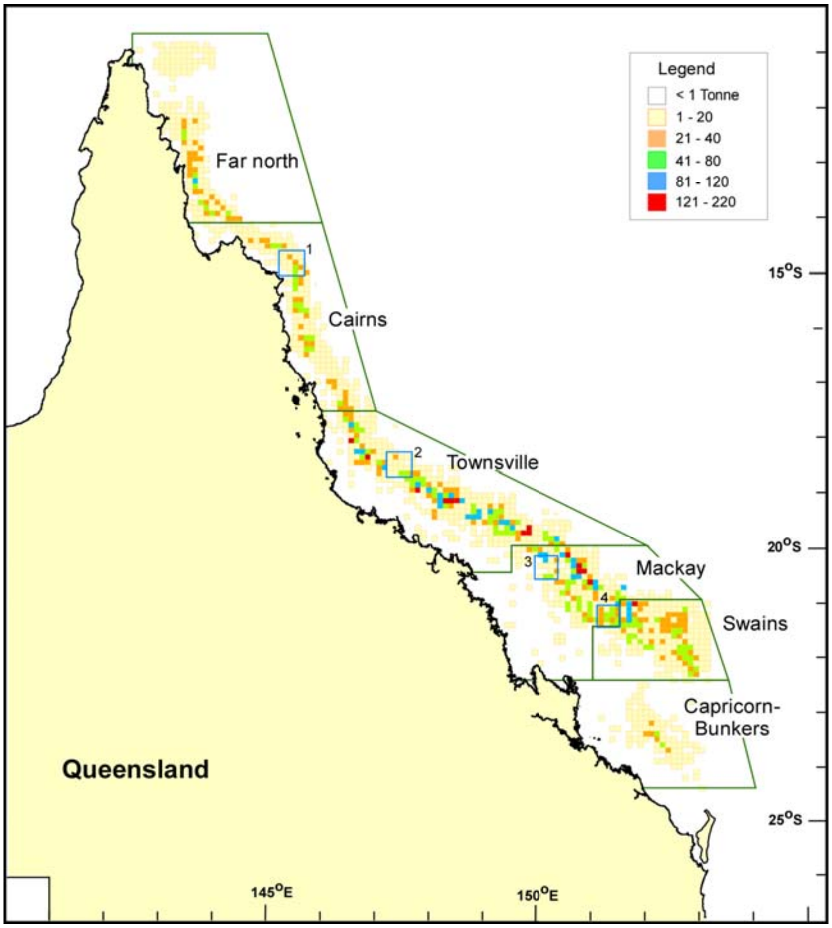


Fig. 1.2. Statistical regions used for analysis of reef fish catches, and the main fishing regions of the Queensland Coral Reef Fin Fish Fishery as defined in Mapstone et al. (1996b) (see also Table 2.2). Numbered squares refer to clusters of ELF Experiment reefs: 1) Lizard Island; 2) Townsville; 3) Mackay; and 4) Storm Cay. Legend refers to commercial catches (t) of Coral Trout, summed across fishing years 1990-2003.

All reefs were sampled each year in the austral spring (October-December) to coincide with the peak spawning period of the major target species, common Coral Trout. Each reef was divided into six approximately equal sized, contiguous blocks, and generally sampled on a single day on each sampling occasion. Sampling on each reef involved both structured line fishing catch surveys and underwater visual surveys. The underwater visual surveys were timed to precede the catch surveys slightly. The catch surveys involved the charter of a commercial fishing vessel where sampling effort and fishing gears were standardised, although still characteristic of commercial fishing practices. Standardised fishing effort was distributed uniformly across two depth strata within each block. All fish caught were measured, tagged for later identification, and kept for weighing and extraction of gonads and otoliths. Common Coral Trout and Red Throat Emperor were aged using standardised methods developed by Ferreira and Russ (1994) and Williams et al. (2003), respectively. For further sampling details of the ELF Experiment see Davies et al. (1998) and Mapstone et al. (1998, 2004).

Results from the ELF Experiment have directly informed management of the fishery and provided key insights on the biology and sustainability of key target fish species, the Environment Protection and Biodiversity Conservation (EPBC) assessment process, and long-term monitoring plans for the CRFFF and RAP. Moreover, results on the biology of common Coral Trout and Red Throat Emperor have been reported in Mapstone et al. (2004) and Davies et al. (2006), respectively, and are used in this project.

1.5. ELFSim

Another fundamental component of the ELF Project is the Effects of Line Fishery Simulator (ELFSim), which has been used to evaluate alternative management strategies relative to specific stakeholder objectives for common Coral Trout (Mapstone et al. 2004). ELFSim provides an MSE framework to examine tradeoffs associated with the performance of alternative conservation and fishery management strategies, which to date have focused on area closures and effort controls respectively. ELFSim is comprised of three integrated components: 1) biological operating model; 2) effort model; and 3) management model (Fig. 1.3). The biological component incorporates the underlying population dynamics of the target species, including vital life history characteristics such as growth, reproduction and mortality. The harvest component incorporates the fishery dynamics and subsequent harvest of the target populations represented in the biological model. The management component allows various management strategies, including spatial and temporal closures, size limits and effort restrictions, to be imposed. ELFSim also incorporates uncertainty in the fish population and fishery dynamics, including variability in recruitment and catchability (Mapstone et al. 2004).

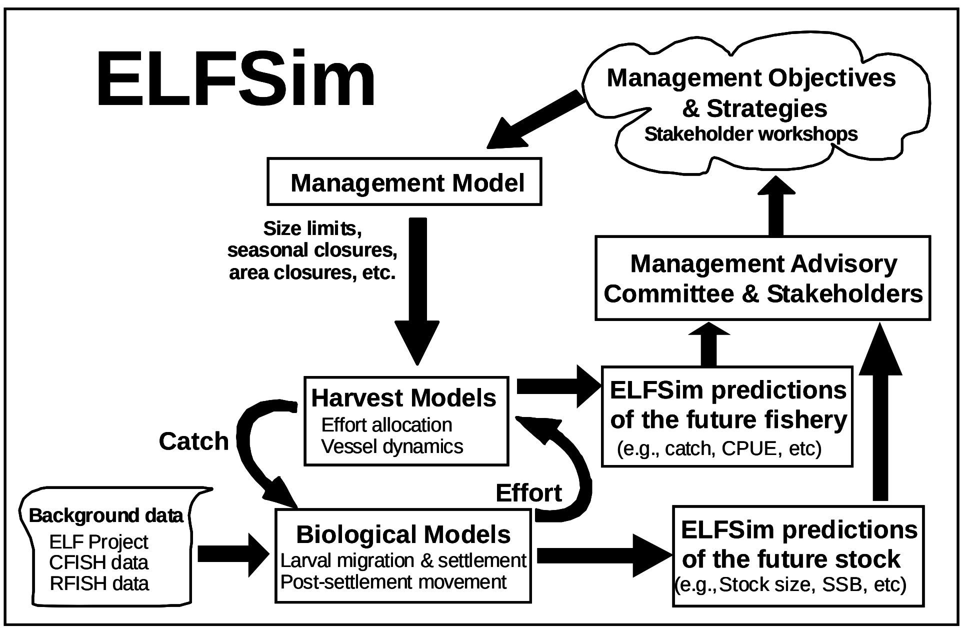


Fig. 1.3. Schematic of ELFSim model components (CFISH : Commercial Fishing Information System, RFISH: Recreational Fishing Information System, SSB: spawning stock biomass, CPUE catch per unit effort).

Prior to this project, the biological model component of ELFSim included only common Coral Trout and the effort model component was based on the aggregate fleet level of the fishery. Mapstone et al. (2004) provide the full details of the earlier MSE analyses for common Coral Trout. In this project, the biological model was extended to include Red Throat Emperor and the effort model component was extended to include an individual-vessel based model. The aim of the individual-vessel model is to be able to more realistically capture the multi-species targeting behaviour and resultant vessel dynamics and effort distribution in the fishery.

1.6. Objectives

Multi-species targeting is a characteristic of the CRFFF and a common feature of tropical coastal fisheries. However, the theory and methods needed to model and predict the potential effects of this behaviour are poorly developed. Understanding fishery systems should involve an approach where not only knowledge of the biology of the targeted species but also fisher behaviour is required. In this project, we build on previous ELF related research and aim to:

1. develop dynamic computer simulation models that predict the spatial distribution of effort by commercial line fishers in response to the harvest of multiple species in the CRFFF, and

2. formally evaluate alternative harvest and conservation management strategies for Coral Trout and Red Throat Emperor for the CRFFF, given models of changes in fishing strategy related to the harvest of multiple species, either through target switching or retention of significant by-product.

The project consisted of three components. In the first component, the population dynamics model of ELFSim was extended to include the two major target species of the fishery, common Coral Trout and Red Throat Emperor. This involved developing a population dynamics model for Red Throat Emperor based on its demographic characteristics and movement patterns. Biological information for Red Throat Emperor was acquired through the ELF Project and related research supported by the CRC Reef, FRDC, GBRMPA and JCU (Williams 2003, Mapstone et al. 2004, Davies et al. 2006). Direct biological interactions between the two species were not part of the extension to a multi-species model. We assumed such interactions did not occur and our current understanding of the ecology of the two species suggests that the assumption was credible. Accordingly, populations of each target species were treated as independent biological entities with overlapping spatial distributions.

The second component of the project involved the development of an individual-based vessel dynamics model that accounted for multi-species targeting behaviour and its parameterization using experimental, interview and monitoring data. This model provided an alternative to the fleet-aggregated effort allocation model developed for common Coral Trout, and included information on catches of Red Throat Emperor and decision rules for when, where and what to fish. It incorporated factors that influenced fisher behaviour and the resulting spatial allocation of effort to the extent these factors could be determined from experimental, interview and monitoring data. The underlying assumption of this approach is that, by modelling the behaviour of individual fishers, it is possible to improve our understanding of effort dynamics in the past and the ability to predict responses to alternative management strategies and stock dynamics in the future.

The third component of the project used these newly developed models within ELFSim to evaluate stakeholder-derived management strategies for both common Coral Trout and Red Throat Emperor. Specific operational management objectives, performance measures and management strategies were defined for both species in consultation with diverse stakeholders and formally evaluated using ELFSim. The process was facilitated by a series of stakeholder workshops and extension activities similar to those reported previously (Mapstone et al. 2004).

2. Fishery

The Queensland Coral Reef Fin Fish Fishery (CRFFF) operates mainly in the GBR, between Gladstone (24.5°S) and the southern boundary of the Torres Strait (10.5°S) and from coastal inshore reefs to outer barrier reefs (Mapstone et al. 1996b, Williams 2002) (Fig. 1.2). The fishery is extremely diverse being multi-sector, multi-species, and spatially heterogeneous in both fishery and biological dynamics. The fishery is comprised of three main sectors: commercial, charter and recreational, with an unknown, but assumed to be negligible, catch of reef fish by the Indigenous communities along the Queensland coast. Although Coral Trout and Red Throat Emperor are the major target species, all sectors target a range of demersal reef fish species using hook-and-line fishing gear. The generic group “Coral Trout” comprises three main harvested species (*Plectropomus leopardus*, *P. laevis* and *P. maculatus*) and four lesser species (*P. areolatus*, *P. oligacanthus*, *Variola louti* and *V. albimarginata*) (Mapstone et al. 2004). *P. leopardus*, known locally as common Coral Trout, is the major targeted species, highest-valued and most abundant. The fishery is managed by the DPI&F, although because it operates in the GBRWHA, the GBRMPA also imposes conservation management measures that influence the fishery, primarily through no-take fishing zones (Williams 2002).

2.1. Commercial sector

The DPI&F Commercial Fisheries Information System (CFISH) collects data from Queensland's commercial fishers through a compulsory logbook program that commenced in 1988. The data are reported on a daily basis and include information on location fished, catch by species, weight landed, and fishing gear used (Williams 2002). No data are available on discards, search time or typically on fishing effort when no fish are caught. The commercial catch of reef fish is divided into Coral Trout (CT), Red Throat Emperor (RTE) and other demersal reef fish (OTH) to reflect the target species groups in the fishery (Table 2.1). Although Coral Trout has been reported in the logbooks as Island or Barred-cheek Trout (*P. maculatus*; species code 37311012), Footballer Cod or Blue Spot Trout (*P. laevis*; 37311079), Passionfruit Trout (*P. areolatus*; 37311081), Coronation Trout (*Variola louti*; 37311166) and Coral Trout (*Plectropomus* and *Variola* spp.; 37311905), we assumed that most of the catch was *P. leopardus* based on both observer surveys and structured catch surveys as part of the ELF Project (i.e., 97% of ELF Coral Trout data comprised of *P. leopardus*). We also assumed that Red Throat Emperor (37351009) was accurately reported in the logbooks, albeit that some catches were undoubtedly reported as sweetlip, emperors or mixed reef fish. We assumed that these catches were negligible.

Table 2.1. Species and DPI&F codes used in the analysis of line-caught reef fish catch and effort data from the Great Barrier Reef.

Species group	DPI&F species code
Coral Trout	37311012, 37311079, 37311081, 37311166, 37311905
Red Throat Emperor	37351009
Other reef fish	37000000, 37118901, 37235001, 37287066, 37311006, 37311011, 37311014, 37311021, 37311044, 37311057, 37311063, 37311068, 37311069, 37311083, 37311086, 37311090, 37311136, 37311137, 37311138, 37311145, 37311147, 37311150, 37311151, 37311152, 37311170, 37311908, 37311909, 37311910, 37320003, 37327047, 37342000, 37346000, 37346002, 37346004, 37346005, 37346007, 37346011, 37346014, 37346015, 37346016, 37346017, 37346018, 37346027, 37346029, 37346030, 37346032, 37346036, 37346038, 37346049, 37346058, 37346065, 37346901, 37346910, 37346911, 37347000, 37347006, 37348001, 37350003, 37350012, 37351000, 37351004, 37351005, 37351006, 37351007, 37351008, 37351016, 37351018, 37351027, 37351901, 37353000, 37353001, 37353004, 37353006, 37353013, 37354006, 37354024, 37355900, 37362000, 37362005, 37378002, 37384000, 37384001, 37384004, 37384007, 37384010, 37384014, 37384038, 37384042, 37384043, 37384072, 37384104, 37384902, 37437019, 37438013, 37439002, 37460000, 37465000, 37465900, 37990006, 37990007, 37990003, 37990005, 37990009, 37990012

The statistical regions defined by Mapstone et al. (1996b) were used to examine the spatial and temporal patterns in catch and effort of the CRFFF (Table 2.2, Fig. 1.2). Annual commercial catches of reef fish species groups (CT, RTE, OTH) were estimated from compulsory individual fisher logbook data, collected as part of the DPI&F CFISH program. All catch data were converted to whole fish weight using DPI&F derived individual species product conversion factors. The product type was assumed to be whole fish and no conversion factor was applied if no product type was recorded in the logbook. For records where there was no catch weight reported, but catch was reported in numbers (<5%), a species derived average individual fish weight was applied based on those records (1988-2005) where both catch weight and numbers at the species level were reported for line fishing methods only (Table 2.3). For records where the average fish weight for a species was absent, a combined species group (i.e., CT, RTE, OTH) average weight was applied (Table 2.4). The number of fish caught was then multiplied by the respective average fish weight to estimate a corresponding catch weight. The CFISH data used in the analyses ranged from 1990 to 2003. Data collected during the first two years of the CFISH program (1988 & 1989) were excluded because of initial difficulties and probable non-compliance associated with the introduction of the logbooks.

Table 2.2. Statistical regions used in the analysis of reef fish catch and effort data from the GBR (Mapstone et al. 1996b).

Region	Latitude (°S)	Longitude (°E)
Far north	≥10.5 and <14.0	>142.5 and ≤(Lat+460.75)/3.25
Cairns	≥14.0 and <17.5	>142.5 and ≤(Lat+460.75)/3.25
Townsville	≥17.5 and <20.0	>142.5 and ≤(Lat+70.8421)/0.597565
	≥20.0 and <20.5	>142.5 and ≤149.5
Mackay	≥20.0 and <20.5	>149.5 and ≤(Lat+70.8421)/0.597565
	≥20.5 and <21.0	>142.5 and ≤(Lat+514.5)/3.5
	≥21.0 and <21.5	>142.5 and ≤151.5
	≥21.5 and <22.5	>142.5 and ≤151
Swains	≥21.0 and <21.5	>151.5 and ≤(Lat+514.5)/3.5
	≥21.5 and <22.5	>151.0 and ≤(Lat+514.5)/3.5
Capricorn-Bunkers	≥22.5 and <24.5	>142.5 and ≤(Lat+514.5)/3.5

Table 2.3. Line fishing gears used in the analysis of commercial reef fish catch and effort data from the GBR (1990-2003).

Fishing gear	DPI&F fishing method code	Total line catch (%)
Line fishing	01	56.6
Handline	11	23.9
Dropline (demersal longline)	31	12.6
Trotline (demersal longline)	51	6.3
Trolling	41	0.5
Demersal longline	61	0.1

Table 2.4. Average fish weight of Coral Trout, Red Throat Emperor and other reef fish species from commercial and charter compulsory logbooks where both catch in weight and numbers reported (live or dead targeting was not specified).

Species group	Commercial (kg)	Charter (kg)
Coral Trout	1.06	1.88
Red Throat Emperor	1.27	1.59
Other reef fish species	1.58	1.80

Reef fish are harvested on the GBR predominantly by commercial fishers using line fishing methods (98% of total summed catch 1990-2003), with small amounts (about 75 t of reef fish per year) taken incidentally by net, trawl, bait, crab and other miscellaneous fishing methods. These latter data were excluded from the total catches of Coral Trout and Red Throat Emperor used for modelling purposes. About 80% of the reef fish line catch reported in the logbooks is harvested by line fishing or handlines, with 19% of the harvest being from demersal longline or multi-hook fishing gear (Table 2.3). Since longline methods are not permitted in the GBR Marine Park, it is most likely that those catches came from deeper water adjacent to the GBRMP but were included in our summaries because of limitations in the spatial scales by which catch is recorded in logbooks (by 30' or 6' grid).

The annual catch of reef fish by the commercial sector ranged from 2246-4702 t between 1990 and 2003, with an average catch of about 3359 t (Fig. 2.1). Coral Trout was the main target species of the commercial sector (mean±SD: 1576±264 t), with significant quantities of Red Throat Emperor (695±112 t) and other demersal reef fish (1087±497 t) also harvested by this sector. Coral Trout was increasingly marketed alive after 1995 with the expansion of the live fish export trade, while whole and filleted Red Throat Emperor and other reef fish typically supported the domestic markets (Fig. 2.2). Average monthly prices from 1996-2003 (nominal value in each year) for live, fillet and whole Coral Trout were about $29, $17 and $13 per kg, respectively. In contrast, average monthly prices for fillet and whole Red Throat Emperor were $12 and $4 per kg, respectively (Fig. 2.3).

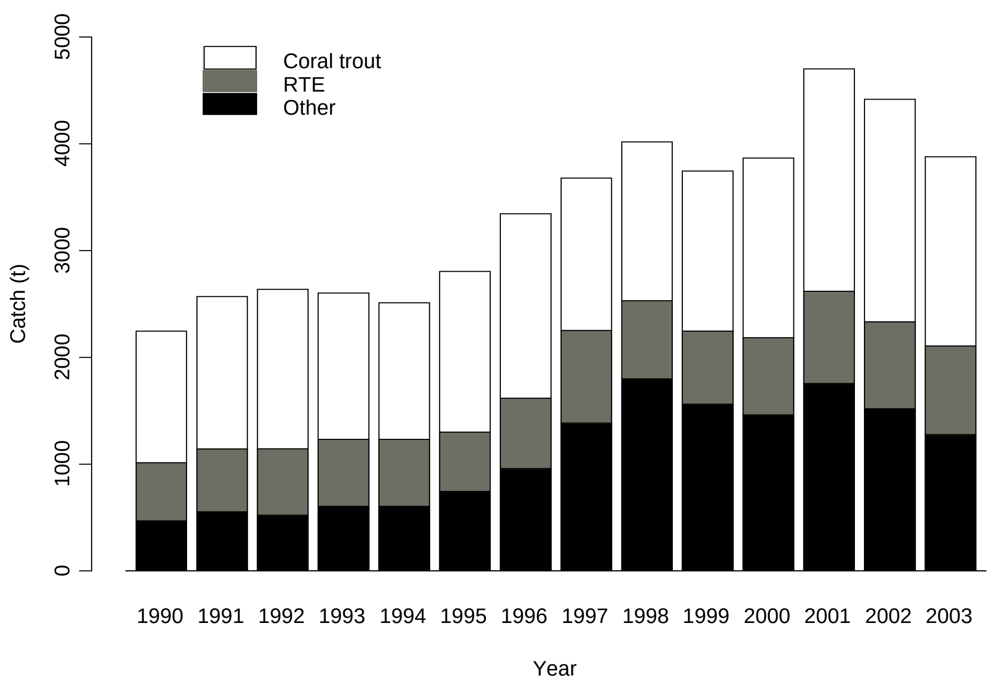


Fig. 2.1. Annual catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from line fishing gears on the GBR (1990-2003).

Most of the reef fish catch by the commercial sector, and particularly that of Coral Trout, is taken from offshore reefs of the Townsville, Mackay and Swains regions (Fig. 1.2 and 2.4). Significant catches of Red Throat Emperor and other demersal reef fish are also caught in the Capricorn-Bunkers region. In the northern regions of Far north and Cairns, Coral Trout and other reef fish are also harvested in large quantities by the commercial sector, but this is not the case for Red Throat Emperor, which is not found in high densities north of about 17^{o}N (Mapstone et al. 1996b, Williams 2003). Strong seasonal patterns in catch of reef fish are also characteristic of the commercial sector, with increasing catches from May to November (Mapstone et al. 1996b; Fig. 2.5-2.6).

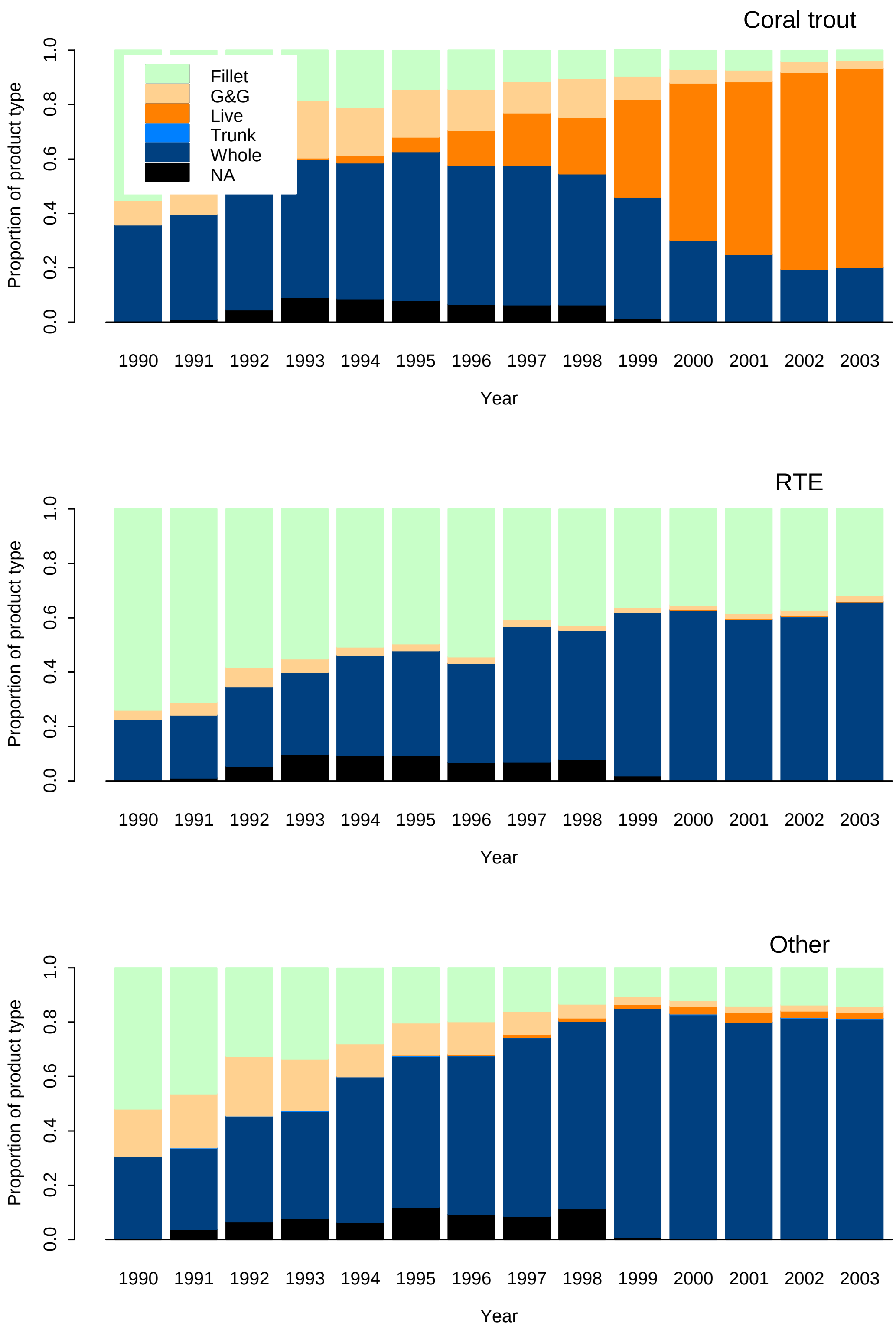


Fig. 2.2. Annual proportion of product type reported for Coral Trout, Red Throat Emperor (RTE) and other reef fish by line fishing gears on the GBR (1990-2003).

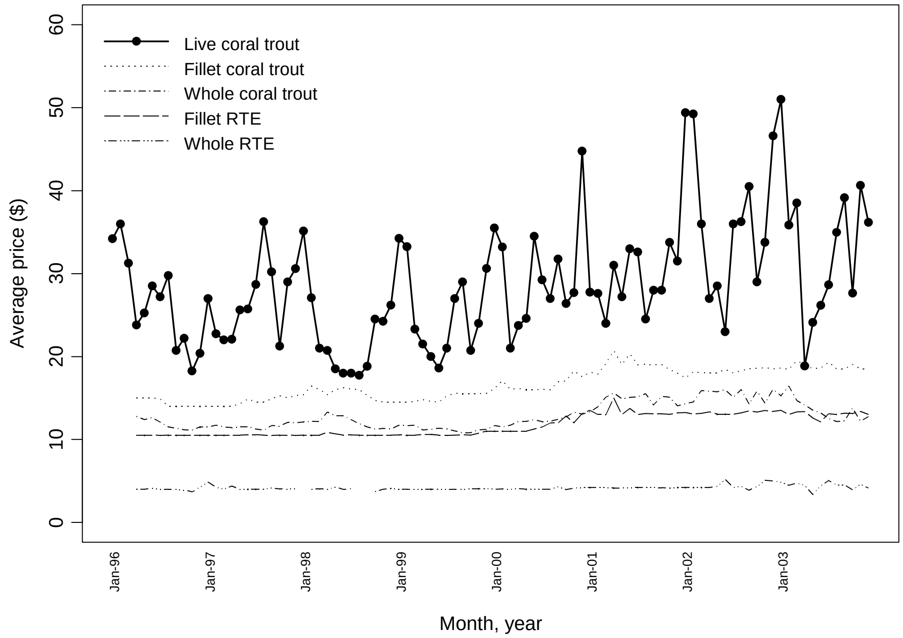


Fig. 2.3. Average monthly fish price (per kg) for live, fillet and whole Coral Trout, and fillet and whole Red Throat Emperor (1996-2003). Prices are derived from processors at Bowen and Mackay, and were those paid directly to fishers.

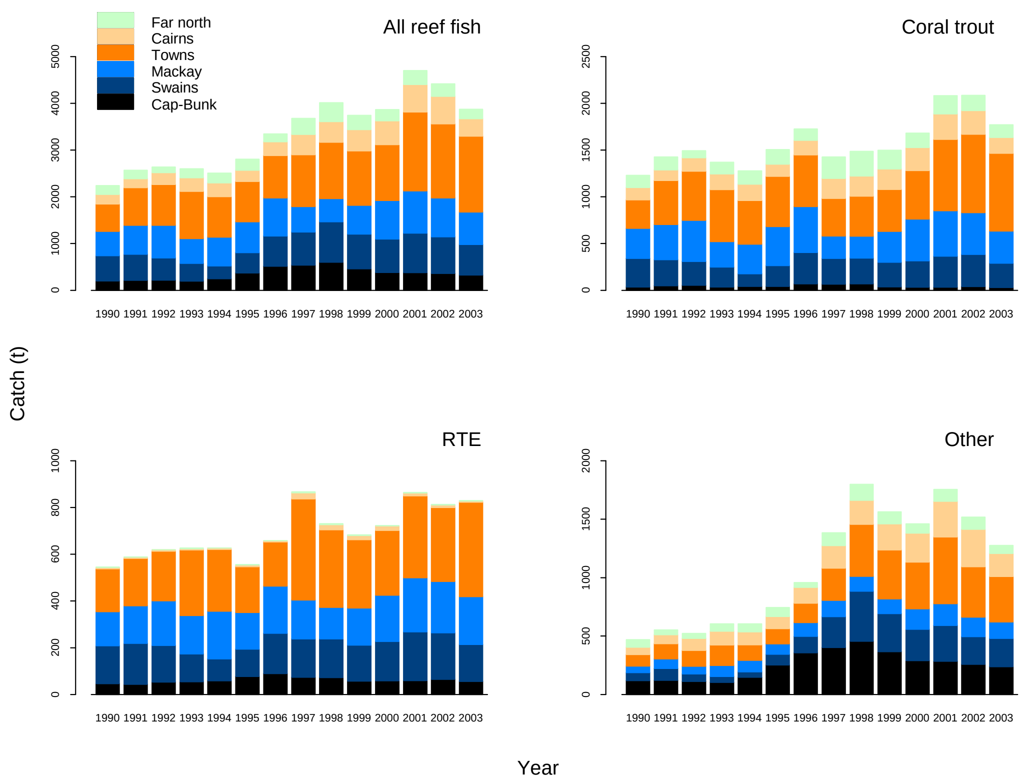


Fig. 2.4. Annual catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from line fishing gears in regions on the GBR (1990-2003). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

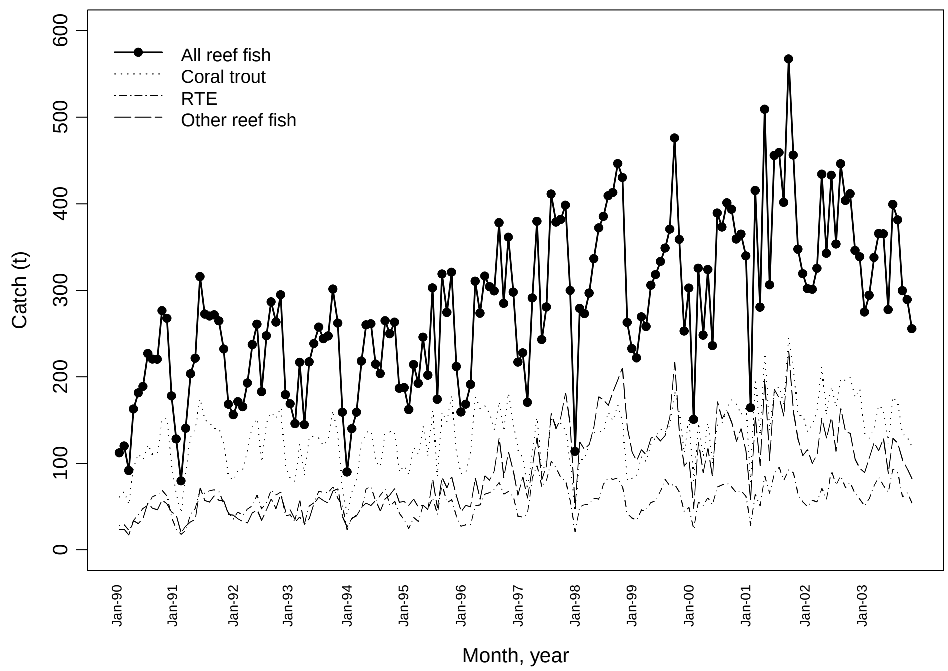


Fig. 2.5. Annual monthly catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish by line fishing gears on the GBR (1990-2003).

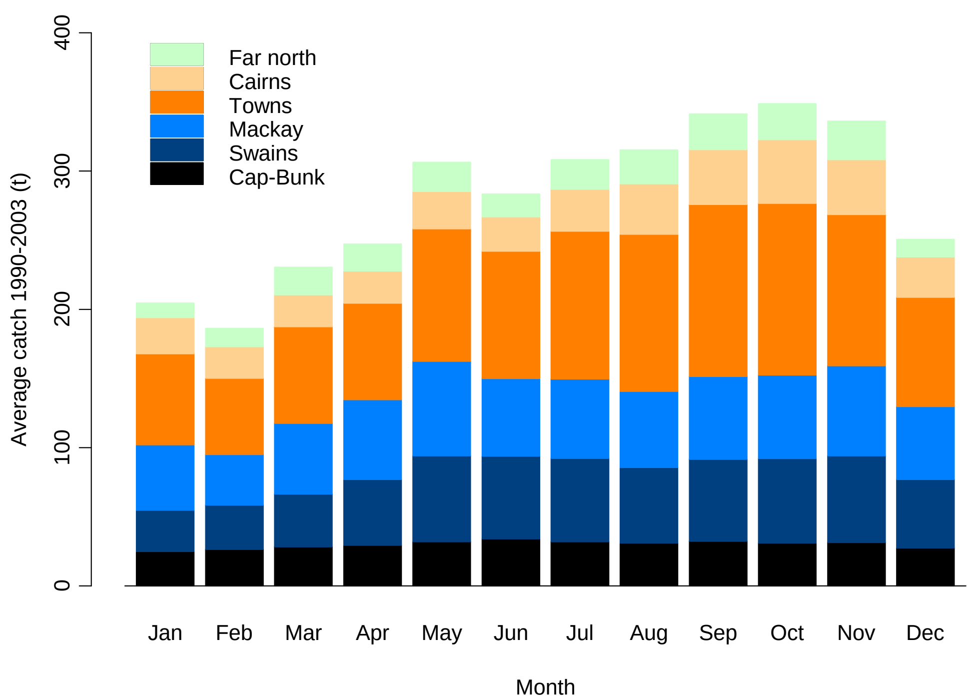


Fig. 2.6. Average monthly catch (t) of reef fish by line fishing gears in regions on the GBR (1990-2003).

The number of commercial operations (primary vessel plus dories) reporting retained catches of reef fish (i.e., fish not released) in the GBR peaked at 684 operations in 1997, the year of an investment warning by QDPI&F (Fig. 2.7). The number of operation days also peaked in 1997 at about 30,000 operation days, with another peak in 2002 at about 38,000 operation days, prior to the introduction of a new Management Plan in 2003. The regional and monthly patterns in fishing effort are similar to those in catch, with most effort occurring in the Townsville and Mackay regions (Fig. 2.8-2.9).

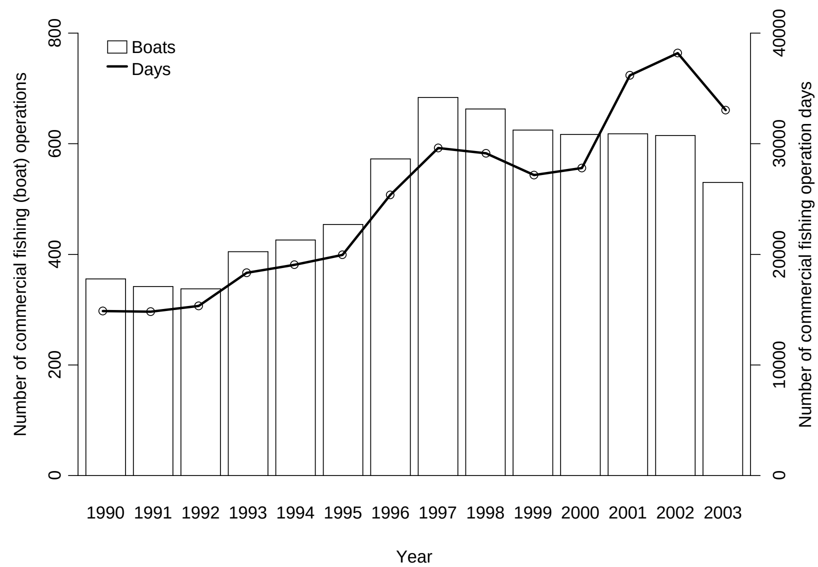


Fig. 2.7. Annual commercial fishing effort (number of operations and days which reported reef fish) by line fishing gears on the GBR (1990-2003).

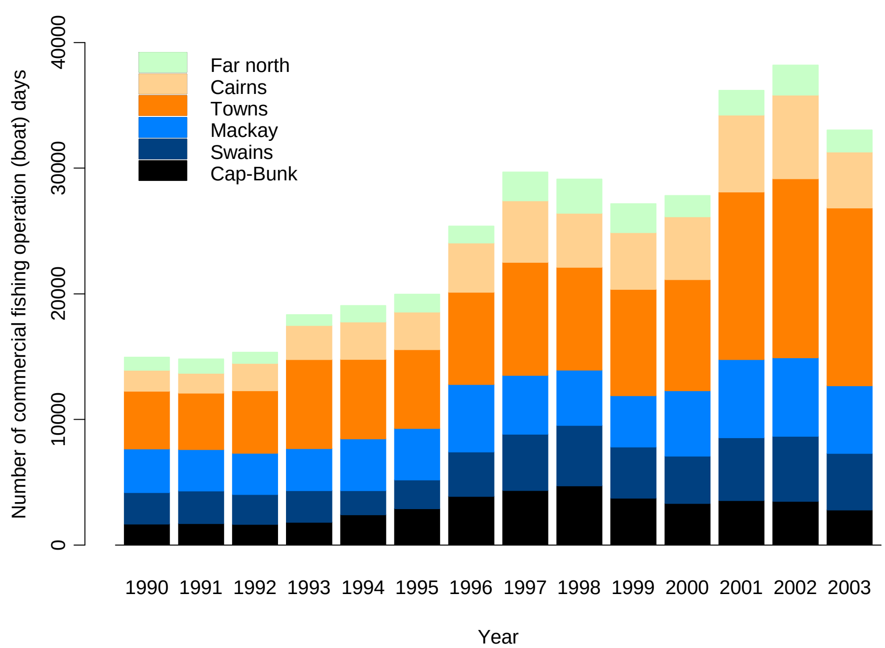


Fig. 2.8. Annual commercial effort (number of operation days where reef fish were retained) by line fishing gears in regions on the GBR (1990-2003). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

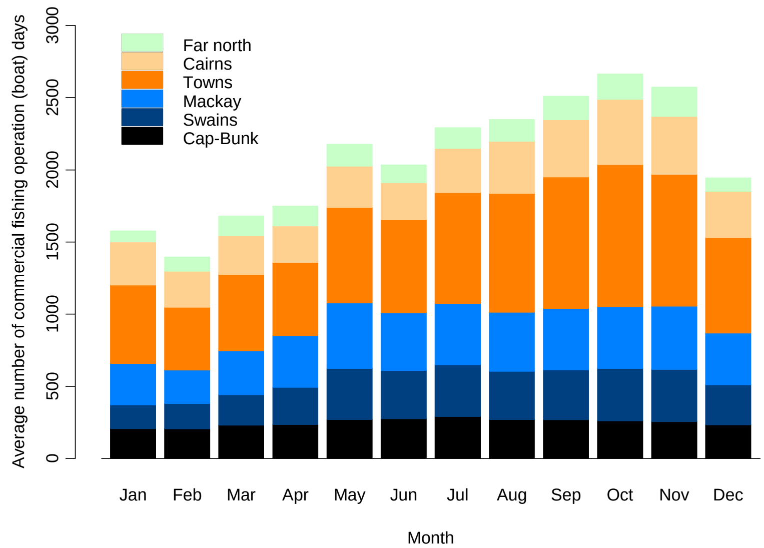


Fig. 2.9. Average commercial monthly fishing effort (number of operation days) by line fishing gears in regions on the GBR (1990-2003).

Annual CPUE (catch per unit effort, kg/operation day) of reef fish has declined in the commercial sector from about 173.4 kg day^{-1} in 1991 to 117.4 kg day^{-1} in 2003 (Fig. 2.10). Similar patterns were observed for Coral Trout and Red Throat Emperor in most regions of the GBR (Fig. 2.11). Average annual CPUE of Coral Trout and Red Throat Emperor in 2003 was about 53.6 kg day^{-1} and 25.1 kg day^{-1}, respectively. CPUE of Coral Trout tended to be higher between January and June than between June and September (Fig. 2.12). This pattern was not repeated for Red Throat Emperor (Fig. 2.12).

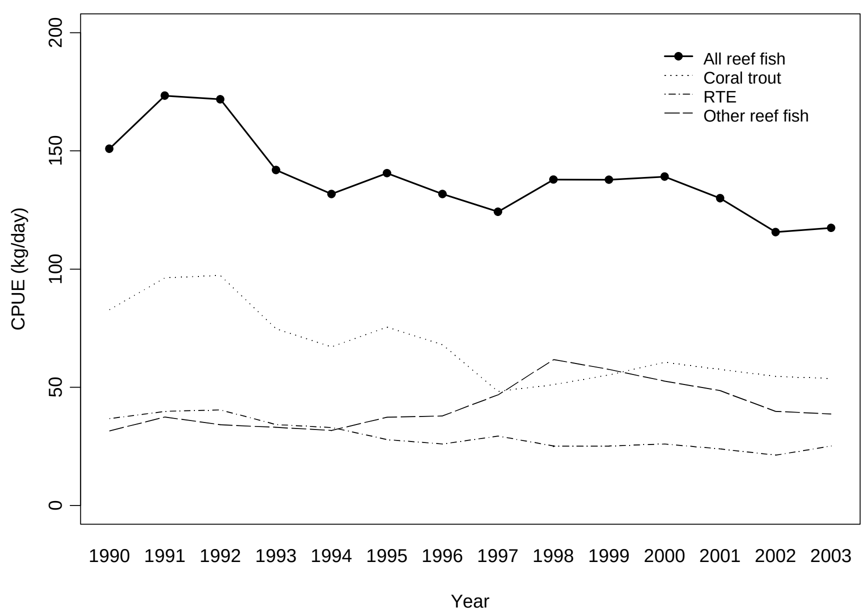


Fig. 2.10. Annual commercial CPUE (kg of fish/operation day) by line fishing gears on the GBR (1990-2003).

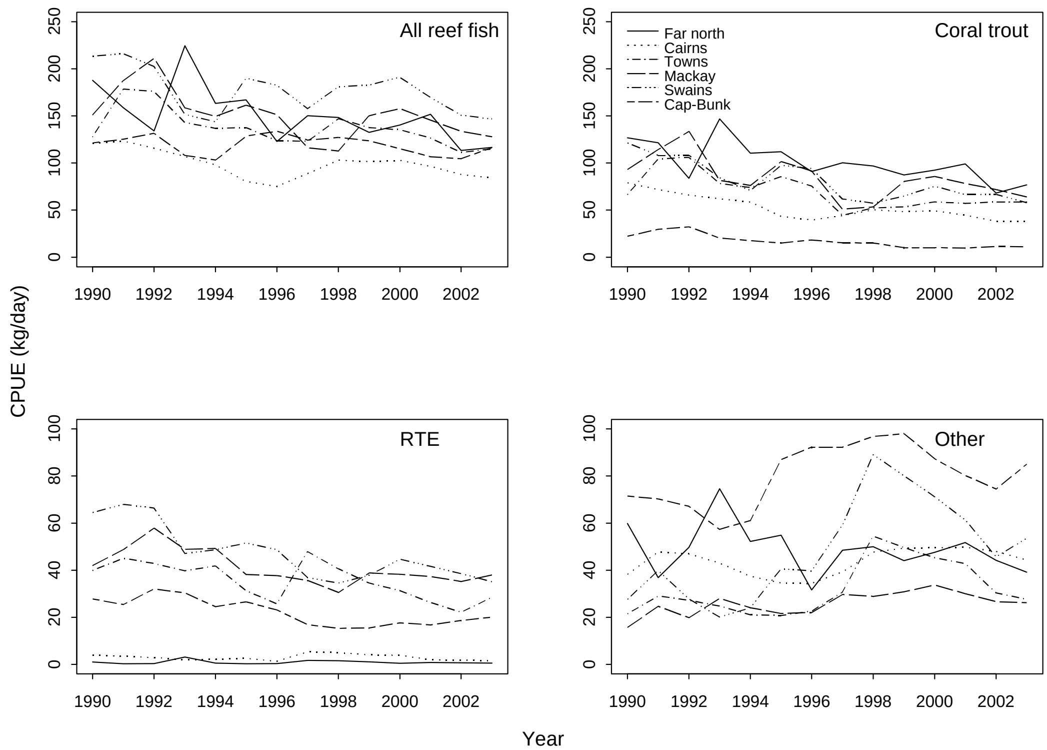


Fig. 2.11. Annual commercial CPUE (kg of fish/operation day) by line fishing gears in regions on the GBR (1990-2003). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

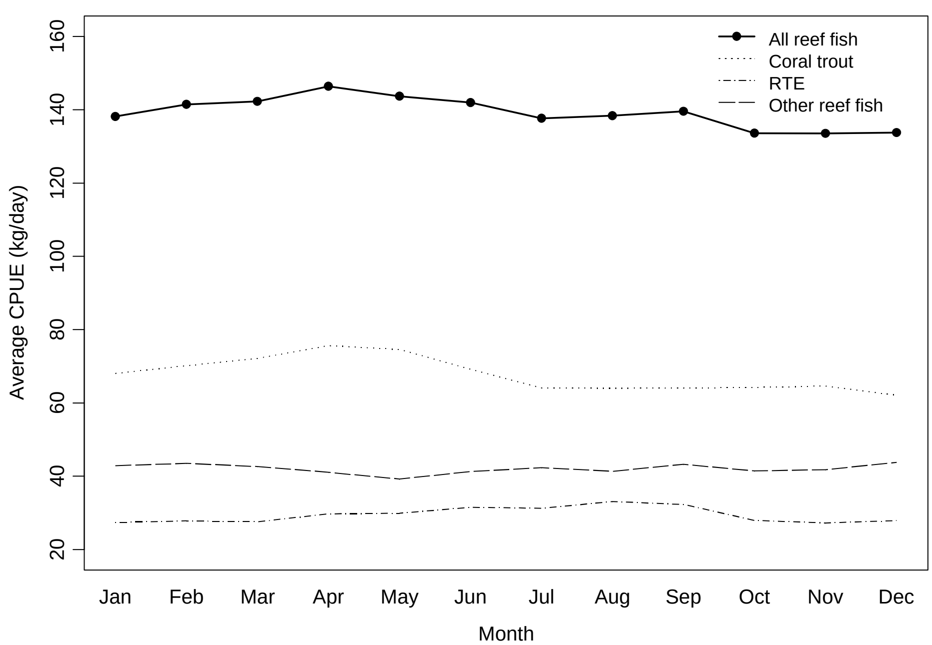


Fig. 2.12. Average commercial monthly CPUE (kg of fish/operation day) by line fishing gears in the GBR (1990-2003).

2.2. Charter sector

Fishing charter boats have been operating for many years in Queensland waters, taking both local and tourist recreational fishers to sea, but have only recently been required to report their catch as part of the DPI&F charter boat logbook program. The logbook program was voluntary when it was introduced in 1992, but was made compulsory for all charter boat operators in 1996. The same method as described above for the commercial sector was used to convert all charter catch data to whole fish weight using DPI&F-derived individual species product conversion factors. The charter data used in the analyses were from 1996 to 2003.

The annual catch of reef fish by the charter sector between 1996 and 2003 ranged from 221-315 t, with an average catch of about 267 t (Fig. 2.13). Typically, other reef fish dominated the charter catch (mean±SD: 144±26 t), with significant quantities of Coral Trout (69±5 t) and Red Throat Emperor (54±9 t) also harvested. Most of the reef fish catch by the charter sector was taken from the southern GBR in the Swains and Capricorn-Bunkers regions, as well as the northern GBR from waters around Cairns (Fig. 2.14). Coral Trout and Red Throat Emperor were mostly caught in offshore waters in the Swains region. Seasonal patterns in catch were also characteristic of the charter sector, with most of the catch taken between May and November (Fig. 2.15-2.16).

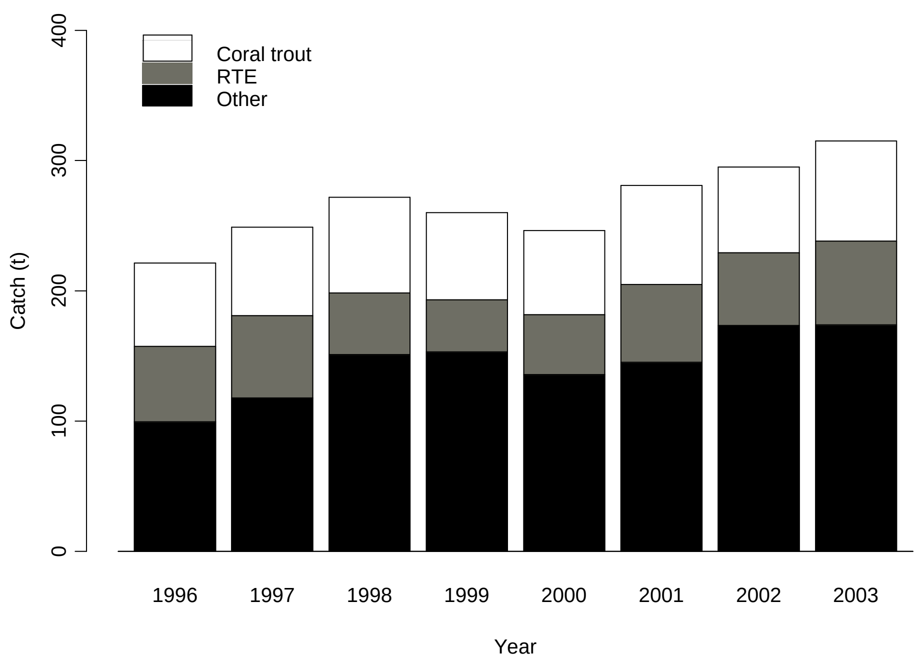


Fig. 2.13. Annual charter catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from the GBR (1996-2003).

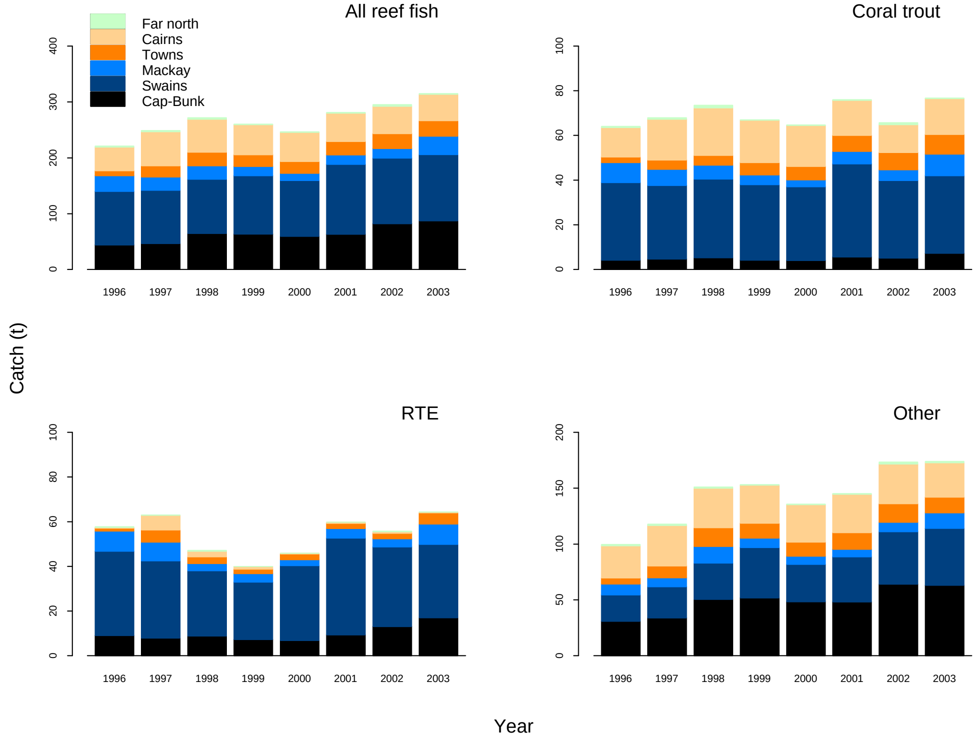


Fig. 2.14. Annual charter catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from regions of the GBR (1996-2003). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

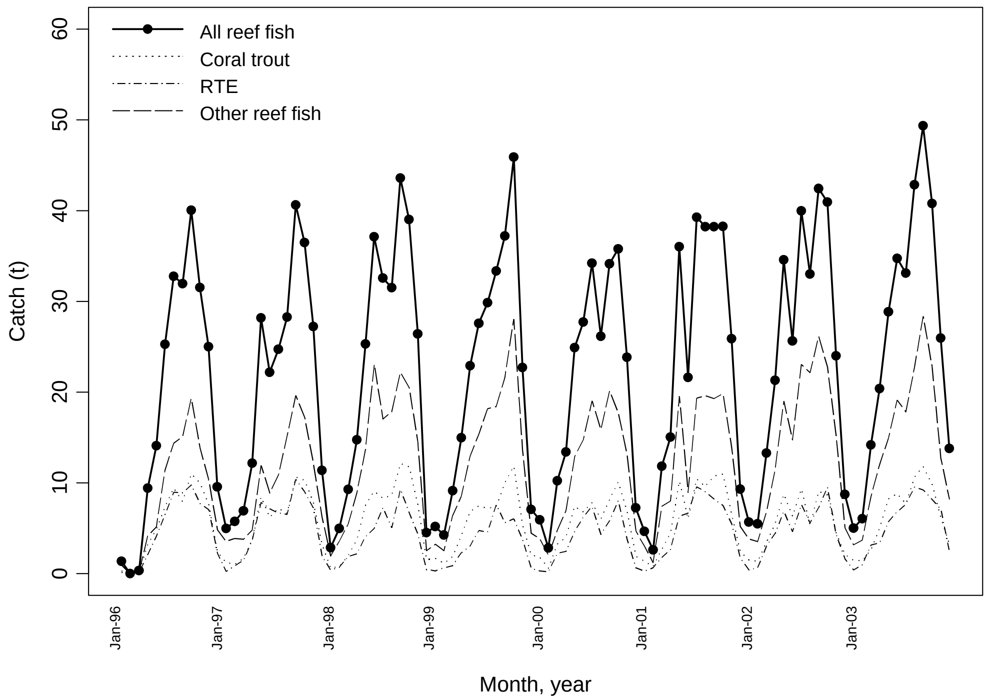


Fig. 2.15. Monthly charter catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from the GBR (1996-2003).

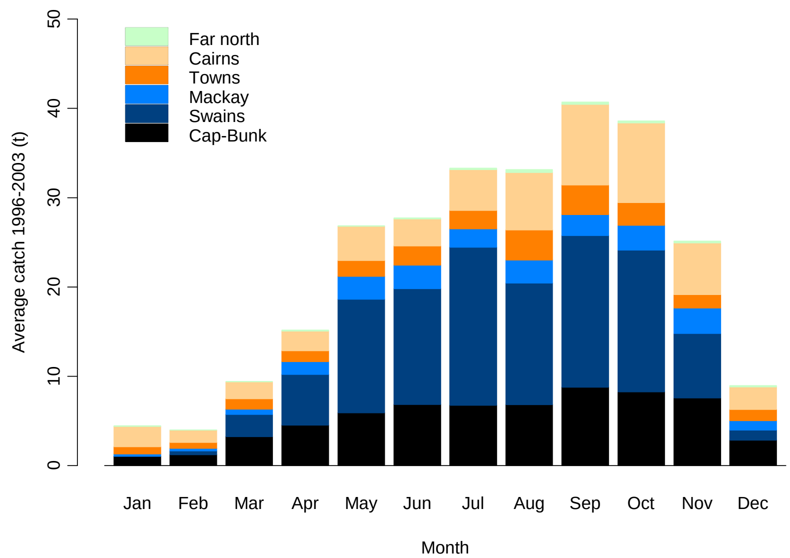


Fig. 2.16. Average charter monthly catch (t) of reef fish from regions of the GBR (1996-2003).

The number of charter boats reporting retained catches of reef fish (i.e., fish not released) in the GBR increased steadily from 103 boats in 1996 to 321 boats in 2003 (Fig. 2.17). Similarly, the number of charter boat days where reef fish were caught and retained increased from 4016 days in 1996 to 9769 days in 2003. The regional and monthly patterns in fishing effort were similar to those in catch, although more effort was exerted in the Cairns region than elsewhere, averaging about 3187 days between 1996 and 2003 (Fig. 2.18-2.19).

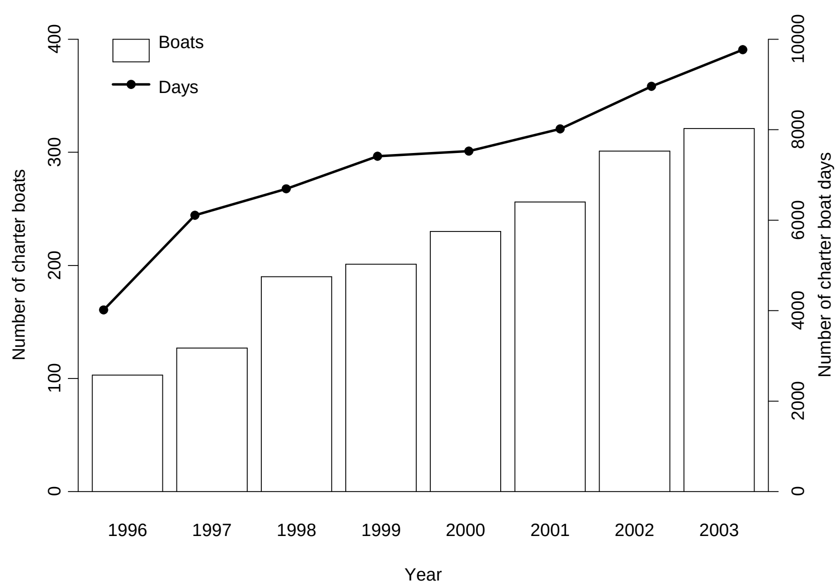


Fig. 2.17. Annual charter effort (number of boats, days reporting catches of reef fish) for line fishing on the GBR (1996-2003).

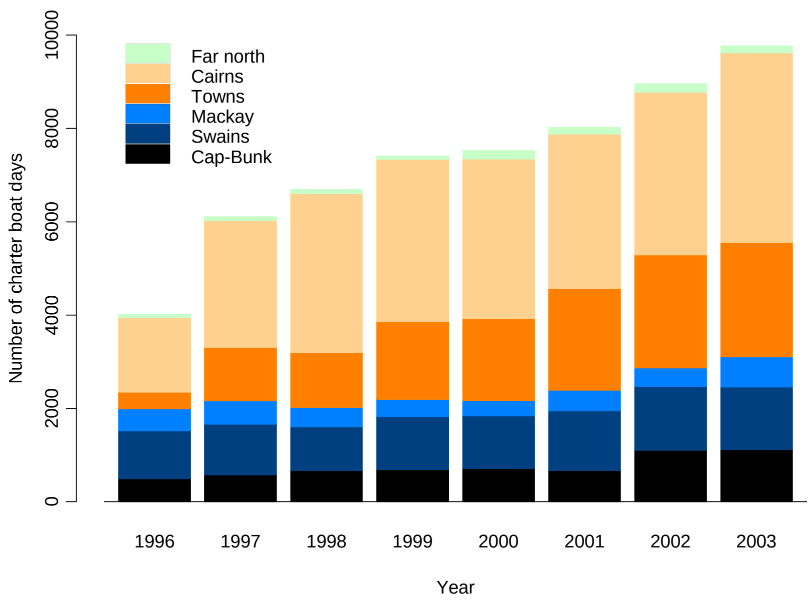


Fig. 2.18. Annual charter effort (number of boat days) by line fishing in regions of the GBR (1996-2003). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

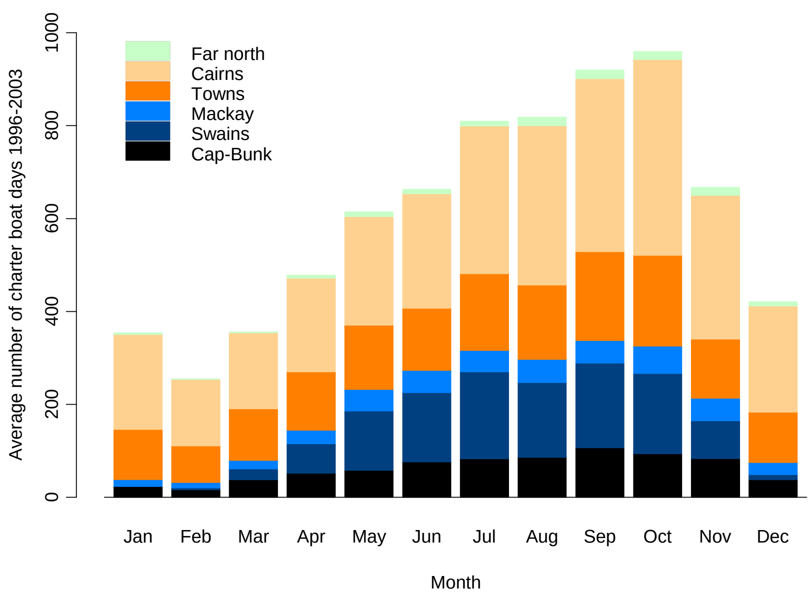


Fig. 2.19. Montly charter effort (number of boat days) for line fishing in regions of the GBR average over the years 1996-2003.

Annual CPUE of reef fish has declined in the charter sector from about 55.1 kg day^{-1} in 1996 to 32.3 kg day^{-1} in 2003 (Fig. 2.20). Although not as pronounced as for the total catch of reef fish, CPUE of Coral Trout and Red Throat Emperor has also declined in the charter sector, mainly in the Cairns and Townsville regions (Fig. 2.21). Average annual CPUE of Coral Trout and Red Throat Emperor was about 9.5 kg day^{-1} and 7.4 kg day^{-1}, respectively, between 1996 and 2003.

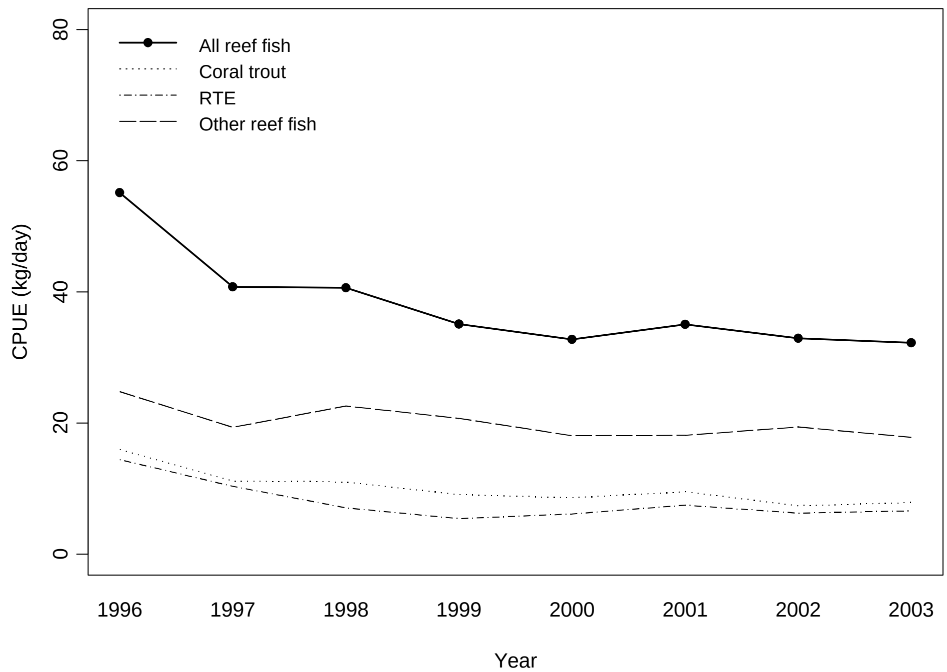


Fig. 2.20. Annual charter boat CPUE (kg of fish/charter boat day) by line fishing gears on the GBR (1996-2003).

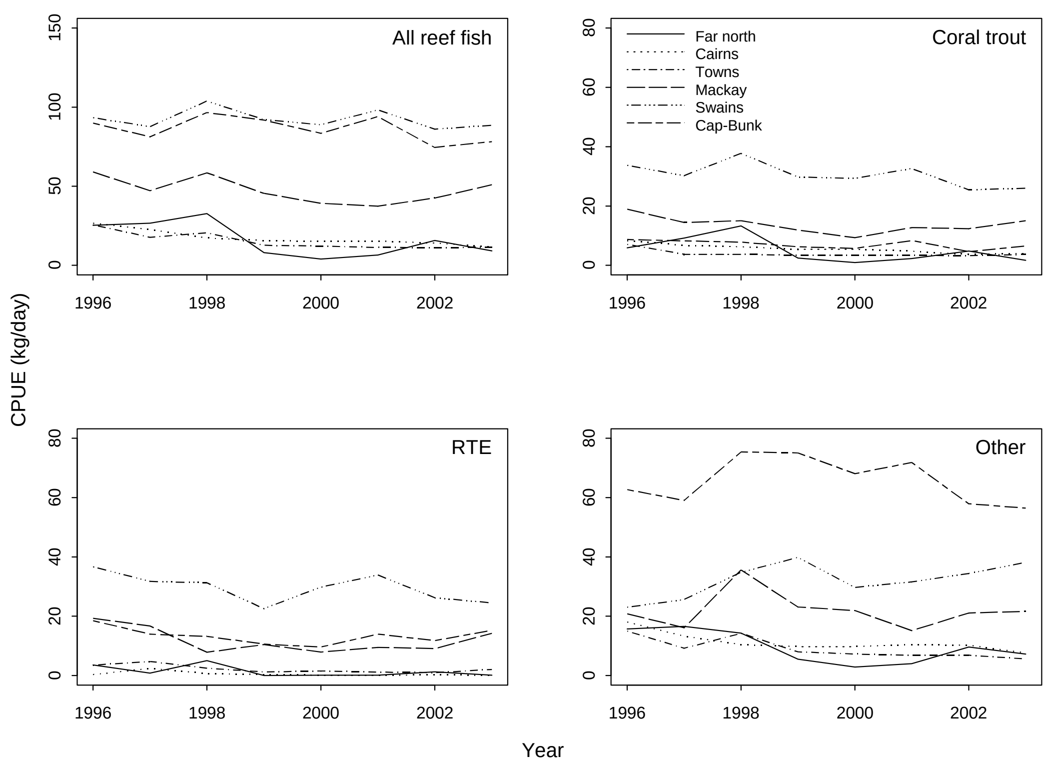


Fig. 2.21. Annual charter boat CPUE (kg of fish/charter boat days) by line fishing gears in regions of the GBR (1996-2003).

2.3. Recreational sector

The DPI&F Recreational Fisheries Information System (RFISH) collects data in 1997, 1999 and 2002 from Queensland's recreational fishers as part of a two-stage sampling program (Higgs pers. comm.). The first stage involves a State-wide telephone survey to determine the number of people participating in recreational fishing and their fishing characteristics (<5000). The second stage involves a sample from the telephone survey of individual recreational fishers voluntarily maintaining a diary for a period of 12 months, about their daily fishing activities. Results from these two stages are combined to provide estimates of State-wide recreational fish catches. Surveys were conducted in 1997, 1999 and 2002.

Individual diary data were used to estimate catch and effort patterns in the recreational sector, prior to extrapolating to the broader State-wide based estimates of the GBR. As with the commercial and charter sector data, the recreational catch of reef fish was divided into Coral Trout, Red Throat Emperor and other demersal reef fish. Coral Trout was reported in the recreational fishing diaries as "Coral Trout – unspec" (311905), "Coronation Trout" (311026) and "Cod – Footballer" (311079). Red Throat Emperor (351009) was reported as "Red Throat Emperor", "Red Throat Sweetlip" and "Tricky Snapper". Other reef fish included all other demersal reef fish specified in the *Coral Reef Fin Fish Fishery Management Plan 2003*.

Individual diary catch records were allocated to a reef based on reported spatial information such as latitude and longitude, nearest town, etc., depending on the level of spatial resolution reported. Catch and effort data were then allocated to the GBR regions defined in Table 2.2. Numbers of reef fish caught (retained and released) are reported in the recreational fishing diaries. Harvested numbers of reef fish (i.e., only those retained) were converted to catch weights by the same method described previously (commercial sector, Section 2.1). Data from the charter, rather than the commercial sector, were used to estimate recreational catch weights as we assumed these to be more reflective of the targeting behaviour of the recreational sector. Unlike the commercial and charter sectors, where fishing effort was based only on days when reef fish were harvested, effort for the recreational sector was based on days when reef fish were caught (either retained or released). The reason for defining effort this way was that almost 50% of the fish caught by the recreational sector are released (Table 2.5). About 85% of the reef fish released by the recreational sector were released because they were below the respective species' minimum legal size. Individual diary catch and effort records were converted to GBR-wide estimates using a catch multiplier which corrected for the sub-sample design of the diary data (Table 2.6). GBR catch conversions used the respective year and species group (i.e., CT, RTE, OTH) catch multiplier, while the GBR effort conversion used the catch multiplier for all reef fish.

The recreational sector harvested an average of almost three million reef fishes annually, weighing a total of about 5370 t (Tables 2.6-2.7). Other reef fishes dominated the recreational catch with about 4373 t taken each year, with significant quantities of Coral Trout (548 t) and Red Throat Emperor (450 t) also harvested. Most of the reef fish catch by the recreational sector occurred in the Capricorn-Bunkers and Townsville regions, with smaller quantities from reefs around Cairns and Mackay (Fig. 2.22). Coral Trout were mostly caught by recreational anglers from northern GBR waters around Townsville and Cairns, while Red Throat Emperor were mostly caught in the southern GBR around the Capricorn-Bunkers. The recreational reef fish catch was less seasonal than those of the commercial and charter sectors, reflecting more the peak holiday seasons such as January (Fig. 2.23-2.24).

Table 2.5. Annual recreational catch (retained and released) in numbers of Coral Trout, sweetlip and Red Throat Emperor (RTE) from Queensland (QLD) and the GBR (RFISH surveys 1997, 1999, 2002). Total = harvest plus release in numbers of fish. GBR catch = %GBR multiplied by QLD catch. RTE catch = % of sweetlip catch (e.g., in 1997 71% of the QLD sweetlip catch was from the GBR, of which 58% was RTE). Gulf = Gulf of Carpentaria; SEQ = South east QLD; TS = Torres Strait.

		% of QLD Catch				QLD			GBR
		GBR	**Gulf**	**SEQ**	**TS**	**Retained**	**Released**	**Total**	**Catch**
Coral Trout	1997	96.2	0.5	2.8	0.6	306000	246000	552000	294372
	1999	91.8	0.5	5.0	1.4	329519	259830	589350	302498
	2002	96.8	0.4	1.4	1.4	332666	297200	629866	322021
	Average	94.9	0.5	3.1	1.1	322728	267677	590405	306297
Sweetlip	1997	71.0	1.0	27.0	0.0	719000	768000	1487000	510490
	1999	71.0	1.0	26.0	1.0	861463	988867	1850330	611639
	2002	82.0	1.0	16.0	0.0	638682	854248	1492931	523719
	Average	74.7	1.0	23.0	0.3	739715	870372	1610087	548616
RTE	1997	58.0	23.0	39.0	16.0	395450	422400	817850	296084
	1999	49.0	77.0	32.0	0.0	396273	454879	851152	299703
	2002	66.0	0.0	33.0	0.0	370436	495464	865900	345655
	Average	57.7	33.3	34.7	5.3	387386	457581	844967	313814

Table 2.6. Annual recreational catch (in numbers) of reef fish (Coral Trout, Red Throat Emperor, others) on the GBR (RFISH surveys 1997, 1999, 2002). Catch multiplier = GBR -wide extrapolated catch estimates divided by diary catch estimates.

Species group	Year	GBR extrapolated Catch	Diary Catch	Catch multiplier
Coral Trout	1997	294372	159458	1.846
	1999	302498	177224	1.707
	2002	322021	165947	1.941
	Average	306297	167543	1.828
RTE	1997	296084	88144	3.359
	1999	299703	83403	3.593
	2002	345655	81338	4.250
	Average	313814	84295	3.723
Other	1997	2233436	498082	4.484
	1999	2322225	721846	3.217
	2002	2402612	645828	3.720
	Average	2319424	621919	3.729
All reef fish	1997	2823892	745684	3.787
	1999	2924426	982473	2.977
	2002	3070288	893113	3.438
	Average	2939535	873757	3.400

Table 2.7. Annual estimated recreational catches (t) of reef fish (Coral Trout, Red Throat Emperor, others) from the GBR (1997, 1999, 2002).

Year	Recreational line catch (t)		
	Coral Trout	**Red Throat Emperor**	**Other reef fish**
1997	526	425	4373
1999	541	430	4508
2002	576	496	4237
Average	548	450	4373

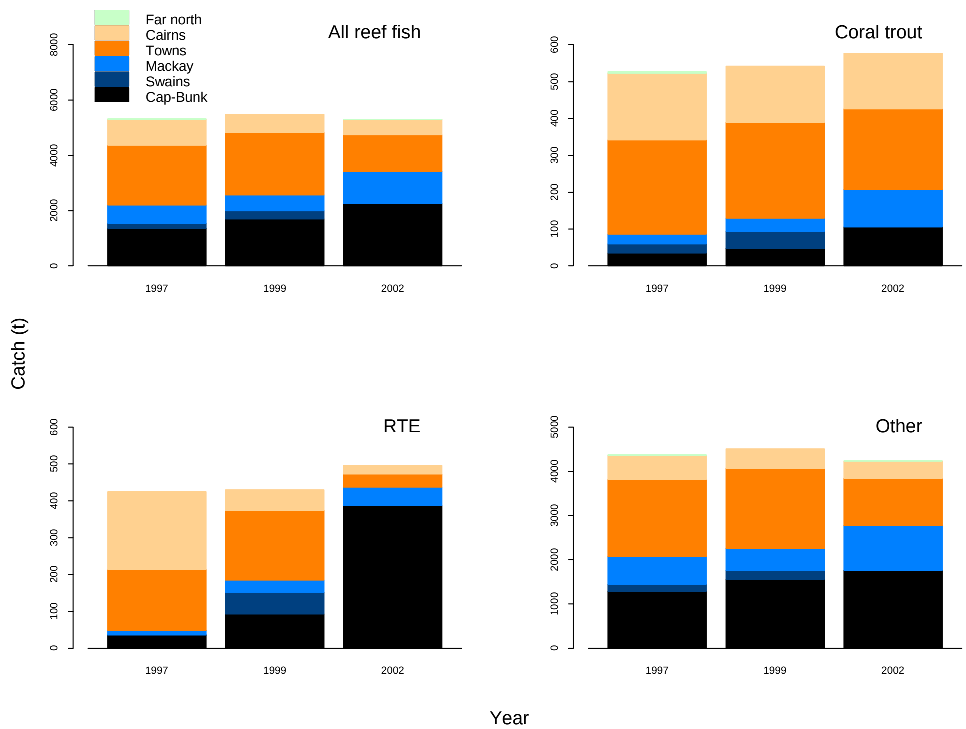


Fig. 2.22. Annual recreational catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from regions of the GBR (1997, 1999, 2002). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

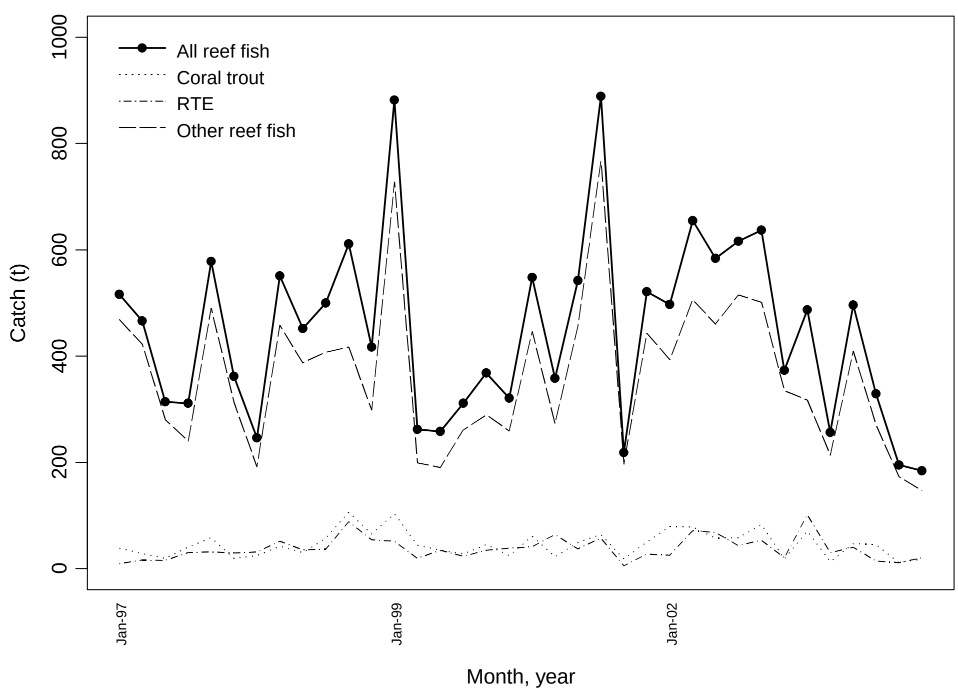


Fig. 2.23. Monthly recreational catch (t) of Coral Trout, Red Throat Emperor (RTE) and other reef fish from the GBR (1997, 1999, 2002).

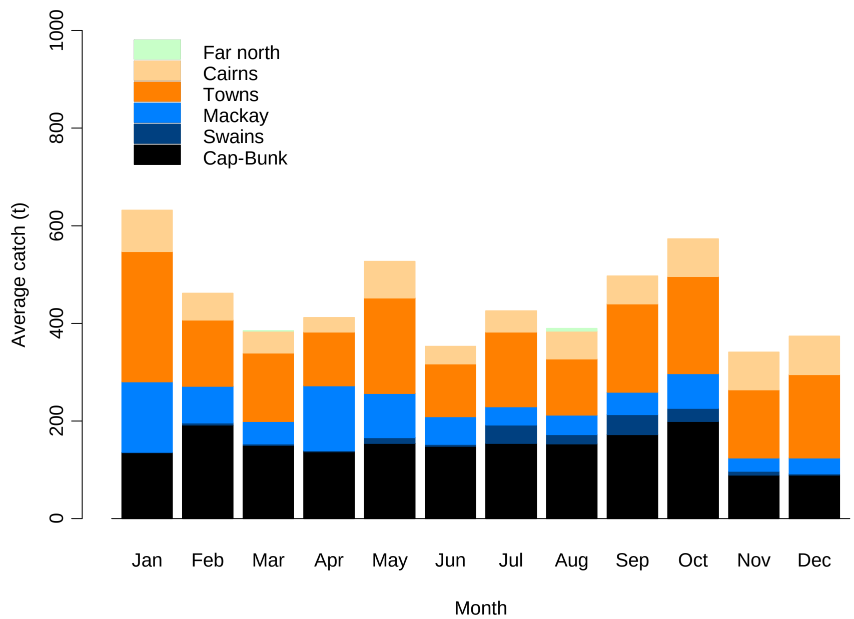


Fig. 2.24. Average recreational monthly catch (t) of reef fish from regions of the GBR (1997, 1999, 2002).

An average of about 730,000 fishing trips were conducted each year by recreational anglers catching reef fish during 1997, 1999 and 2002, with an overall slight increase in fishing effort over these years (Fig. 2.25). In 2002, when trip length started to be reported in the fishing diaries, more than 96% of the trips were one day or less in duration. Similar to catch, most of the recreational fishing effort on the GBR occurs in the Townsville and Capricorn-Bunkers regions, with smaller, but still substantial, amounts in the Cairns and Mackay regions, particularly during January (Fig. 2.25-2.26).

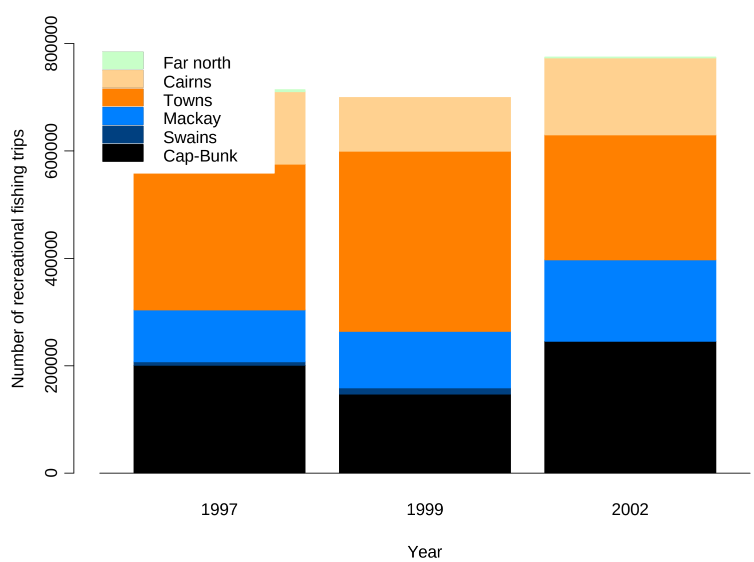


Fig. 2.25. Annual recreational fishing trips for reef fish from regions of the GBR (1997, 1999, 2002). Towns = Townsville; Cap-Bunk = Capricorn-Bunkers.

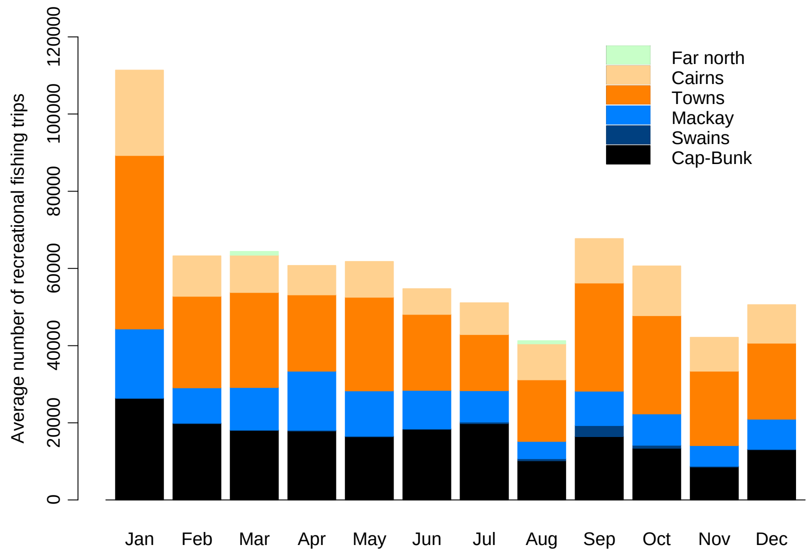


Fig. 2.26. Average (over years) number of recreational fishing trips for reef fish from regions of the GBR.

Annual CPUE of reef fish by recreational anglers has remained relatively stable throughout the survey years of 1997, 1999 and 2002, with an average of about 7.4 kg per fishing trip (Fig. 2.27). CPUE of Coral Trout and Red Throat Emperor were much lower in the recreational sector than in the commercial and charter sectors, with an average of about 0.75 and 0.62 kg per fishing trip or less than one fish per trip, respectively (Fig. 2.27).

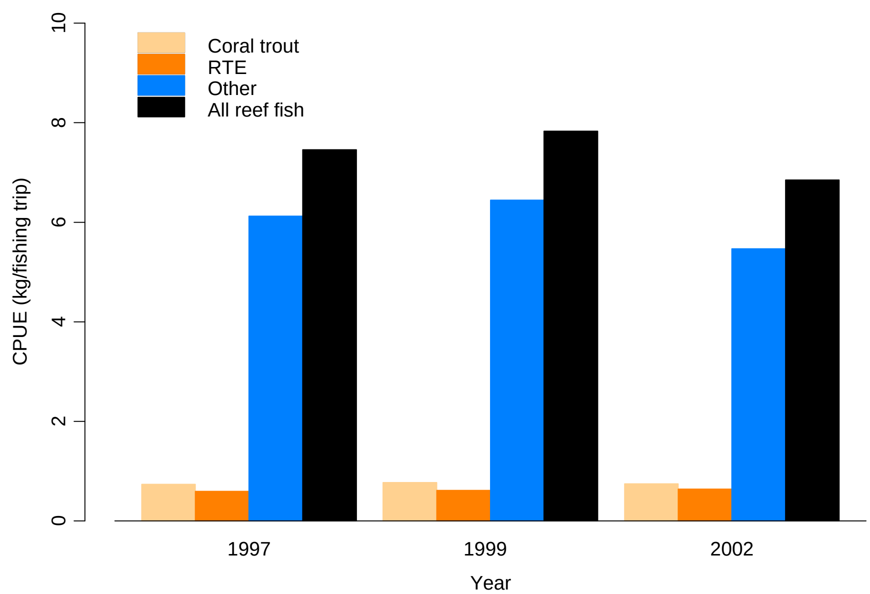


Fig. 2.27. Annual recreational CPUE (kg of fish/fishing trip) from the GBR (1997, 1999, 2002).

2.4. Fishery data for use in ELFSim

Annual catches of Coral Trout and Red Throat Emperor on the GBR were derived from the commercial, charter and recreational sectors to construct a time series of total catch and effort for input into ELFSim for the years 1965-2000. Actual catch and effort data exist from 1989 for the commercial sector, from 1996 for the charter sector and for 1997, 1999 and 2002 for the recreational sector. As in previous applications of ELFSim, for the years prior to these dates, catches were interpolated linearly for each calendar month backwards to a value of zero in 1965, when it was assumed the fishery started (Fig. 2.28). The starting points for these interpolations were the years immediately prior to the earliest year for which actual data exist for each sector. At this point the catch for each month is assigned the average of reported values in that month from 1989-1992 for the commercial sector and 1996-1998 for the charter sector. The average values over 1997, 1999 and 2002 were used as the starting points for the recreational sector. This strategy preserves the historical seasonality dynamics observed in the fishery since 1989 (Mapstone et al. 2004).

The spatial distributions of catch and effort for the commercial and charter sectors, as reported in the respective logbooks, were at the 30’ or 6’ statistical grid site resolution. In contrast, the spatial distribution of catch and effort in the recreational sector were derived from a variety of reported spatial information in the individual fishing diaries such as latitude and longitude, nearest town, etc, depending on the level of spatial resolution reported. Catch and effort data for the different fishing sectors at the grid scale were transformed to the scale of individual reefs by allocating the Coral Trout and Red Throat Emperor catches, and the line fishing effort data in each grid to the reefs occupying that grid, based on the proportion of the total habitat (reef perimeter) lying within the grid. Logbook data also contained catch records in grids that had no mapped reef. This was dealt with by creating “virtual” reefs in 6’ x 6’ grids with which to associate the records. Although there were many records of fishing in such locations, the total catch taken from them and effort expended in them was low. They contributed only 8% and 11% of the combined commercial and charter catch of Coral Trout and Red Throat Emperor, respectively. In addition, 12% of the total commercial effort and 23% of the charter effort was distributed to virtual reefs. In the recreational catch, 14% of Coral Trout and 10% of Red Throat Emperor were assigned to the virtual reefs, which also received 35% of the total effort by the recreational sector, reflecting greater targeting by the recreational sector of inshore and inter-reef areas. This strategy captured the major regional patterns in fishing activity throughout the GBR and was consistent with previous studies (Blamey and Hundloe 1993, Higgs 1996, Mapstone et al. 1996b, 2004).

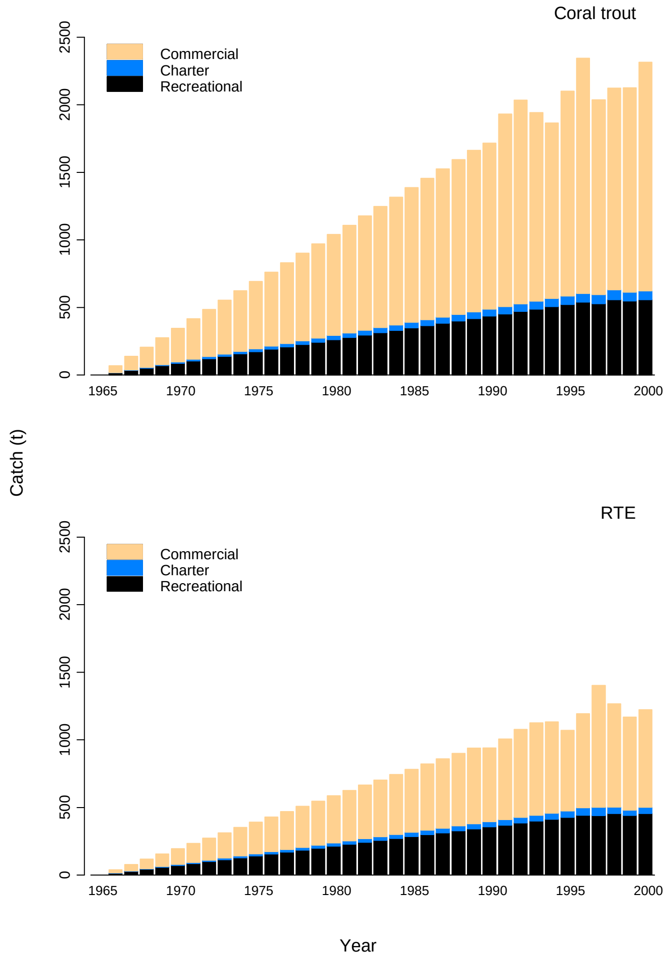


Fig. 2.28. Annual total catches of Coral Trout and Red Throat Emperor for the commercial, charter and recreational fishing sectors from the GBR (1965-2000).

3. Biological models

An integral component of ELFSim is the biological model which captures the underlying population dynamics of the target species and includes growth, reproduction and mortality (Fig. 1.3). Prior to this project, the biological model applied only to Coral Trout (Mapstone et al. 2004, Little et al. 2007) and was based on earlier models developed by Walters and Sainsbury (1990) and Mapstone et al. (1996a). The population dynamics model is age-, sex- and size-structured, assumes that the number of 0-year-olds is related to the size of the reproductive component of the population, takes account of sex change and allows for larval migration among reefs and variation in settlement (Punt et al. 2001, Mapstone et al. 2004, Little et al. 2007), as well as post-settlement movement among reefs. The model considers fish populations on approximately 3,800 individual reefs on the GBR (including virtual reefs), and accounts for the effects of the catches and effort reported by commercial, charter and recreational fishers. The modular nature of ELFSim readily facilitates the extension of the single-species population dynamics model developed for Coral Trout (Mapstone et al. 2004, Little et al. 2007) to a two-species (or more) population dynamics model incorporating the second major target species in the fishery, Red Throat Emperor. In this project, therefore, the biological model was extended to include Red Throat Emperor to more explicitly capture the multi-species targeting behaviour in the fishery.

Coral Trout are large, mobile serranids distributed throughout the GBR, and although comprised of several species, common Coral Trout is the most abundant, particularly on mid-shelf reefs where the commercial sector mainly operates (Williams 2002). Common Coral Trout are relatively fast growing and live to about 18 years of age, reach 70 cm fork length (FL) and 5 kg in weight (Ferreira and Russ 1994, 1995, Russ et al. 1996, 1998, Lou et al. 2005). Like many other reef fish, Coral Trout are mostly protogynous hermaphrodites, meaning they change sex from female to male as their body size reaches about 45 cm, which can occur at a wide range of ages (Ferreira 1995, Samoilys and Roelofs 2000, Adams 2003, Davies et al. 2006), although some local populations in the southern GBR have been shown to be diandric, with some individuals developing directly as males whilst others change sex after maturing first as females (Adams 2003). Consequently, despite the presence of some small, young males, the larger, older size groups are generally male dominated (Adams et al. 2000). Coral Trout mature as females at about 28 cm and 2 years of age, well below the size and age when they recruit to the fishery, which is currently at the minimum legal size of 38 cm or about 3-4 years (Adams et al. 2000, Davies et al. 2006). Peak spawning tends to occur between September and December around the new moons, when Coral Trout form multiple small aggregations on individual reefs (Samoilys 1997, Zeller 1998). Eggs and progeny are dispersed via a pelagic larval stage of about 3 to 6 weeks before settling on the same or distant reefs at about 18 mm in length (Doherty et al. 1994). Although adult Coral Trout have been found to move within reefs (up to 10 km), there is little evidence of movement among reefs, which is indicative of separate sub-populations on individual reefs throughout the GBR (Davies 1995, Zeller and Russ 1998).

Red Throat Emperor (are distributed mostly in the central and southern GBR (from Cairns south to the Capricorn-Bunkers). They are typically associated with coral or rocky reefs, although they also are commonly encountered on shoal habitats between reefs and are nearly always found on mid- and outer-shelf reefs to a maximum depth of at least 128 m (Newman and Williams 1996). Red Throat Emperor is a relatively large coral reef fish, growing to a maximum size of about 60 cm FL, 3.5 kg and 25 years of age (Church 1995, Brown and Sumpton 1998, Williams 2003, Williams et al. 2003). Regional patterns in growth have been found for Red Throat Emperor, with populations in the southern GBR reaching larger maximum sizes than those in the northern GBR (Williams 2003, Williams et al. 2003). Red Throat Emperor are also protogynous hermaphrodites, changing sex from female to male at about 42 cm and 6 years of age (Bean et al. 2003, Williams 2003, Sumpton and Brown 2004). Similar to Coral Trout, female Red Throat Emperor mature at about 28 cm and 1-2 years of age (Williams 2003). Peak spawning for Red Throat Emperor is earlier than that for Coral Trout, occurring between July and November (Williams 2003, Sumpton and Brown 2004). Little else is known about the spawning and reproductive behaviour of Red Throat Emperor, particularly in terms of their early life history stages, primarily due to difficulties in identifying Lethrinid larvae to the species level and a lack of information about the juvenile habitat (Leigh et al. 2006). Movement patterns of Red Throat Emperor are also not well known although recent tag-recapture studies suggest they are capable of moving among reefs, with maximum distances travelled exceeding 20 km in a period of 6-24 months (W. Sawynok, Infofish, unpublished data; Williams 2003).

The main differences in the biology of the two target species are: i) the pattern of abundance and distribution; ii) the timing of spawning; iii) growth and mortality schedules; and iv) the extent of post-settlement movement among reefs. Extension of the biological model to capture the population dynamics of Red Throat Emperor involved modifying how larval migration and settlement are modelled to allow for movement patterns specific to Red Throat Emperor. Because Red Throat Emperor, like common Coral Trout, is a protogynous hermaphrodite, the extension to the biological model in ELFSim was achieved by specifying appropriate parameter values for a second 'class' of the existing population model. Parameter values for growth, longevity, mortality, size- and age-at-maturity, sex change, etc for the Red Throat Emperor population model were derived from current and previous research (Brown et al. 1994, Williams 2003, Davies et al. 2006). The current population dynamics model for common Coral Trout assumes that there is no post-settlement movement among reefs (Davies 1995). A model of post-settlement migration was therefore developed to capture the hypothesis that adult Red Throat Emperor move among reefs. No direct biological interactions between the two species were included in the extended model. Thus, populations of each target species were also assumed to be independent biological entities with overlapping spatial distributions.

3.1. Larval migration and settlement model

The biological component of the operating model for Coral Trout and Red Throat Emperor incorporates many of the features developed by Walters and Sainsbury (1990) and Mapstone et al. (1996a). Both species were assumed to exist as a widespread metapopulation consisting of relatively discrete post-settlement subpopulations, each associated with an individual reef. The population dynamics model is age- and size-structured, assumes that the number of 0-year-olds is related to the size of the reproductive component of the population according to a stock-recruitment relationship, and allows for larval movement among reefs. Several sources of process error (Francis and Shotton 1997) such as variation in natural mortality and larval survival are included in the model.

The model can account for variation in size-at-age by dividing each cohort into 'growth groups' at birth. All fish within a growth group are assumed to grow according to the same growth curve, but the growth curve differs among growth groups. Fish do not change growth groups. Growth groups, however, were not included in the analyses of this report because the effect of including growth groups is small, and such inclusion increases the computational requirements of the calculations substantially. The model allows for movement of Coral Trout, larvae among reefs but ignores the possibility of movement of Coral Trout aged 1 year and older (see Davies, 1995). In contrast, movement of adult as well as larval Red Throat Emperor among reefs is considered.

For ease of presentation, the equations below assume that the parameters determining fecundity, sex-change and growth are independent of reef, although the software that implements the model has the functionality to allow these parameters to be specified as reef dependent.

Basic population dynamics
The basic population dynamics are defined by the equations:

$$N_{y+1,a}^{r,k} = \begin{cases} N_{y+1,0}^{r,k} & \\ \sum_{r'} T_a^{r',r} N_{y+1,a}^{r',k} & a = 1 \\ \sum_{r'} T_a^{r',r} N_{y,12,a-1}^{r',k} e^{-Z_{y,12,a-1}^{r',k}} & a = 2, \ldots, x-1 \\ \sum_{r'} (T_{x-1}^{r',r} N_{y,12,x-1}^{r',k} e^{-Z_{y,12,x-1}^{r',k}} + T_x^{r',r} N_{y,12,x}^{r',k} e^{-Z_{y,12,x}^{r',k}}) & a = x \end{cases} \quad (3.1)$$

where $N_{y,a}^{r,k}$ is the number of fish of age *a* in growth group *k* on reef *r* at the start of year *y*,

$N_{y,m,a}^{r,k}$ is the number of fish of age *a* in growth group *k* on reef *r* at the start of month *m* of year *y* (by definition $N_{y,1,a}^{r,k} = N_{y,a}^{r,k}$):

$$N_{y,m+1,a}^{r,k} = N_{y,m,a}^{r,k} \, e^{-Z_{y,m,a}^{r,k}} \quad (3.2)$$

$Z_{y,m,a}^{r,k}$ is the total mortality on fish of age *a* in growth group *k* on reef *r* during month *m* of year *y*:

$$Z_{y,m,a}^{r,k} = M_{y,a}^{r} / 12 + \sum_{f} F_{y,m,a,f}^{r,k} \quad (3.3)$$

$M_{y,a}^{r}$ is the instantaneous rate of natural mortality on fish of age *a* during year *y,*

$T_a^{r',r}$ is the probability that a fish of age *a* on reef *r'* moves to reef *r*,

$F_{y,m,a,f}^{r,k}$ is the fishing mortality on fish of age *a* in growth group *k* on reef *r* during month *m* of year *y* by vessel-class *f*, (0: commercial, 1: charter, 2: recreational) and

x is the maximum age considered (taken to be a “plus group”).

The maximum age *x* (years) for each species (18 for Coral Trout, 15 for Red Throat Emperor; Table 3.1) has little effect on the results because the rate of natural mortality (0.45 yr^{-1} for Coral Trout, 0.40 yr^{-1} for Red Throat Emperor; Table 3.1) assumed for fish aged 2 years and older implies that a relatively small number of fish reach that age.

0-Year olds
All fish are born as females, where births are assumed to occur at the start of the year following Ferreira and Russ (1994) and Russ et al. (1996). The number of 0-year-olds on reef *r* at the start of year *y* is determined from a contribution from spawning on reef *r* and from a contribution from all reefs (Mapstone *et al.,* 1996a):

$$N_{y,0}^{r,k} = K^k \left[st \, \tilde{f}^{\,r} \, S_y^r + (1-st) c^r \, BL_y^r \right] \quad (3.4)$$

where S_y^r is size of the reproductive component of the population on reef *r* at the start of year *y* (taken to be the biomass of mature females – also referred to as the spawner biomass):

$$S_y^r = \sum_{a=1}^{x} \sum_k f_{L_{k,a}} \, w_{L_{k,a}} \, N_{y,a}^{r,k} \quad (1 - P_{L_{k,a}}) \tag{3.5}$$

$$\tilde{f}^r = \frac{N_{0,0}^r}{S_0^r}; \quad c^r = \frac{N_{0,0}^r}{\sum_{r'} N_{0,0}^{r'} \Omega^{r',r}} \tag{3.6}$$

S_0^r is the size of the reproductive component of the sub-population on reef *r* at pre-exploitation equilibrium,

$N_{0,0}^r$ is the number of 0-year-olds on reef *r* at pre-exploitation equilibrium,

st is the fraction of the larvae that settle on reef *r* that originated from reef *r*,

$L_{k,a}$ is the length of a fish of age *a* in growth group *k*,

K^k is the fraction of larvae that fall into growth group *k*,

w_L is the mass of a fish of length *L*,

f_L is the proportion of animals of length *L* that are mature,

P_L is the proportion of fish of length *L* that are male,

BL_y^r is the background supply of larvae to reef *r* from all reefs during year *y*:

$$BL_y^r = \sum_{r'} \tilde{f}^{r'} S_y^{r'} \Omega^{r',r} \tag{3.7}$$

c^r is the scaling factor for reef *r* to account for variation in background larval supply among reefs, and

$\Omega^{r',r}$ is the fraction of larvae that move from reef r' to reef *r*.

The proportion of fish that are mature, f_L, and those that are male, P_L are determined from logistic functions of fish length (Table 3.2). It is assumed that the proportion of larvae that settle on the same reefs on which they were spawned is constant across all reefs. The values in the larval dispersal matrix, Ω, are proportional to the fraction of larvae that move from reef r' to reef *r* because the value for c^r provides an overall scaling factor. The values in the larval dispersal matrix are determined using one of three approaches:

a) "Uniform" distribution of larvae: $\Omega^{r,r'} = 1/n_r$, where n_r is the number of reefs.

b) Pre-specified. The values for the $\Omega^{r',r}$ are determined directly from models of larval movement (e.g., James et al. 2002).

c) Distance-based distribution of larvae: $\Omega^{r,r'} = \exp(-3.4d(r,r') - 3.91)$ where the function $d(r,r')$ is the distance between the centres of reefs *r* and r'(in degrees). This relationship is based on fitting a linear model to the logarithm of the fraction of the larvae which move from one reef to another derived from a hydrodynamic model (James et al. 2002) of larval movement for a hypothetical species over 324 reefs in the Cairns region (Fig. 3.1). The extrapolation of the hydrodynamics from such a small domoain to the entire GBR currently represents one of the key uncertainties in applying the model. The same relationship was applied to both species.

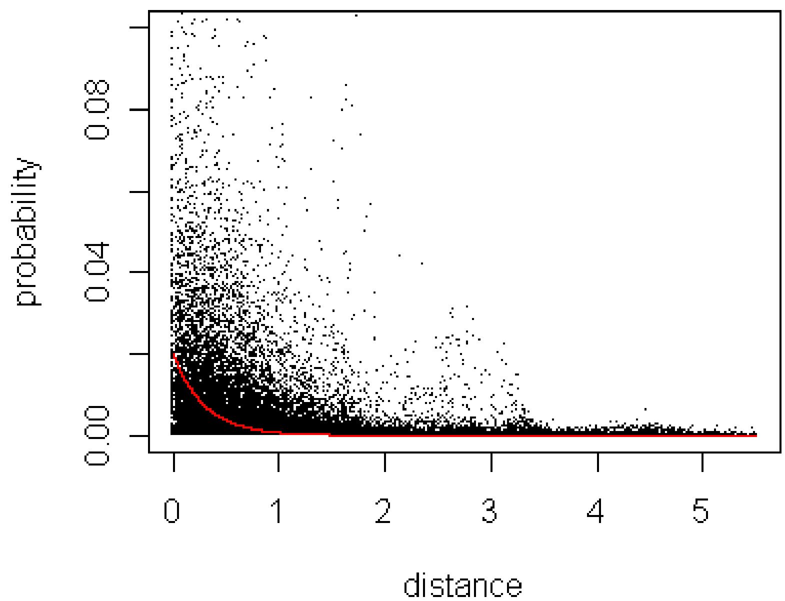


Fig. 3.1. Data plot and exponential line fit of probability of larval migration between reefs as a function of distance (in degrees).

Most simulations to date have used the distance-based approach (Approach c) because a uniform distribution of larvae is unrealistic, particularly when the model is applied to a large geographic area such as the entire GBR. Use of larval dispersal rates determined from models of larval advection and larval behaviour are clearly desirable. However, at present, such a model exists for only a small fraction of the GBR (most of the Cairns region) and does not include all the reefs to which the ELFSim model is applied.

The value of c^r (see Appendix A for derivation) depends on the larval dispersal matrix. The value of c^r is recalculated annually for scenarios in which the larval dispersal matrix is based on the model of larval advection and behaviour, and hence varies among years.

Because Red Throat Emperor are thought to spawn in a more restrictive geographical range than Coral Trout, the number of 0-year-old Red Throat Emperor on reef *r* in a given month is defined as,

$$N_{y,m,0}^{r,k} = \begin{cases} N_{y,0}^{r,k}\, e^{-(L_r-\bar{L})^2/(\sigma_1)^2} & \text{if } m=0 \text{ and } L_r \le \bar{L} \\ N_{y,0}^{r,k}\, e^{-(L_r-\bar{L})^2/(\sigma_2)^2} & \text{if } m=0 \text{ and } L_r > \bar{L} \\ N_{y,m-1,0}^{r,k} & \text{if } m>0 \end{cases} \qquad (3.8)$$

where $N_{y,0}^{r,k}$ is the expected number of Red Throat Emperor larvae in growth group *k* settling on reef *r* during year *y* (see Eq 3.4),

L_r is the latitude of reef *r*,

$\overline{L}$ is the latitude at which 0-year-old density is maximised,

σ_1 determines the rate at which 0-year-old density drops off with decreasing latitude (estimated values are in Table 3.4), and

σ_2 determines the rate at which 0-year-old density drops off with increasing latitude (estimated values are in Table 3.4).

Recruitment to reefs

The number of 1-year-olds in growth group *k* on reef *r* at the start of year *y*+1 is the number of 0-year-olds in growth group *k* on reef *r* the previous year modified by the density-dependent mortality between ages 0 and 1 plus the effect of random environmental variability and 'recruitment pulses'. These stochastic or "noise" terms can also be considered to effect larval mortality rather than that between ages 0 and 1:

$$N^{r,k}_{y+1,1} = N^{r,k}_{y,0}\, e^{-M_{y,0} - \beta^r (U^r_{y+1}/U^r_0 - 1)}\, e^{\varepsilon^r_y - \sigma^2_r/2}\, e^{\sum_i x_{y,i} \exp(\omega_p\, dist(r,c_i))} \tag{3.9a}$$

$$U^r_{y+1} = \sum_k (N^{r,k}_{y,0}\, e^{-M_{y,0}} + \sum_{a=2}^{J} N^{r,k}_{y+1,a}) \tag{3.9b}$$

$$\varepsilon^r_y = \tau_r\, z_y + \sqrt{1-\tau^2_r}\, z^r_y \tag{3.9c}$$

where β^r is the density-dependence parameter for reef *r*,

U^r_0 is the value of U^r_y at pre-exploitation equilibrium,

J is the maximum age of a 'juvenile',

z_y, z^r_y are independent and identically distributed random deviates from $N(0;\sigma^2_r)$, and uncorrelated between species,

σ^2_r is the overall inter-annual variation in larval abundance,

τ_r is the correlation in larval abundance among reefs,

$x_{y,i}$ is the magnitude of the *i*'th 'recruitment pulse' during year *y*, generated from the normal distribution, $N(0;1^2)$,

ω_p is the parameter that determines the spatial extent of a 'recruitment pulse', and

c_i is the centre of the *i*'th 'recruitment pulse'.

The value for the parameter β^r is determined by solving the system of equations for a pre-specified value of the stock-recruitment steepness parameter, *h* (Appendix B). Steepness is defined after Francis (1992) to be the fraction of the pre-exploitation number of 1-year-olds to be expected when the spawner biomass is reduced to 20% of its (average) pre-exploitation level.

Given the formalism adopted, recruitment variability can lead to higher or lower than expected survival rates from age 0 to 1 (see Appendix C). The centres for the 'recruitment' pulses are distributed randomly over the GBR. Note that if the model is run for a subset of the GBR, it is possible that the centres for some of the 'recruitment pulses' may fall outside the area considered in the model. 'Recruitment pulses' do not form part of the simulations in this report.

Natural mortality

The model used to determine natural mortality by age and year allows for differences in the mean value of natural mortality among ages, variability in natural mortality over time, the effect of catastrophic events, and time-trends in natural mortality:

$$M^r_{y,a} = (M^r_{y-1,a})^{\tau^M} (M'_{y,a})^{1-\tau^M} e^{\left[\varepsilon^M_{y,a} - \frac{(\sigma^M)^2}{2}\right]\sqrt{1-(\tau^M)^2}} \qquad \varepsilon^M_{y,a} \sim N(0;(\sigma^M)^2) \qquad (3.10a)$$

$$M'_{y,a} = \begin{cases} M_a + M_c\,\eta_y & \text{if } y \le y_{fst} \\ M_a + M_{fin,a}\frac{(y-y_{fst})}{(y_{fin}-y_{fst})} + M_c\,\eta_y & \text{if } y_{fst} < y < y_{lst} \\ M_a + M_{fin,a} + M_c\,\eta_y & \text{otherwise} \end{cases} \qquad (3.10b)$$

where M_a is the expected rate of natural mortality on fish of age *a*,

σ^M is the parameter that determines the extent of temporal variation in natural mortality,

τ^M determines the extent of temporal correlation in natural mortality,

y_{fst} is the year in which the natural mortality rate begins to change,

y_{lst} is the year after which the natural mortality rate ceases to change and remains constant,

$M_{fin,a}$ is the amount by which natural mortality changes between years y_{fst} and y_{lst} for a fish of age *a*,

M_c is the amount by which natural mortality increases during a catastrophic event,

η_y is a random variable that is 1 with probability p_c and 0 otherwise, and

p_c is the probability of a catastrophic event.

Equation (3.10) allows for catastrophic events (such as the effect of a cyclone) to increase natural mortality on all fish by M_c yr^{-1}. The probability of a catastrophic event is assumed to be p_c (base-case value zero). The value of η_y is independent of reef so that it is assumed a catastrophic event has the same effect across all of the reefs included in the model. More spatially restricted catastrophic events could be implemented with relative ease. Time-trends in natural mortality cause natural mortality for age *a* to increase from M_a to $M_a + M_{fin,a}$ over the years y_{fst} to y_{lst}. This formulation provides a framework within which some of the possible effects of global climate change can be investigated. The simulations in this report ignore the possibility of climate change and catastrophic events. The values for the remaining parameters that determine natural mortality (M_a, σ^M and τ^M) are listed in Table 3.1. The values for natural mortality-at-age are based on the assumption that natural mortality declines with age, and the observed age-structure of Coral Trout (see Appendix C) and Red Throat Emperor on closed reefs.

Growth

The growth of an individual is assumed to follow the von Bertalanffy growth equation:

$$L_{k,a} = \ell^k_\infty (1 - e^{-\kappa^k (a - t^k_0)}) \qquad (3.11)$$

where ℓ_∞^k is the maximum length of group group *k*

κ^k is the von Bertalanffy growth rate for growth group *k*

t_0^k is the length at age 0 for growth group *k*

Variation in growth among individuals is modelled by assuming that the parameters κ, ℓ_∞ and t_0 differ among growth groups, but that all fish in a growth group grow according to the same growth curve. The values for the parameters that determine growth (i.e., values for κ, ℓ_∞ and t_0) and those that determine the proportion of 0-year-olds in each growth group (i.e., the values for the K^k) are determined by fitting a model to data collected on length-at-age, after accounting for gear selectivity (Appendix D).

Mass as a function of length is determined using the standard allometric equation:

$$w_L = b_1 (L)^{b_2} \tag{3.12}$$

where b_1, b_2 are the parameters of the relationship between length and mass (Table 3.1; Appendix E).

3.2. Post-settlement movement model

There is no movement of Coral Trout post-settlement, so the matrix ***T*** for Coral Trout is an identity matrix. The age-specific probability of a Red Throat Emperor moving among reefs is assumed to depend on the distance among reefs, the size of the “destination” reef, and the direction of migration, i.e.:

$$T_a^{r,r'} = \begin{cases} \alpha P_a / (C + D(r-r')) S_r S_{r'} \tilde{L}(L_r, L_{r'}) & \text{if } r \neq r', D(r-r') \leq \tilde{D} \\ 0 & \text{if } r \neq r', D(r-r') > \tilde{D} \\ (1-P_a) & r = r' \end{cases} \tag{3.13}$$

$$\alpha = 1 / \sum_{r' \neq r} T_a^{r,r'} \tag{3.14}$$

where $D(r_1 - r_2)$ is the square of the distance between reef r_1 and r_2,

$\tilde{D}$ is the maximum distance a fish can travel in a month (in degrees),

C is a constant,

S_r is a measure of the size of reef *r* (i.e. reef perimeter),

P_a is the relative probability that an animal of age *a* migrates from a reef :

$$P_a = \chi P_\infty + \frac{(1-\chi) P_\infty}{1 + \exp(-(a - a_{50})\delta)} \tag{3.15}$$

P_∞ is the maximum probability of movement,

χ is a parameter that determines the basal level of diffusion,

$a_{50,} \delta$ are parameters that determine how the movement rate changes with age a ,

$\tilde{L}(,)$ is the function of the difference in latitude, e.g.:

$$\tilde{L}(L_r, L_{r'}) = \lambda_1 + \frac{1-\lambda_1}{1+\exp(-(L_r - L_{r'})\lambda_2)} \tag{3.16}$$

λ_1 allows for a "basal" level of diffusion, (estimated values are in Table 3.4) and

λ_2 is the parameter that allows for the extent of directed (northward) migration (estimated values are in Table 3.4).

3.3. Catches

The landed catch (in mass, kg) of fish from reef *r* during month *m* of year *y* by vessel-class *f*, $C^r_{y,m,f}$, is computed using the equation:

$$C^r_{y,m,f} = \sum_{a=0}^{x}\sum_{k} \frac{w_{L_{k,a+(m-0.5)/12}} \dfrac{D'_{L_{k,a+(m-0.5)/12}}}{Q_{L_{k,a+(m-0.5)/12}}} F^{r,k}_{y,m,a,f}}{Z^{r,k}_{y,m,a}} N^{r,k}_{y,m,a} (1-e^{-Z^{r,k}_{y,m,a}}) \tag{3.17a}$$

$$F^{r,k}_{y,m,a,f} = Q_{L_{k,a+(m-0.5)/12}} V_{L_{k,a+(m-0.5)/12}} F^r_{y,m,f} \tag{3.17b}$$

where $Q_L = D'_L + R'_L$

$$D'_L = \begin{cases} D & \text{for } L < L_{MLS} \\ 1 & \text{otherwise} \end{cases}$$

$$R'_L = \begin{cases} R & \text{for } L < L_{MLS} \\ 0 & \text{otherwise} \end{cases}$$

L_{MLS} is the minimum legal size,

D is the fraction of fish that are retained following capture,

R is the fraction of fish that die after being released,

V_L is the selectivity of the gear on fish of length *L*,

$F^r_{y,m,f}$ is the "fully-selected" fishing mortality applied to reef *r* by vessel-class *f* during month *m* of year *y*:

$$F^r_{y,m,f} = q^r_f (B^r_{y,m} / B^r_0)^{\phi} E^r_{y,m,f} e^{\varsigma^r_{y,m,f} - \sigma^2_{\varsigma}/2} \tag{3.18}$$

$B^r_{y,m}$ is the biomass on reef *r* at the start of month *m* of year *y* available to the fishery (i.e., exploitable biomass):

$$B^r_{y,m} = \sum_{a=0}^{x}\sum_{k} w_{L_{k,a+(m-0.5)/12}} D'_{L_{k,a+(m-0.5)/12}} V_{L_{k,a+(m-0.5)/12}} N^{r,k}_{y,m,a} \tag{3.19}$$

B_0^r	is the value of $B_{y,m}^r$ at the pre-exploitation equilibrium level,
ϕ	is a parameter that permits catchability to be density-dependent,
$E_{y,m,f}^r$	is the effort applied by vessel-class *f* on reef *r* during month *m* of year *y*,
$\varsigma_{y,m,f}^r$	is a factor to account for random variation in catchability ($\varsigma_{y,m,f}^r \sim N(0;\sigma_\varsigma^2)$), and
q_f^r	is the catchability coefficient for vessel-class *f* and reef *r*.

The catch, therefore, is a function of the biomass available to the fishery on each reef at the start of the month, the amount of effort from each sector of the fishery applied to that reef in that month, the selectivity function and catchability coefficient. Selectivity is assumed to be constant across sectors, and to depend on length. Retained and discarded catch are defined according to the respective species minimum legal sizes (MLS), which for both common Coral Trout and Red Throat Emperor is 38 cm TL.

If catch and effort data are available for reef *r*, the catchability coefficients for each vessel-class are computed using the formula:

$$q_f^r = \exp(\frac{1}{n_y n_m}\sum_y \sum_m \ell n(F_{y,m,f}^r / E_{y,m,f}^r /(B_{y,m}^r / B_0^r)^\phi)) \qquad (3.20)$$

where n_y and n_m are the number of years and months over which the data span. The variance is calculated as

$$\sigma_{q_f^r}^2 = \frac{1}{n_y n_m}\sum_y \sum_m \left[\ell n(F_{y,m,f}^r / E_{y,m,f}^r /(B_{y,m}^r / B_0^r)^\phi / q_f^r)\right]^2 \qquad (3.21)$$

where the summations over year are restricted to the years for which effort data are available (see below *Historical catch and effort data*). This approach cannot be applied to reefs for which there are no catch and effort data. Therefore, the commercial catchability coefficients for the few reefs for which there are no commercial catch and effort data are taken to be equal to the catchability coefficient of the closest reef. This approach is not used for the charter and recreational vessel-classes because there are many reefs without recreational or charter catch and effort data and so the approach would lead to an unrealistically exaggerated spread of charter and recreational effort over the GBR in the future. Instead, the catchability coefficients for the charter and recreational vessel-classes for reefs without catch and effort information are set equal to zero which, given the effort allocation algorithm, prevents effort occurring on those reefs in the future.

3.4. Initial conditions

The population is assumed to have been at pre-exploitation equilibrium with the corresponding age- and sex-structure at the start of 1965. This date is arbitrary within the constraint that there is sufficient time from pre-exploitation to the period for which catch and effort data exist (1989-) to tune the model to those catches. The population sizes and the corresponding age- and sex-structures on each reef at the start of the first year are computed using the following algorithm:

1. The number of 20+ cm animals (the lowest size included in UVS srveys) on reef *r*, n^r, is generated from the lognormal distribution, $LN(I_1^r\ rp^r, 0.5^2)$ where rp^r is the perimeter of reef *r* in km and I_1^r is a reef-specific tuning parameter, describing the density of fish per unit of reef habitat (i.e. km of reef perimeter). (It was an assumption that the standard

deviation of this distribution was 0.5) For Coral Trout, the model assumed the I_1^r are derived from a relationship between reef density and latitude (Fig. 3.3). The value for I_1^r is determined by dividing the value from the curve in Fig. 3.3 by the value for a latitude of 16.5°S (i.e., I_1^r=1 for reefs at 16.5°S). This divisor can be modified to achieve different scenarios regarding the status of the resource at the start of 1999. For Red Throat Emperor I_1^r is assumed to be unity. Reef perimeter is used as the measure of habitat because much of the central areas of most reefs on the GBR are either emergent consolidated substratum or sand, and so not reef habitat relevant to the target species of the reef line fishery. Reef perimeter is therefore expected to represent the extent of sub-tidal coral reef habitat inhabited by the target species better than (enclosed) reef area. The relationship between perimeter and area of such habitat is likely to vary among reefs but is not well known.

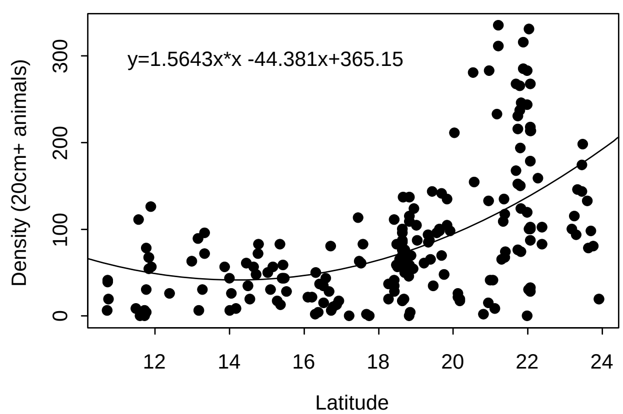


Fig. 3.3. Density of Coral Trout (20+ cm fish per unit area) from visual surveys and a fitted quadratic curve.

2. The number of 1-year-olds on reef *r* is then determined using the formula:

$$N_{0,1}^r = n^r / \sum_{a=1}^{x} \sum_{k} \tilde{N}_a^k \tag{3.22}$$

where $\tilde{N}_a^k$ is the relative age-structure of the pre-exploitation population, expressed as a fraction of the number of 1-year-olds, and the summation over age and growth group is restricted to fish for which $L_{k,a} > 20\text{cm}$. For Coral Trout, the initial age-structure is computed straightforwardly based on the per-recruit age structure. However, for Red Throat Emperor calculation of the initial, equilibrium, age-structure is more complicated because the per-recruit age structure is reef specific, and depends on migration rates that are different for different ages of fish. The initial per-recruit age structures are determined by running the model over a number of years in the following manner:

a. The initial identical age distributions $N_{0,a}^{*r}$ (where $N_{0,1}^{*r} = 1$, $N_{0,a}^{*r} = N_{0,a-1}^{*r} e^{-M_a}$ for $a > 1$, and $N_{0,0}^{*r} = e^{M_0}$) are scaled to reflect latitudinal variation (Equation 3.8), and the lognormal variate based on the reef perimeter, n^r, i.e. $\tilde{N}_{0,a}^{r,k} = n^r N_{0,a}^{*r,k} e^{-(L_r - \bar{L})^2/(\sigma_1)^2} e^{-M_a}$.

b. These reef-specific age structures are then projected forward using the post-settlement migration model for 2*x* years at a monthly time step and constant recruitment, i.e., $\tilde{N}^{r,k}_{y,0} = \tilde{N}^{r,k}_{0,0}$.

c. The larval migration and recruitment parameters $\tilde{f}^r, c^r, U^r_0$ and β^r are then calculated based on the age structures generated by the first projection, $\tilde{N}^r_{2x,a}$.

Using these parameters and the calculated age structures by reef, the populations on each reef are again projected forward using the post-settlement migration model for *x* years. Recruitment and larval migration are generated as specified above.

3. The biomass corresponding to the generated value for n^r can be such that the population would be extinct prior to the start of the projection period, after all of the historical catch was taken from it. If this occurs, the previous value used for the log-normal mean, (i.e., $I^r_1\ rp^r$), is increased by 5% and steps a to c are repeated since the available catch data are not consistent with such extinctions of *P. leopardus*.

3.5. Model parameters

The values for the parameters of the biological model are listed in Tables 3.1 and 3.2.

Table 3.1. Base-values for the fixed parameters of the biological models for Coral Trout and Red Throat Emperor. Values for the parameters related to changes over time in natural mortality and to catastrophic events are not listed as these factors are not part of the base-case analyses.

Parameter	Coral Trout	Red Throat Emperor	Source
Maximum age – *x*	18 yr	15 yr	Mapstone et al. (1996a) Williams (2003)
Mortality-at-age (for all ages)	0.45 yr^{-1}	0.40 yr^{-1}	Appendix G
Temporal variation in natural mortality – σ^M	0.05	0.05	Mapstone et al. (1996a)
Temporal auto-correlation in natural mortality – τ^M	0	0	Assumed
Length-mass – $\ell n(b_1)$	-19.2317	-18.1728	Appendix H
Length-mass – b_2	3.1914	3.0497	Appendix H
Larval self seeding – *st*	0.1	0.1	Assumed
Steepness – *h*	0.5	0.5	Pre-specified
Maximum age of a 'juvenile' - *J*	18 yr	15 yr	Mapstone et al. (1996a)
Variation in 0-year-old survival – σ_r	0.6	0.6	Mapstone et al. (1996a)
Spatial correlation in 0-year-old survival – τ_r	0.5	0.5	Assumed
Extent of density-dependence in catchability – Φ	0	0	Assumed
Fraction of fish that die after being released - D	0.15	0.15	Assumed
Fraction of fish that are retained after being captured - R	0	0	Assumed

Table 3.2. Parameters related to selectivity, maturity and the proportion male / sex-change.

Parameter	Coral Trout	Red Throat Emperor	Source
Selectivity			
Length-at-50%-selectivity	322 mm	395 mm	Coral Trout: Fulton et al. (1999), Red Throat Emperor: Appendix E
Length-at-95%-selectivity	375 mm	485 mm	Coral Trout: Fulton et al. (1999), Red Throat Emperor: Appendix E

Maturity			
Length-at-50%-maturity	280 mm	280 mm	S. Adams (pers. comm.)
Length-at-95%-maturity	360 mm	360 mm	S. Adams (pers. comm.)
Sex change			
Length-at-50%-sex change	450 mm	450 mm	S. Adams (pers. comm.)
Length-at-95%-sex change	500 mm	500 mm	S. Adams (pers. comm.)

Table 3.3. von Bertalanffy growth parameters for Coral Trout and Red Throat Emperor (source: Appendix G Coral Trout; Appendix F Red Throat Emperor).

Parameter	Coral Trout	Red Throat Emperor
Number of growth groups	1	1
ℓ_∞	54.05 cm	47.2 cm
κ	0.339	0.319
t_0	-0.367	-0.496

Determination of post-settlement migration parameters for Red Throat Emperor

The values for the Red Throat Emperor parameters of the post-settlement migration model (Equations 3.8, 3.13-3.16) were obtained by fitting the biological model to age data for three regions of the GBR (Storm Cay, Mackay and Townsville) (see Fig. 1.2; Williams 2003) under the assumption of constant recruitment. These regions were defined latitudinally: a) the Storm Cay region consisted of all reefs south of 21°S, b) the Mackay region consisted of all reefs north of the Storm Cay region, but south of 19.5°S, and c) the Townsville region consisted of all reefs north of the MacKay region, but south of 17.26°S. Reefs north of 17.26°S typically have little or no Red Throat Emperor so these reefs were ignored for the purposes of estimating the movement parameters. The model was also fitted to the observed mean weight and catch-rate in these regions. A maximum distance that a fish could travel in a month was used based on recent tag-recapture studies showing maximum distances travelled of approximately 20 km in a period of 6-24 months (W. Sawynok, Infofish, unpublished data; Williams 2003). The analyses are based on the highest rate from this range (20 km in 6 months), leading to a maximum distance a fish could travel in a month $\tilde{D}$ of 0.034, or approximately 3.4 km in a month.

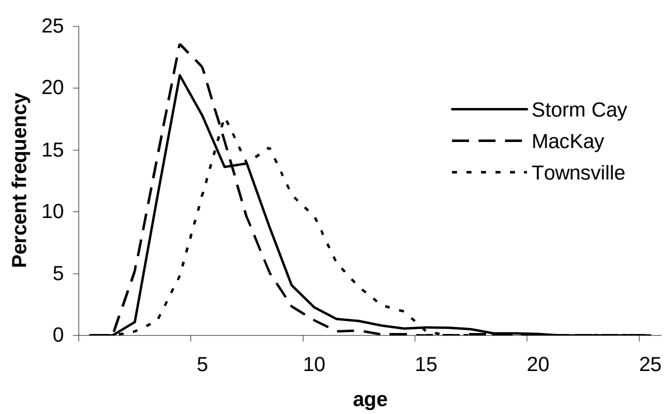


Fig. 3.4. Observed Red Throat Emperor age structures from Storm Cay, Mackay and Townsville.

The negative log-likelihood minimised to find the values for the free parameters of the post-settlement model for Red Throat Emperor is:

$$\lambda = \sum_{\Phi} 0.5\left[\frac{1}{k_{weight}}\ln(\frac{W^{\Phi}}{\hat{W}^{\Phi}})\right]^2 + \sum_{\Phi} 0.5\left[\frac{1}{k_{CPUE}}\ln(\frac{U^{\Phi}}{q\hat{U}^{\Phi}})\right]^2 - 100\sum_{\Phi}\sum_{a}\rho_a^{\Phi}\ln(\frac{\hat{\rho}_a^{\Phi}}{\rho_a^{\Phi}}) \quad (3.23)$$

where the weighted component of the age composition of 100 reflects the assumed sample size of the age data,

k_{weight} is the coefficient of variation for the regional weight data, and was calculated as 0.2,

W^{Φ} is the observed mean weight of a fish in region Φ, (Table 3.4),

$\hat{W}^{\Phi}$ is the model-estimate of the mean weight of a fish in region Φ:

$$\hat{W}^{\Phi} = \frac{1}{\hat{U}^{\Phi}}\sum_{a_k}^{a_{max}}\hat{\rho}_a^{\Phi} S_a w_a^{\Phi} \quad (3.24)$$

w_a^{Φ} is the weight of a fish of age *a* in region Φ,

ρ_a^{Φ} is observed fraction of the animals in region Φ that are of age *a*,

$\hat{\rho}_a^{\Phi}$ is the model-estimate of the fraction of the animals in region Φ that are of age *a*:

$$\hat{\rho}_a^{\Phi} = \frac{\sum_{r\in\Phi} S_a N_{y^*,12,a}^r}{\sum_{r\in\Phi}\sum_{a'} S_{a'} N_{y^*,12,a'}^r} \quad (3.25)$$

y^* is the final time period of the model,

S_a is the selectivity of the fishing gear on a fish of age *a*:

$$S_a = \frac{1}{1+\exp(-\ln(19)(a-a_{50})/(a_{95}-a_{50}))} \quad (3.26)$$

a_{50}, a_{95} are the parameters of the selectivity function (Table 3.2),

k_{CPUE} is the coefficient of variation for the regional CPUE data which was calculated as 0.2,

U^{Φ} is the observed CPUE in region Φ (Table 3.4),

$\hat{U}^{\Phi}$ is the model-estimate of the CPUE in region Φ:

$$\hat{U}^{\Phi} = \sum_{a_k}^{a_{max}}\hat{\rho}_a^{\Phi} S_a \quad (3.27)$$

a_{max} is the maximum fish age (Table 3.1),

a_k is the minimum age of fish retention,

q is the catchability coefficient $q = \exp(\frac{1}{n_{\Phi}}\sum_{\Phi}\{\ln[U^{\Phi}] - \ln[\hat{U}^{\Phi}]\})$, and

n_{Φ} is the number of regions (equal to 3).

Table 3.4. Regional data for fitting the post-settlement migration parameters.

Region	W^{Φ}	U^{Φ}

Townsville	1.4489	0.0388
Mackay	1.2684	0.0481
Storm Cay	1.2812	0.0499

The resulting migration parameters are given in Table 3.5. The model estimated only a 1-tail distribution in recruitment, because movement was assumed to only occur in a northerly direction.

Table 3. 5. Estimated post-settlement migration parameters for Red Throat Emperor.

Parameter	Value
Latitude at which 0-year-old density is maximised - $\overline{L}$	21.3
Rate at which 0-year-old density drops off with decreasing (northerly) latitude - σ_1	0.19
Rate at which 0-year-old density drops off with increasing (southerly) latitude - σ_2	1000
Constant - C	0.44
Maximum rate of movement - P_∞	0.99
Parameter that determines the basal level of diffusion - χ	0.29
Parameter that governs how the movement rate changes with age - a_{50}	0.97
Parameter that governs how the movement rate changes with age - δ	0.12
Basal level of diffusion, and - λ_1	4.8×10^{-6}
Parameter that allows for the extent of directed (northward) migration - λ_2	6.49

4. Effort models

Effort models impose fishing mortality on targeted fish stocks and attempt to represent distributions of fishing effort in response to management strategies (Mapstone et al. 2004). However, modelling the distribution of fishing effort and fisher behaviour has received little attention relative to the investment that has been made in modelling the population dynamics of fish stocks (Hilborn 1985, Holland and Sutinen 1999). Multi-species targeting behaviour of fishers, such as that which occurs in the multi-sector and spatially-diverse CRFFF, needs to be taken into account when evaluating management strategies so that the flexibility in fishing operations is recognised and that all targeted species are adequately protected. Although over 125 species groups have been recorded in the CRFFF (Mapstone et al. 1996b), common Coral Trout and Red Throat Emperor are the major target species of the commercial, charter and recreational fishing sectors (see Chapter 2). Operators in all sectors of the fishery at times switch among these species in response to low CPUE or changing market demands. Little is known, however, about the effects of this multi-species targeting behaviour on either the patterns of fishing or the sustainability of the fish stocks upon which the fishery depends.

In this Chapter, we build on the fleet-aggregated effort allocation model developed previously for common Coral Trout by including information on catches of Red Throat Emperor and decision rules for when, where and what to fish. We also develop an alternative individual- and decision-based vessel dynamics model that accounts for multi-species targeting of the two major species in the fishery. This more dynamic and realistic model explicitly incorporates factors that may influence fisher behaviour and the resulting spatial allocation of effort, which in turn may improve our understanding of effort dynamics in the past and our ability to predict responses to alternative strategies in the future. Data for parameterising the vessel dynamics model were derived from structured skipper interviews, compulsory commercial logbooks, and voluntary skipper and observer logbooks collected as part of the ELF Project. Both models, (i.e. the fleet aggregated effort allocation model, and the individual-based vessel dynamics model) are developed and used to evaluate management strategies in a multi-species context.

4.1. Effort allocation model

The effort allocation model in ELFSim, used previously for the single-species MSE of Coral Trout, is not intended to mimic the decision-making behaviours of individual skippers, but rather to capture the net effect of all such decisions when aggregated to the fleet level (Mapstone et al. 2004). Although the underlying principles of this model are reported in detail elsewhere (see Mapstone et al. 2004), we outline the major facets of the model here to demonstrate differences between it and the individual-based vessel dynamics model and to explain how this effort allocation model can be extended to handle multiple species.

The effort allocation model is based primarily on the historical catch and effort data of the commercial and charter fleets (1989-2000) (see Chapter 2). The model allocates fishing effort for the charter and commercial sector over the GBR on a monthly time step during a nominated projection period (i.e., 2001-2025). The total annual effort is divided among the time steps within each year according to intra-annual patterns observed in historical catch and effort data to preserve the seasonality in the distribution of fishing effort. This is accomplished by selecting a year at random from the period for which there are data (1989–2000 commercial, 1996–2000 charter,1998 recreational), calculating the fraction of that year's effort that occurred in each month during the year, and using these fractions to distribute the annual effort to be allocated among the months during the projection years.

Once the effort available for allocation in each month and sector is determined, it is then allocated among reefs based on historic CPUE, weighted by the species beach price, and the management status of each reef (i.e., open or closed to fishing). We set the beach price for

Coral Trout to be $14.75, and for Red Throat Emperor to be $4.18, based on historical fish prices reported in Chapter 2. The management status (*M*) of each reef is set between 0 (open) and 1 (closed), with intermediate values capturing the effects of some level of infringement. The effort assigned to a reef is calculated as that effort which would have been allocated to the reef if it was open to fishing multiplied by 1-*M*. The value of *M* can also vary with time, allowing for implementation of temporal closures and temporal variation in infringement.

The effort allocation process then involves ranking reefs that were fished in the previous month according to their weighted CPUE up to that time. The weighted historical CPUE is calculated as the ratio of summed previous catches to summed previous effort over the current calendar month in all previous years (to account for the known seasonality in the dynamics of the fleet), multiplied at each time step by a discount factor (0.85) that progressively down-weights older data. The amount of effort allocated to a reef depends on the average historical amount of effort allocated to it. This amount of effort is allocated first to the highest ranked reef and then to the next ranked reefs in turn, until there is no effort left or all of the reefs that were fished in the previous time step have been assigned effort. Any remaining effort is then allocated in the same manner to the reefs that were not fished in the previous time step but had been fished at some earlier time. If unallocated effort still remains after this step, it is allocated randomly to previously unfished reefs in small portions (5% of the balance) until all remaining effort is allocated. This allows for exploration of new fishing grounds and is the only way that effort can be allocated to reefs that have not been fished historically. The catch of Coral Trout and Red Throat Emperor from each reef in each month is then calculated separately for each sector from relevant catch equations (Equation 3.17).

Model projections of fishing effort distribution derived from the fleet-aggregate effort allocation model were compared to those from the individual-based vessel dynamics model to evaluate their relative performance and both were compared to patterns in the historical data when run under historical management conditions to assess their credibility.

4.2. Skipper interviews

An alternative effort model to the fleet-aggregated effort allocation model is an individual-based vessel dynamics model that incorporates decision-making processes of when, where and what to fish. Recent studies have developed these models based on discrete choice random utility functions to explain fishery and spatial effort distributions (Bockstael and Opaluch 1983, Holland and Sutinen 1999, Pradhan and Leung 2004, Salas et al. 2004). An important aspect of these models, and perhaps an impediment to their application limitation, is their requirement for extensive data on the decision-making processes of a fishing operation. Consequently, we interviewed a broad range of commercial skippers and fishers in the fishery to examine their individual fishing behaviours, motivations and decision-making processes. Responses from these interviews provided insights into the multi-species targeting behaviour in the commercial sector that were used to inform model development. The interviews also provided fishers with an opportunity to make additionally valuable contributions to our understanding of how the fishery works, how fishers think, and how recent management initiatives might affect their fishing behaviour and operations: information essential for making realistic and acceptable projections about the fishery.

A structured interview was designed, in collaboration with a few commercial reef line fishers, to gather information on the factors that influence their fishing practices and so assist in modelling fisher behaviour. In particular, we were interested in where fishers operated, the durations of fishing trips, how reefs were selected, what fish were targeted, and which ports were used. The interview was divided into eight major sections: 1) fishing history; 2) ports and vessel characteristics; 3) financial arrangements; 4) fishing operations; 5) decision-making; 6) fishing effort; 7) targeting behaviour; and 8) management (see Appendix F). Only skippers responsible for the operation of primary vessels (and associated dories) in the fleet were interviewed as they were assumed to be the main decision-makers on the fishing grounds. A series of one-to-one interviews with the skippers allowed us to posit specific scenarios and elicit their expected responses. These responses assisted in the formulation of hypotheses related to fishing effort distribution and skippers' decision-making processes and were used to inform the development of the individual-based vessels dynamics model.

Fishing history

A total of 76 commercial skippers from a fleet of about 411 active licensed vessels from the major fishing ports along the Queensland east coast were interviewed between 8 October 2003 and 28 March 2004 (Table 4.1). We assumed that the sample of skippers interviewed was representative of the fleet as a whole. Seventy eight percent of the skippers interviewed were full-time skippers who had been operating in the reef line fishery for an average of about 16 years. A total of 55% of the skippers fished for reef fish to supply the live fish market, with most commencing their ‘live’ operations between 1996 and 1997. Lifestyle, financial and traditional reasons were all motivations for fishing commercially, while expectations of increased profitability, shorter fishing trips and the need to stay competitive in the industry were all reasons for entering the live fishery.

Table 4.1. Home port and region of skippers interviewed. NA = no home port.

Home port	Home Region[1]	Latitude (°S)	Longitude (°S)	Number of Interviews
Port Douglas	Cairns	16.48	145.46	3
Cairns	Cairns	16.92	145.77	11
Innisfail	Townsville	17.53	146.04	3
Mourilyan Harbour	Townsville	17.60	147.16	3
Kurrimine	Townsville	17.75	146.10	2
Townsville	Townsville	19.27	146.84	7
Ayr	Townsville	19.60	147.40	1
Bowen	Mackay	20.03	148.26	9
Airlie Beach	Mackay	20.27	148.70	3
Mackay	Mackay	21.16	149.21	16
Yeppoon	Mackay & Swains	23.04	150.75	2
Gladstone	Swains & Cap-Bunker	23.85	151.27	7
Agnes Waters	Capricorn Bunker	24.20	151.90	1
Bundaberg	Capricorn Bunker	24.75	152.38	7
NA				1
Total				76

1. Regions refer to those defined previously for the commercial fishery (Mapstone et al 1996b).

Ports and vessel characteristics

The skippers interviewed operated from 14 home ports and 5 regions, extending over about 8° of latitude (Table 4.1). Moreover, 71% of the skippers had operated from the same home port for all of their reef line fishing experience, and 53% of them had not visited another port for any part of their operations (e.g., offloading catch, emergency repairs, etc) during the past year. Therefore, we assumed that most vessels in the fleet tended to operate from a home port, with a minor, more mobile, suite of vessels operating from more than one port.

The primary vessels operated by the skippers interviewed ranged from 5.6 m to 18.1 m in length (mean±SD: 11.1±3.0 m), steamed at an average speed of about 11 knots, and could carry about 1 t of live fish and 2.4 t of frozen product. Skippers tended to operate less than their full complement of dories, which on average was 1.6 against an average endorsement of 2. The dories ranged from 3.6 m to 7 m in length (4.9±0.6 m) and, where applicable, could carry up to 400 litres of seawater in live fish tanks.

In this project we did not attempt to model the mobile vessels operating from multiple ports or the movements of individual dories. We considered the primary vessel as the fishing operation and the base unit under which the vessel dynamics model operated. The main movements and operations of the dories were assumed to be captured in the dynamics of the primary vessels with which they were associated.

Financial arrangements

Although we were not interested in the actual financial arrangements *per se* with respect to pricing structures, we were interested in the contractual arrangements of each skipper and their relative investment in the fishery as we assumed this would influence their decision-making and potential level of risk behaviour. For example, we postulated that contract skippers may be more inclined to explore new fishing grounds, while owner-operators may be more risk-averse and interested in stable, reliable fishing patterns. Most of the skippers interviewed, however, were owners of their primary vessel (83%) and associated fishing endorsements (77%), with only a small number of contract skippers (17%). The main endorsements held were L1 (east coast line fishing outside GBRMP, 75%), L2 (line fishing in GBRMP with 2 or more dories, 55%) and L3 (line fishing in GBRMP with 0 or 1 dories, 46%). Two skippers interviewed held L8 endorsements (deep water multi-hook drop line fishing outside GBRMP). Most fishers held multiple endorsements, including a net (53%) and crab (46%) endorsements, amongst others (see Queensland Fisheries Regulation 1995 (Queensland Fisheries Act 1994) for full description of fishery symbols). Typically, contract skippers and dory fishers were paid a percentage of the catch (either collectively or individually) with amounts and prices varying according to species and product type. Live Coral Trout were the highest valued product, followed by dead Coral Trout, mixed A (e.g., Red Throat Emperor, nannygai, jobfish) and mixed B (e.g., stripey sea perch, hussar, cod) species (see Section 4.1).

Fishing operations

Fundamental to understanding the level of effort in the fishery is knowledge about actual fishing operations. An average of 27 fishing trips were conducted by each skipper over the 12 months prior to interview, with about 80% of the trips between 1 and 9 days duration. Five of these trips on average were cut short due to bad weather and one to gear failure. Typically, more fishing effort was distributed when the weather was better and higher prices attained, particularly leading into the Chinese New Year in January and early February. Fishing effort tended to be reduced throughout the cyclone season from about February to April with skippers often using this time for vessel maintenance. On average, about 197 days were spent in port during the year preceding interview, which was about the same as in previous years for more than half of the skippers interviewed.

Most skippers (83%) did not use transport (i.e., “mother”) ships during their fishing operations, further supporting our assumption that the fleet tends to operate from specified home ports. Those skippers that used motherships tended to operate north of Cairns where access to ports for offloading catch and reprovisioning is limited. About 1 to 2 days (95%CI) was the minimum time required in port to unload and reprovision vessels when operations were based from ports., We have specified in the vessel dynamics model that each vessel spends at least one day in port between fishing trips and no vessels use motherships.

Generally, each fishing operation involved about three crew members (including the skipper), which was consistent with the average number of dories operated (assuming the skipper fished from the primary vessel). An average of about 27% of the total catch derived from the primary vessel when one or more dories were used, with this estimate roughly proportional to the number of dories fishing. Most fishing tended to occur on reefs and shoals, with a limited number of skippers (7%) favouring only the deeper water (Fig. 4.1). The depths normally fished by the skippers also reflected their target species: Coral Trout for live markets were caught on average down to 24 m (maximum 40 m), Coral Trout to be frozen down to 41 m (maximum 135 m), Red Throat Emperor down to 42 m (maximum 150 m), and other reef fish species down to 67 m (maximum 360 m). The shallower depths were preferred for targeting live Coral Trout to minimise the effects of barotrauma on the fish, and hence increase their survival to offloading.

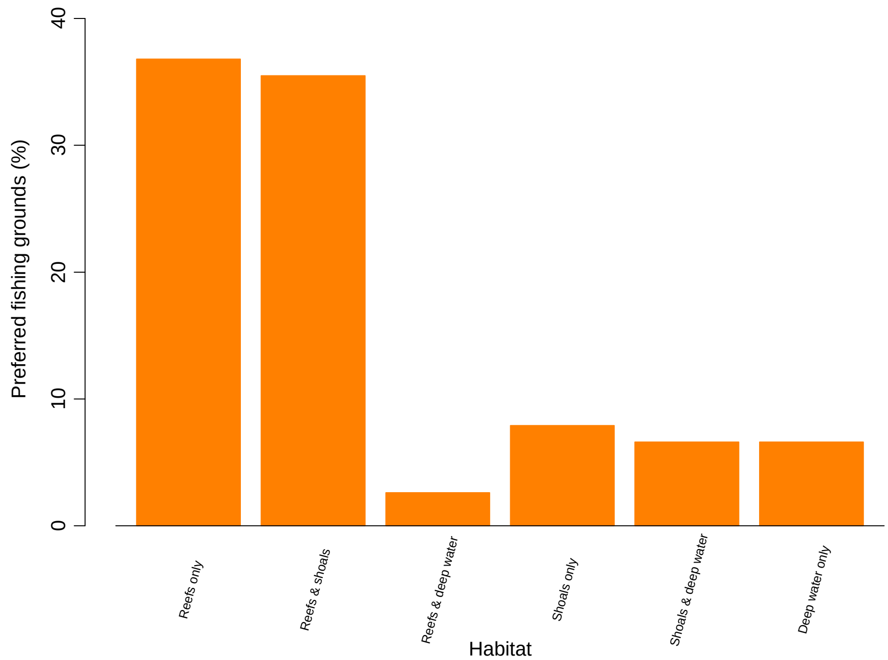


Fig. 4.1. Fishing grounds typically favoured by commercial reef line skippers (n=76).

Perceptions of a "good" day's catch varied widely amongst skippers for the different target species and the size of the respective operation (Table 4.2). However, across all skippers, an average of 181 kg of live Coral Trout or 91 kg of dead Coral Trout was considered a good day's fishing, while 35 kg and 13 kg, respectively, was a poor day. Typically, skippers would continue to fish on a small reef (1.4-2.3 nm wide) that produced good catches for up to 2 days, whilst for large reefs (6.1-8.8 nm) about 4 days was the average duration of fishing if CPUE remained acceptable (Table 4.3). Skippers often would remain on a reef until CPUE declined or it was time to return to port. Most skippers would not persist in fishing on a reef and would move on before the end of the day if catches were poor (Table 4.3). Dories would be more inclined to fish on other neighbouring reefs if a small reef on which the primary vessel was anchored produced average CPUE, but not so for a large reef where there was more space to disperse. Furthermore, about 37% of the skippers tended to follow the practice of fishing big reefs on big tides and small reefs on small tides.

Table 4.2. Average (minimum, maximum) catches (kg or fish) for total fishing operation (primary and dories combined).

Product	Good day		Average day		Poor day	
	kg	**Fish**	**kg**	**fish**	**kg**	**Fish**
Live Coral Trout	181 (55-500)	117 (10-300)	83 (20-250)	63 (6-130)	35 (0-100)	31 (0-100)
Dead Coral Trout	91 (3-500)	33 (2-109)	45 (1-250)	12 (1-35)	13 (0-100)	3 (0-10)
Other	303 (20-1600)	108 (30-300)	135 (10-650)	49 (15-100)	41 (0-250)	18 (4-50)

Table 4.3. Average number of days skippers remained on a small (average 1.9 nm across; 1.4-2.3 nm 95%CI) or large reef (average 7.4 nm; 6.1-8.8 nm 95%CI) when experiencing good, average or poor CPUE.

Reef size	**CPUE**		
	Good	**Average**	**Poor**
Small	1.8	1.0	0.4
Large	3.6	2.0	0.7

Sharing of catch information is a dynamic social interaction that occurs in many fisheries. It may have a significant effect on fishing operations, particularly where skippers direct their effort (e.g., Palmer 1991, Little et al. 2004). Of the skippers interviewed, 71% shared information about their fishing locations and CPUE with an average of three other skippers that tended to be associated with the same operation. Similarly 61% of the skippers received information, with about 42% of those frequently receiving misleading information.

Decision-making

Deciding which reef to fish involves consideration of a complex set of factors. The decision-making process underpins the vessel dynamics model, which attempts to capture some of the complexity of reef choice. Although we do not account for all the factors that influence where a skipper fishes, results from the interviews provided insights into some of these factors. Overall, most skippers were prepared to travel greater distances if they expected greater CPUE at the distant reef than at closer reefs, suggesting that expected CPUE influenced the decision-making and resultant effort allocation process. For example, 71% of the skippers interviewed would move to a reef that was two hours away for an expected 50% better CPUE than on a reef that was only one hour away.

Vessel avoidance and its interaction with reef size was another factor that influenced where a skipper decided to fish. On average, skippers avoided a small reef if they expected only moderate CPUE and another primary vessel (range 0-4 vessels) or five dories were already present. A large reef would be avoided if two primary vessels (range 0-6 vessels) or nine dories were already present. Similarly, if a skipper was already fishing a small reef, the arrival of another two primary vessels or six dories would cause a skipper to cease fishing and leave, while for a large reef, three primaries or 10 dories would trigger this response. In the vessel dynamics model, therefore, we allowed from zero to four primary vessels on small reefs and zero to six primary vessels on large reefs, noting that we were not modelling dory behaviour, with each vessel in the model assigned a specific avoidance level (or tolerance of other vessels on destination reefs).

Other factors important in deciding where to fish included: weather conditions (99% of skippers), tidal flow (93%), historical catches (number of fish caught at a reef on previous visits) and proximity to other reefs (91%). Only 37% of the skippers considered positive feedback about a reef from other fishers to be important, emphasising the relative weight skippers placed on their own knowledge rather than information from others.

Exploration of new fishing grounds was also a consideration in the decision-making process of skippers, involving a trade-off between unknown but potentially high CPUE at ‘new’ reefs and expected stable CPUE from known historical patterns. Most skippers (62%) tended to fish the same reefs and had not visited new reefs in the 12 months prior to interview. Skippers who ventured beyond their usual fishing grounds visited on average seven new reefs in the year preceding interview, with about three of those reefs being fished on subsequent trips. Proximity to traditional reefs fished, presence of other reef line vessels (66% of skippers), apparent attraction of a reef on a chart (64%), and information from other fishers (58%) were all important factors in considering whether to fish a new reef.

Fishing effort
Information from the compulsory commercial logbook program (CFISH) showed that fishing effort was distributed unevenly across the fishery, both spatially and temporally (Chapter 2, Fig. 1.2). Data from the CFISH program have limited in spatial resolution, however, with fishers only historically required to report their fishing locations within 30 minute grid squares and the option of reporting at the scale of 6 minute sites. These data provide a relatively coarse description of fishers' movements among individual reefs since many grid or site squares contain multiple reefs or only parts of some reefs. Furthermore, these limitations create an inherent level of uncertainty in the use of these data such as in our historical reconstruction of patterns of fishing effort and the effort allocation model (Section 4.1). To partly overcome these issues we collected finer spatial movement data on actual fishing trips from skippers during interviews and from voluntary logbooks collected during other research in the ELF Project. Approximately 57% of skippers followed regular routes, fishing a common set of reefs on all trips, consistent with the above low level of exploratory fishing.

Targeting behaviour
Deciding which species to target is another important step in the decision-making process of commercial skippers operating in a multi-species fishery such as the CRFFF. Common Coral Trout and Red Throat Emperor are the two major target species in the CRFFF, even though over 125 species groups have been recorded in the logbooks (Mapstone et al. 1996b). Live Coral Trout (95%CI: 24-40% by weight) dominated the annual catch by skippers interviewed, while smaller, but significant amounts of Red Throat Emperor (9-15%), Spanish mackerel (7-17%) and dead Coral Trout (7-14%) were also harvested. Significant quantities of other reef fish (25-42%) were also caught, reflective of the diverse, multi-species nature of the fishery. Catches of each species varied seasonally, with Red Throat Emperor and Spanish mackerel tending to be harvested most in winter and early spring and Coral Trout in late spring and summer. Coral Trout intended for the live fish markets were preferred to weigh about 1 kg, while the preferred weight for Coral Trout for frozen markets was 3-4 kg. Skippers generally stated that they stopped targeting Coral Trout for live sale if beach prices declined to about $\$22\pm6$ kg^{-1} and switched to marketing dead product.

Some skippers specifically targeted different species at different times of the year, particularly when CPUE for the Coral Trout was poor. About 30%, 50% and 55% of the skippers respectively targeted Red Throat Emperor, Spanish mackerel (*Scomberomorus commerson*) and other reef fish at some time. Red Throat Emperor were often targeted during winter and at night; Spanish mackerel during winter and while steaming with trolling lines; and red emperor (*Lutjanus sebae*), nannygais (*Lutjanus erythropterus, L. malabaricus)*, spangled emperor (*Lethrinus nebulosus*), jobfish (*Aprion* spp) and goldband snapper (*Pristipomoides multidens*) from deeper water at night. Spotted mackerel (*Scomberomorus munroi*) and shark mackerel (*Grammatorcynus bicarinatus*) also were targeted occasionally. Only 11% of the skippers harvested Coral Trout exclusively at some times, again reflecting the multi-species nature of the fishery.

Another common characteristic of the multi-species reef line fishery is the potential for high-grading and discarding, which can occur at various stages in the production chain. Dory fishers at times discard marketable catch from the hook (13%), icebox (1%) and live holding well (5%) to accommodate higher value product (high-grading). Dead or injured Coral Trout (in the case of live operators), mixed reef fish species, trevally, shark and big cods are discarded in favour of live or dead Coral Trout and other higher valued product if holding space is limited. Similarly, about 4% of the skippers occasionally discard marketable catch from the freezer to accommodate more valuable product. Notably, 78% of the skippers interviewed thought discarding would increase with the introduction of the ITQ system.

Management

The final section of the interviews provided information on the skippers' responses to recent management initiatives (GBRMPA Representative Areas Program (RAP) and DPI&F CRFFF Management Plan 2003) and how these were likely to affect their decision-making and fishing behaviours in the future. This information provided us with insights into their likely behaviour which could be examined under specific modelling scenarios. Most skippers (87%) considered reef fish stocks in their usual area of operation were moderately to over-fished, with moderate to too much effort currently exerted by the commercial (91%) and recreational (71%) sectors. Combined with their concerns for current levels of effort, such factors as poor management (92%), over-fishing (75%), pollution (57%), runoff (54%) and tourism (28%), were all considered by the skippers to be major threats to the CRFFF.

Concerns were also expressed by the skippers over the introduction of the GBRMPA RAP, with about 40% of the area they previously fished expected to be closed to fishing under ther revised zoning. Skippers were likely to respond to the new spatial closures by adopting one or more (non-mutually exclusive) behaviours; namely extending their fishing grounds into other areas (64%), concentrating effort into remaining areas (74%), moving elsewhere (17%), changing to another fishery (28%) or stopping fishing (41%). Furthermore, skippers expected that the new 'no take' zones would decrease their access to productive fishing areas (86%), decrease the profitability of their business (86%) and diminish the long-term sustainability of the fishery (49%). In contrast, they expected that the number of commercial (74%) and recreational (58%) fishers, who fished in their area, and the long-term sustainability of the GBR (39%), would increase as a result of the closures. Eighty three percent of the skippers thought a few reef line fishers operated in closed zones on occasion, while 66% thought those fishers were likely to get caught. Most skippers (82%) expected better CPUE on closed reefs than on reefs open to fishing, with 75% considering this a major reason for infringement. Only 42% of the skippers thought infringement into no-take zones would increase following the introduction of the RAP.

The DPI&F CRFFF Management Plan evoked similar responses from the skippers to those expressed over the GBRMPA RAP. Most skippers expected the new reef line management plan to decrease access to the species they currently targeted (75%) and diminish the profitability of their businesses (83%). In contrast, they expected an increase in the amount of discarding or high-grading (93%) and the long-term sustainability of the fishery and GBR in general (54%). Most skippers also supported the new size limits for Coral Trout (76%) and Red Throat Emperor (71%), catch quotas (69%), spawning closures (64%) and protection of potato cod (E*pinephelus tukula*) (71%) and Queensland grouper (E*pinephelus lanceolatus*) (68%). fewer skippers supported the protection of Maori wrasse (*Chelinus undulates*) (36%), however, or barramundi cod (*Cromileptes altivelis*) (24%). Ninety six percent of skippers interviewed were allocated Coral Trout quota under the new CRFFF Management Plan, 93% Red Throat Emperor quota, 79% other species quota, and 47% Spanish mackerel quota. Most skippers, however, considered they were allocated less quota than that to which they were entitled, with 65%, 53%, 75% and 93% of the skippers, for Coral Trout, Red Throat Emperor, other species and Spanish mackerel, respectively being dissatisfied with their allocated quota. In addition, some skippers were likely to buy (59%) or sell (38%) quota in the first two years of the ITQ system, while only about half of them (46%) expected to still be in the fishery in five years.

Model assumptions

In summary, information from the skipper interviews provided significant insights into the daily fishing operations and decision-making processes that occur on the fishing grounds of the CRFFF. This information was used to develop hypotheses, formulate assumptions and parameterise the vessel dynamics model.

The key points highlighted from the skipper interviews and incorporated into the individual-vessel dynamics model included:

- Most primary vessels operate from 10 main home ports (Cairns, Innisfail, Townsville, Bowen, Mackay, Yeppoon, Gladstone) and only these ports were used in the model;
- Each primary vessel is associated consistently with the same home port;
- The movement and fishing practices of a primary vessel adequately captures the effort distribution of its associated dories;
- Vessels follow a seasonal pattern of fishing activity;
- Each primary vessel requires a minimum of one day in port between trips;
- Fishing effort is only allocated to reef habitats;
- Each reef is classified as small or large for implementing avoidance behaviour by skippers (small reefs had diameters less than 19 nm, large reefs had diameters that were greater);
- Vessels have a vessel avoidance characteristic, tolerating up to 4 primary vessels on small reefs and six primary vessels on large reefs;
- Expected catch is based predominantly on a vessel's own catch history with a background contribution from a 'fleet-wide' catch history for each reef;
- Most primary vessels follow regular fishing routes and fish subsets of a consistent group of reefs on successive trips.

The vessel dynamics model was also based on several of the assumptions on which the analysis of the interview data was based:

- The skippers interviewed were representative of the fleet;
- The reef line fishery consists of 411 primary vessels (the number of licences to which quota was allocated in 2003);
- Primary vessels were not differentiated into operations targeting live or dead fish markets, with all vessels assumed to function within the same range of fishing behaviours;
- No transport or motherships were used to offload catch or reprovision;
- Skippers were the main decision-makers on the fishing grounds.

4.3. Parameterising the vessel dynamics model

The ELFSim vessel dynamics model operates at the level of individual vessels fishing individual reefs. The model attempts to simulate a fishing fleet whose behaviour is a reasonable representation of the actual fleet. The simulated vessels, or *agents*, possess attributes that determine their fishing behaviour. Examples of such attributes are: species-specific catchability relative to the fleet; preferred direction of trip; avoidance behaviour when encountering other vessels on reefs; preferred trip length; and 'stay/move' behaviour following each day's fishing at a reef.

These behaviours were captured by specifying a probabilistic model for the behaviour of each vessel. The parameters of this model were derived by analysing fleet data from two sources: the skipper interview data described above; and data from voluntary logbooks kept by skippers participating in other ELF Project research (hereafter 'the ELF logbook data'), in which the fishers logged their positions and catches during a subset of their trips at greater resolution than in the QDPI&F compulsory logbooks (e.g., recording reef-specific effort and catches by dory and species).

We used the ELF logbook data to attempt to ascribe the fishers' motives to external drivers or covariate information that we could measure. Vessels in ELFSim are presented with choices, such as available reef to which to move, and the vessel dynamics model then calculates probabilities for each choice, based on the covariate values in effect. The simulation then proceeds by selecting one choice at random using the computed probability distribution.

The interview data provided information that was mostly complementary to, but sometimes overlapping with, the logbook data. In some respects the information from the survey was directly applicable to the model because the questions were designed to quantify certain types of fisher behaviour. The interviews were especially valuable in capturing the variation of vessel characteristics across the fleet, such as capacity, live product capability, trip duration, home port and range. They also addressed issues such as vessel avoidance behaviour and information sharing, both of which were practically invisible in the logbook data. An overlapping issue was the reef-tide-wind behaviour, which was reported by some fishers but difficult to identify from ELF logbook data. Simply stated, some fishers tended to avoid small reefs when the tidal flows were high or during strong winds. Parameterising such behaviours was difficult from interview data but provided cues about potential patterns to explore in the logbook data.

4.3.1. ELF logbook data

The ELF logbook data comprise the catch by weight or number of each species for a sample of vessels in the commercial fleet at the level of session (AM or PM) within day. A total of 35 vessels contributed a total of 16,554 sessions to the ELF database from 257 trips. The level of contribution per boat ranged from 4 to 3,068 sessions and from 1 to 56 trips. Fig. 4.2 shows fishing trips over a six year period by vessel. Each horizontal line within a panel represents the trips carried out by the same boat, with different trips denoted by different colours. (In 1998 one boat had a very long trip of over 100 days.) The percentage of records in each year from 1996 to 2001 was 2%, 40%, 26%, 22%, 8% and 1%, respectively. The coverage in 1997 was fairly broad with most of the sample of vessels contributing over most of the year. In 1998–2000 the whole year was covered but with diminishing numbers of vessels. The coverage in 2001 and 1996 was limited to the later part of the year and to only one or a few vessels. The highly unbalanced nature of the logbook data puts certain constraints on the type of analysis possible. For instance, the very uneven coverage of years would make it dubious to include year explicitly in any analytical model.

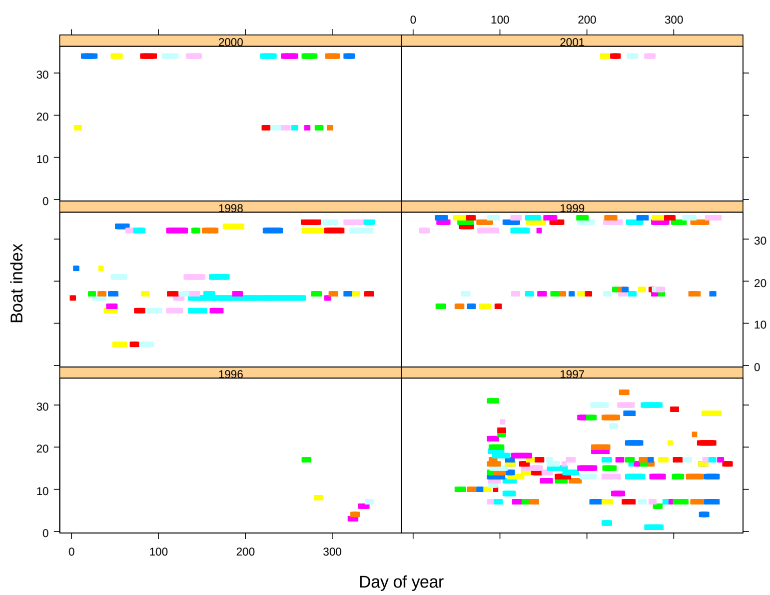


Fig. 4.2. Distribution of the ELF logbook data over boats and dates. Different colours denote different trips.

Catch

The catch records consisted of non-specific Coral Trout (31%), Coral Trout identified to species (13%), Red Throat Emperor (17%), 'mixed reef A' (10%) and 'mixed reef B' (24%) species. ('Mixed reef A' and 'mixed reef B' are market categories for product (usually fillets) of higher and lower quality flesh respectively, with significantly different prices for each. Each category comprises many species but the species composition of the categories is generally non-overlapping.) Other species accounted for 5% of records. Fig. 4.3 shows the distribution of sessions that caught the two major target species, Coral Trout and Red Throat Emperor. There were virtually no Red Throat Emperor catches in the north. Note that Fig. 4.3 does not purport to show the density of the two target species but merely the distribution of the sessions reported in the database from the ELF logbook program.

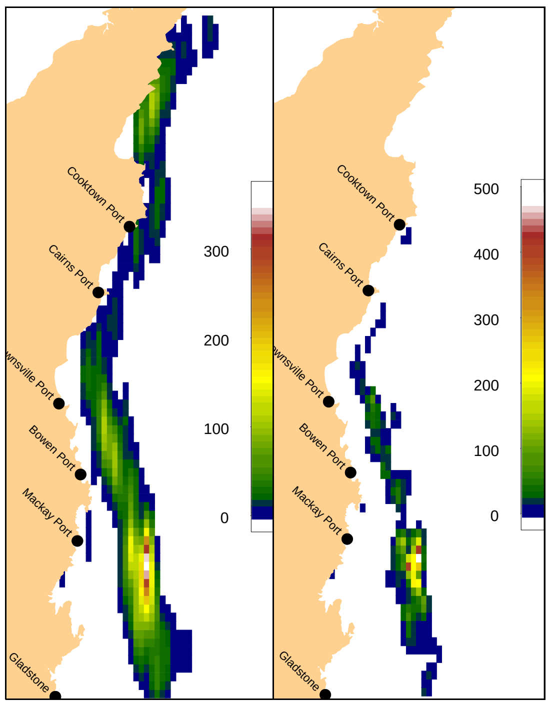


Fig. 4.3. Kernel density maps of fishing session when Coral Trout (*left*) or Red Throat Emperor (*right*) were caught by fishers maintaining ELF logbooks. Density is proportional to number of sessions in which each species was caught.

The majority of catch information was expressed as weight, although a significant number of records (mainly live Coral Trout catch) only gave the number of individuals caught. In order to do a quantitative analysis, conversion of all data into weights was necessary. This was done by using the 1,478 catch records for which both weight and number were recorded (Fig. 4.4), and using a robust linear fit to determine a mean weight per fish of 1.21 kg for Coral Trout, 1.34 kg for Red Throat Emperor, 1.00 kg for mixed A, and 0.95 kg for mixed B. Records of catch by number (only) were then converted to catch by weight by multiplying the number or each species or species group by the respective mean weight per fish. Specific and non-specific Coral Trout groups were amalgamated for these analyses.

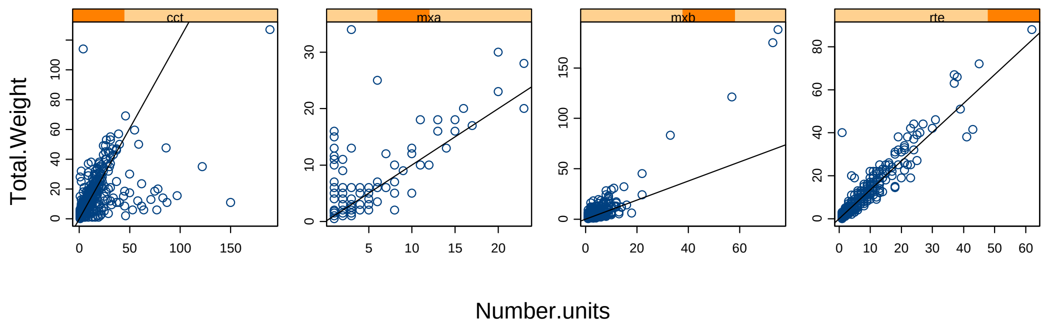


Fig. 4.4. Robust linear fit through the origin of total weight to number of units for (*left to right*) Coral Trout, mixed A, mixed B and Red Throat Emperor. This robust procedure (lmRob in Splus) is resistant to outliers.

Trips

Trips are an important unit in vessel dynamics. Figure 4.5 shows all the trips recorded in the database from ELF logbooks. Lines indicate daily movement, in the displacement from the first session of one day to the first session of the next day. Just under half (114) of the trips in the database operated in the south (east of Mackay), and most of the remainder (108) operated in the mid-region (off Townsville and Cairns), with 32 trips in the far-north of the GBR (north of Cooktown). These three localities are termed hereafter the south, north and mid provinces respectively.

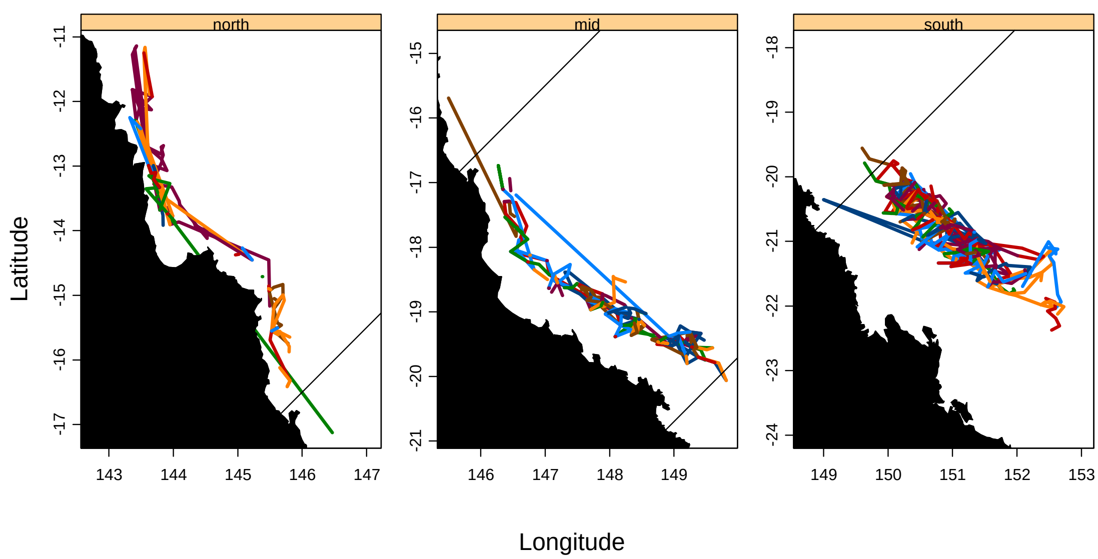


Fig. 4.5. All trips recorded in the ELF database from ELF logbooks, drawn by locality. The lines denote daily movement from the first reef of the day to the first reef of the next day. Different colours denote different trips. The thin lines separate the localities. Reefs are not shown for clarity.

The distribution of trip lengths can be used to guide the vessel dynamics model (Fig. 4.6). The distribution was roughly bimodal with some outlying longer trips of over 30 days. Trips targeting live Coral Trout tended to last less than about 10 days. On the other hand, trips targeting dead product were of very variable lengths. Because it was not possible to reliably distinguish live trips from dead trips on trip length alone, did not the vessel dynamics model did not make such a distinction.

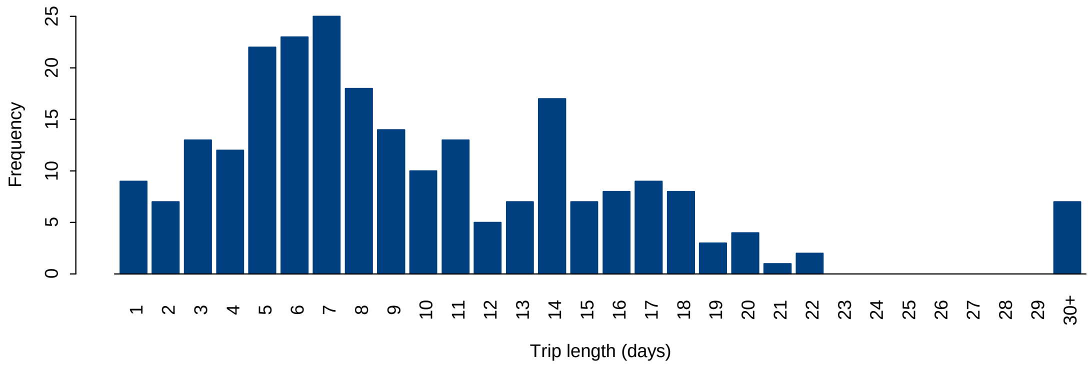


Fig. 4.6. Trip length in days as determined from the interval between first session and last session of each trip.

Trip distance is defined as the distance travelled by the vessel from the first reef fished to the last reef fished, assuming straight lines between successive reefs. Trip distance ranged from a few nautical miles (nm) to over 1000 nm for the very long trip mentioned earlier (Fig. 4.7). The distribution is roughly symmetrical on the log scale with mean around 50 nm. Twenty eight trips recorded no movement whatsoever. Of these, 13 were 1- or 2-day trips, where staying on the same reef might be reasonable. This was consistent with the interview results. The information is probably erroneous for the rest, however, since it is at odds with findings from the interviews.

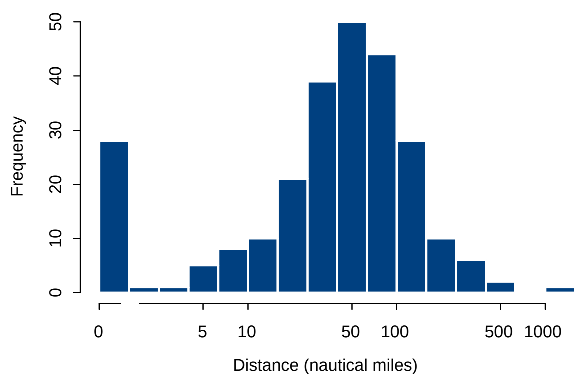


Fig. 4.7. Frequency histogram of total trip distance (excluding travel to and from port). The scale is logarithmic except at the left end, where it is broken. The bar at left represents trips with zero trip distance, i.e. the boat stayed at the same reef for an entire trip.

Figure 4.8 shows the directional data of trip displacement by locality with rose diagrams: a two-dimensional histogram for direction and distance. The direction is split into 16 compass bearings (N, NNE, NE, …, WNW, NW, NNW) and distance is split into quartiles plus the upper 1 percentile. These splits are then arranged as coloured ‘petals’ on the rose diagram with the radial size of the petal proportional to the frequency of the group. The proportion of observations in each direction is indicated by the percentage labels. Trip displacement, which is the vector linking the first reef of a trip to the last, can show whether there are overall net directional biases to trips. In the north and mid localities, trips recorded in the ELF logbooks tended to run parallel to the coast. Moreover, they ran predominantly in either a north westerly or south easterly direction. The directionality was much less marked in the south, where trips progressed in most directions though with a slight north westerly dominance and a second easterly mode. Such directional properties were most likely dictated by the geography of the reef.

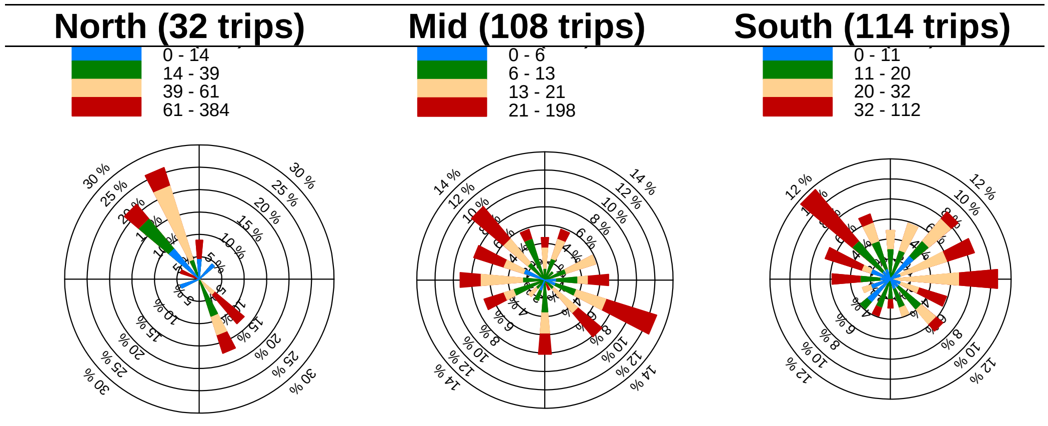


Fig. 4.8. Rose diagrams of the total trip displacement (nm) by trip locality (north, mid, south). The blue, green, yellow and red ranges are approximate quartiles.

The number of dories and crew taken on the trip determines the fishing power of an operation. Fig. 4.9 shows that vessels keeping ELF logbooks typically had 4 or 5 dories, but the number ranged from 1 to 8.

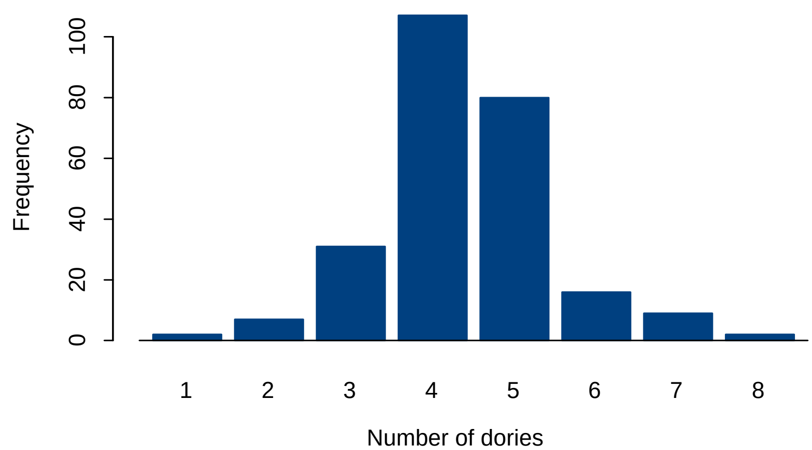


Fig. 4.9. Histogram of dories per vessel over all trips.

The ELF logbooks consisted of exclusively fishing on reefs by session and dory, and so had very limited information about the port of origin for the trips. It was possible, however, to establish the port of origin for 29 trips from auxiliary passage data (Fig. 4.10). Auxiliary passage data set was small and only represented only a couple of dozen vessels and so could not be used to accurately describe the fishing behaviour of the fleet. Figure 4.10 shows that the port of origin mostly was close to the first reef visited. This result accorded with findings from the interview data, and supported the idea that trips mostly started on a reef relatively local to the home port.

Fig. 4.10. Passages from port to first reef visited.

Movement

The characterization of movement was complicated greatly by two features. Firstly, each main vessel supported several dories, each working somewhat independently, and although the dories moved with the vessel throughout the trip, they did not all fish the same reef during any one session. Secondly, there were usually two (and, rarely, three) sessions reported in a day (typically AM & PM), and the dories were sometimes on different reefs in the two sessions. In fact, there were some cases of dories fishing multiple reefs in the same session. In addition, about 10% of fishing days were reported as a single 'all-day' session.

We did not attempt to capture the fine-scale details of dory behaviour in the vessel dynamics model, but instead worked at the level of the *main vessel* operating *daily* on a *single reef*. In reality, because of multiple dories and multiple sessions, a vessel could fish several reefs in a single day, especially in areas where the reefs are small and close together. The ELF logbook data were used to assess the effect of ignoring the fine detail: 91% of all sessions reported only a single position, meaning that all dories were fishing the same reef. Of the remainder, most were fishing two reefs. However, 61% of all fishing days reported fishing only a single reef, whereas 31% reported 2 reefs and 5% reported 3 reefs being fished in a day. Clearly there was a certain loss of resolution in going from sessions to days. There may be a case for working at the half-day scale in a later version of the vessel dynamics model, although the information content from the finer resolution might not warrant the cost of gathering the extra data required for parameterisation as well as the additional computational overhead in running the vessel dynamics model with a half daily time step.

Figure 4.11 shows the absolute daily movements recorded in the ELF logbooks. The most striking feature of the data was that just under half of the time vessels stayed on the same reef. When there was movement, the log distance was roughly symmetrically distributed with mean around 10 nm. This dichotomous stay/move behaviour formed an important part of the vessel dynamics model.

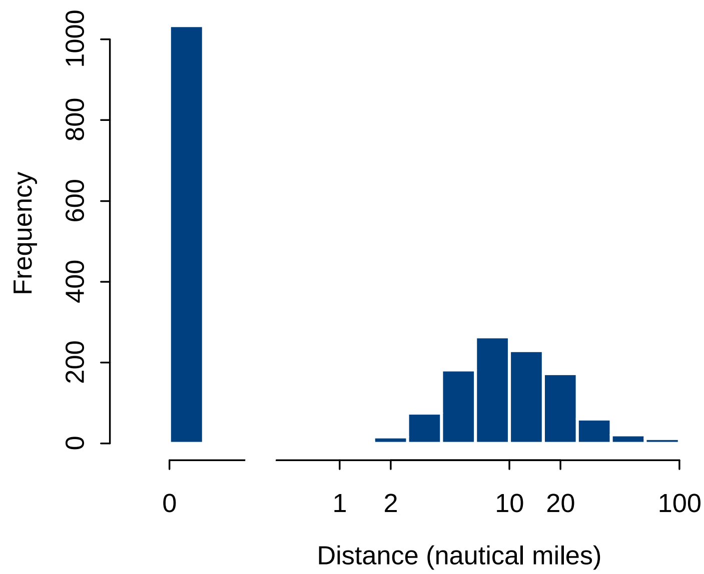


Fig. 4.11. Frequency histogram of daily travel distances reported in the ELF logbooks. The scale is logarithmic except at the left end, where it is broken. The bar at left represents daily movements of zero distance, i.e. the boat stayed at the same reef.

Figure 4.12 shows the angular distribution of non-zero movements among reefs using a rose diagram. In the north and the mid localities, the daily movements were again mainly parallel to the coast. In the south, movement had a slight east-west tendency but tended to be much more isotropic (the same in all directions) than in the other two localities. The smaller displacements (the blue petals), however, show that short movements were fairly isotropic in all regions. This suggests that, at least away from the south, fishers tended to move parallel to the coast but with small departures off the main direction of travel. In the south, movement appeared to be more random.

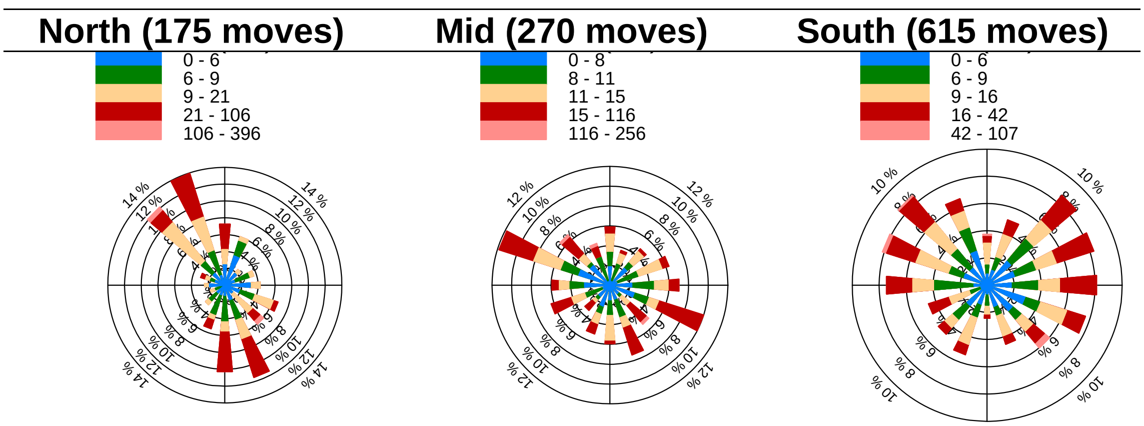


Fig. 4.12. Rose diagrams of non-zero daily vessel displacements (in nm). The longer displacements in the NW-SE directions are necessarily along the general direction of the GBR and represent passages from one locality to another. The blue, green and yellow ranges are approximate quartiles. The last quartile is split into red and pink; the pink range (the 99th percentile) being included to emphasise large, relatively rare, movements among localities.

4.3.2. Covariate drivers of fishing behaviour

The vessel dynamics model consists of four main components to fishing behaviour: (1) first reef selection (2) movement; (3) fishing and (4) trip termination. The movement component has two parts: a decision whether to stay on the current reef or move to another reef, and, given the latter, a decision about where to go. Both parts are parameterised from analyses of the ELF logbook data. In the fishing component, the vessel catches fish according to the catch equations which depends on vessel catchabilities, which are also derived from analyses of the ELF data.

Various data sets were constructed from which potential drivers for fisher behaviour could be determined. These included geographic data (inter-reef distance and reef perimeter), fishery data (fleet catch and catch per unit effort by reef, month and species), tide data and wind data. A vessel-dependent catchability was also derived from the ELF logbook data which was used as a covariate in determining the factors affecting vessel reef to reef movement.

QDPI&F compulsory log book data, gridded into 30 nm or 6 nm cells, were used to assign CPUE to individual reef. Three types of CPUE were considered: yearly, monthly averaged across years and monthly within year. Where there was no effort on a reef in a particular month the average CPUE for that reef in the same month across all years was substituted. A refinement of this approach was to assign QDPI&F catch (and therefore CPUE) to each reef within a grid in proportion to reef perimeter, as used by ELFSim in its historical phase (see Sections 2.4, 4.1). We also considered catch *per se*, as being a potential driver for reef choice and associated vessel movement.

It is reasonable to suppose (and supported by skipper interviews) that fishers base their decisions on their knowledge about reefs. This knowledge would be acquired partly from their own fishing experience and partly through the ‘grape vine’ of the collective fleet experience. It was not possible, however, to incorporate in our analyses the fisher’s own catch experience on the reefs. The ELF logbook records are quite patchy for many vessels, with only single records of catch on a particular reef or, if there were multiple records, they were widely separated in time. The analysis of the ELF logbook data, therefore, could only provide us with the fleet component.

Fishers have also reported that the preference for big reefs depends on the weather as well as tidal flow. We used windspeed data from 6 weather stations at Bowen, Creal Reef, Gannet Cay Reef, Gladstone, Green Island and Townsville to test for such relationships in the ELF logbook data. Wind speeds were available three times daily in 1994–1999. Windspeed on a reef was determined by interpolating over latitude the daily average windspeed at the nearest two stations. The windspeed at the extreme station was used for reefs beyond the most northerly or southerly stations, and for dates outside 1994–1999, the median value for that day over annual data was used.

4.3.3. Deriving parameters for the vessel dynamics model

Fishing the reef: vessel catchabilities

The ELF logbook and observer data provided information on the variation in catchability among vessels and days, with total catches reported by species for each vessel at the reefs that they fished. We modelled the catch per unit effort (CPUE) $u_{r,v,s}$ of species s by vessel v on reef r as a product of a reef-specific term $u_{r,s}$ a vessel-specific term $q_{v,s}$, and a lognormal random variate :

$$u_{r,v,s} = u_{r,s} q_{v,s} \exp(\varepsilon_{r,v,s}) \qquad (4.1)$$

This was recast as an additive linear model as:

$$\log(u_{r,v,s}) = \log(u_{r,s}) + \log(q_{v,s}) + \varepsilon_{r,v,s} \qquad (4.2)$$

The reef-specific and vessel-specific catchabilities could be estimated as a simple main-effects model with normal errors. However, our interest was not in the catchabilities of the particular vessels covered by the ELF logbook data, but rather in the distribution of catchability across the entire commercial fleet. It was appropriate, therefore, to treat the vessel-specific catchabilities as a random sample from a population of catchabilities, and so include them in the analytical model as a random effect. The data were therefore analysed using a linear mixed-effects model. A model in which the reef catchabilities were a fixed effect (Model A) was first considered. The full specification was:

$$\begin{gathered} \log u_{r,v,s} = \alpha_{r,s} + \beta_{v,s} + \varepsilon_{r,v,s}, \\ \beta_{v,s} \sim N(0, \sigma_s^2), \quad \varepsilon_{r,v,s} \sim N(0, \tau_s^2). \end{gathered} \qquad (4.3)$$

Since the parameters were distinct for the two species, they could be analysed separately. The `lme` software (Pinheiro and Bates, 2000) in S-Plus for this analysis.

One problem with this approach was that the CPUE for reefs visited by only a single vessel was fitted exactly, because there was a parameter in the statistical model for each reef. This effectively meant that such reefs contributed no information to the vessel catchabilities. Indeed, when such reefs were eliminated from the data set, exactly the same estimates were obtained for the vessel random-effects and residual standard deviations.

An alternative was to regard the reef log CPUE also as a random variable, so that the model consisted entirely of random effects. The full specification of this model (Model B) was:

$$\begin{gathered} \log u_{r,v,s} = \alpha_{r,s} + \beta_{v,s} + \varepsilon_{r,v,s}, \\ \alpha_{v,s} \sim N(0, \nu_s^2), \quad \beta_{v,s} \sim N(0, \sigma_s^2), \quad \varepsilon_{r,v,s} \sim N(0, \tau_s^2). \end{gathered} \qquad (4.4)$$

The catch and effort data from the ELF logbooks were aggregated to days, reefs, vessels and species for this analysis. The resulting 2,833 records consisted of a highly unbalanced distribution of 35 vessels among 520 reefs. The weight data for species coded ‘ct’ (generic Coral Trout) and ‘cct’ (common Coral Trout) were combined and the CPUE was computed by dividing by the respective effort in dory-sessions. Note that the model used a log-transform and so could not handle zero catches. Since only 20 of the 2,833 records had zero Coral Trout catch, those records were ignored.

The estimates from the analysis are shown in Table 4.4. When reefs were treated as a fixed effect the vessel catchabilities appeared to come from a population with standard deviation 0.468 and a residual variation of standard deviation 0.665. These figures increased to 0.494 and 0.671 respectively when the reefs were treated as random because some variation was artificially absorbed into the reefs in Model A. Model B used 2,813 records as opposed to 2,655 for Model A.

Table 4.4. Parameter estimates with 95% confidence intervals for Coral Trout and Red Throat Emperor mixed-effects models.

Species	Model	Parameter	Estimate	Confidence interval	
				Lower	Upper
Coral Trout	Random reef	ν	0.285	–	–
		σ	0.494	–	–
		τ	0.671	–	–
	fixed reef	σ	0.468	0.344	0.637
		τ	0.665	0.656	0.685
Red Throat Emperor	Random reef	ν	0.552	–	–
		σ	0.508	–	–
		τ	0.941	–	–
	fixed reef	σ	0.244	0.108	0.550
		τ	0.914	0.878	0.952
Adjusted Red Throat Emperor	Random reef	ν	0.403	–	–
		σ	0.558	–	–
		τ	0.915	–	–

Figure 4.13 illustrates tests for the assumption of normal residual variation independent of vessels. As the residuals were standardised, their means should be zero and their quartiles should align with the dashed lines. This was roughly the case for vessels with more than about 10 data points. There was some evidence that the residuals were skewed to the left, i.e smaller CPUEs tended to be more common than larger CPUEs.

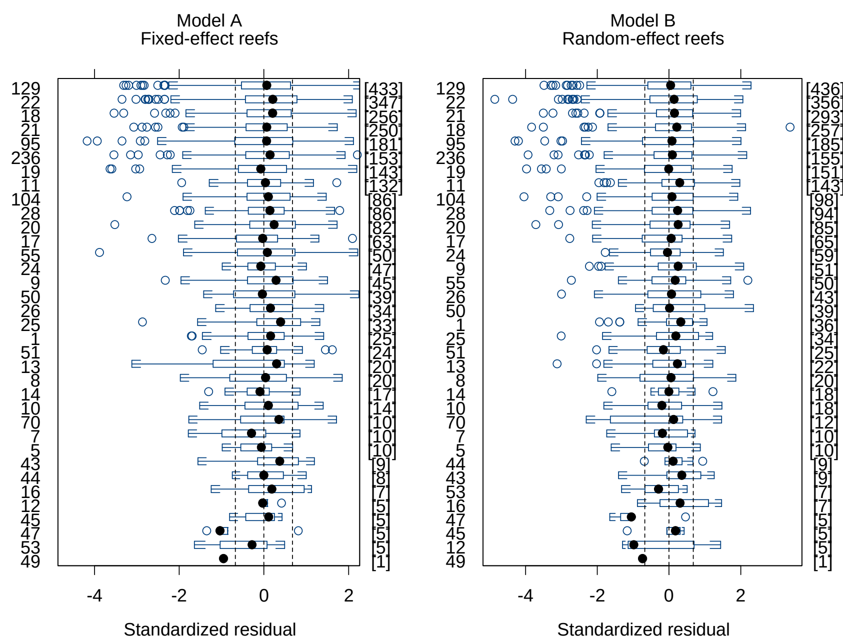


Fig. 4.13. Boxplots of standardized residuals by vessel ID for Models A and B for Coral Trout. The vessels are ordered by data frequency, with most frequent at the top. Brackets contain the number of observations (reefs) per boat. Boxes enclose the interquartile range and dots denote the median. The dashed lines mark the 1st, 2nd and 3rd quartiles of a standard normal variate.

The QQ-plots in Fig. 4.14 test the assumption that the random effects and residuals were normal. Centred normal data should lie on a straight line with slope equal to the standard deviation. This was the case for the both vessel and reef random effects (Model B), although the reef random effects had a slope (0.1) smaller than the estimated value (0.285). This is a shrinkage phenomenon that is well-known in random-effects models and was more noticeable for the reefs than for vessels because there were fewer observations per reef than per vessel. The residuals were roughly normal with a slight left skew. Model A had residuals that were more symmetric, but also more compressed towards the centre of the distribution.

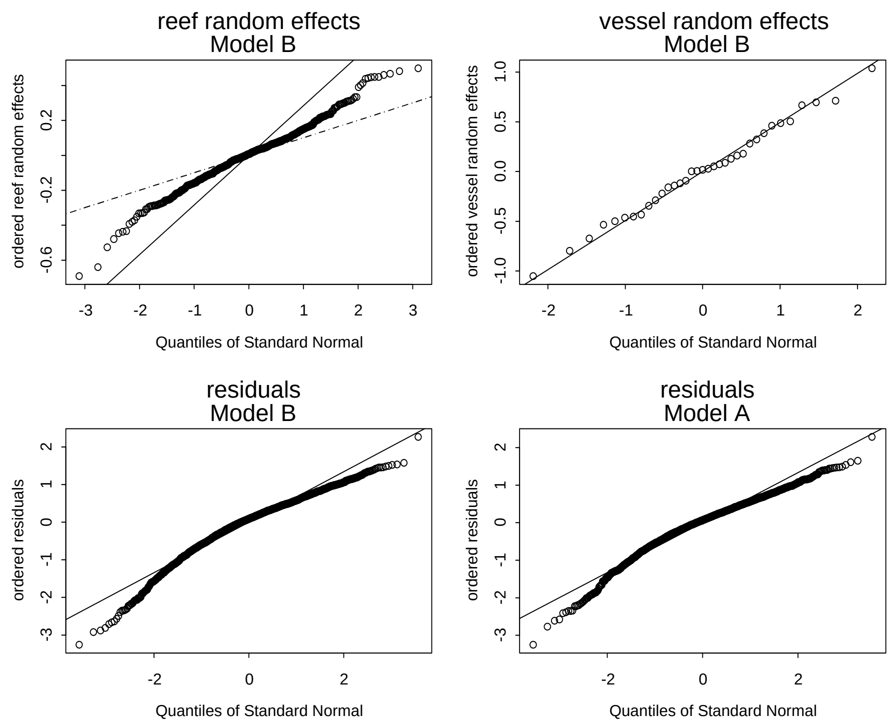


Fig. 4.14. QQ-plots of reef and vessel random effects for Model B and raw residuals for both models for Coral Trout. The solid lines have slopes equal to the estimated random-effects and residual standard deviation (0.285, 0.494 and 0.671). The dashed line is a fit-by-eye line of slope 0.1; it shows the 'shrinkage' phenomenon common to random-effect models.

1515 of the 2833 ELF logbook records had non-zero CPUE for Red Throat Emperor, partly due to the restricted geographic range of the species where Red Throat Emperor are rarely seen north of 18°S. Of the 2370 daily records from south of 18°S, however, 715 had zero Red Throat Emperor catch. This suggested definite targeting by fishers away from Red Throat Emperor or discarding of Red Throat Emperor during fishing. Furthermore, only 24 of the 35 vessels reported landing any Red Throat Emperor, so the variation in catchability was based on a smaller sample than for Coral Trout. This may have reduced the variation in catchability of Red Throat Emperor.

Notwithstanding these remarks, a mixed effects analysis using Models A and B was carried out for Red Throat Emperor. Table 4.4 shows that the estimate of σ was 0.24 with rather wide confidence intervals. In contrast to Coral Trout, Model B increased this value to 0.51. The residual standard deviation was reasonably high for both models (0.91 and 0.94). Because of the over-parameterization issue noted above (1 datum per reef), Model A used 1391 observations whereas Model B used all 1515 records. Again, Model B was preferred to Model A.

Figure 4.15 shows that the within-vessel homogeneity assumption was reasonable at least for the more common vessels. The QQ-plots of all random effects (not shown) were also reasonable.

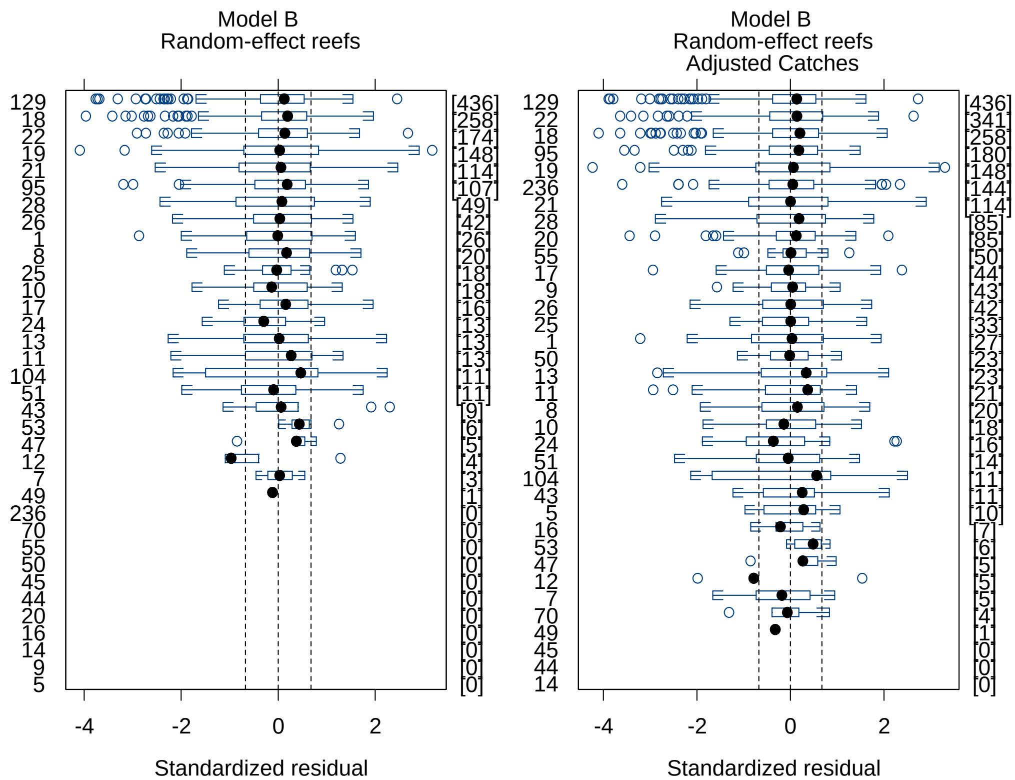


Fig. 4.15. Boxplots of standardized residuals by vessel ID for Model B for Red Throat Emperor raw data (*left*) and adjusted data (*right*). The vessels are ordered by frequency, the most frequent at the top. Brackets contain the number of observations (reefs) per vessel. Boxes enclose the interquartile range and dots denote the median. The dashed lines mark the 1st, 2nd and 3rd quartiles of a standard normal variate. Note that some vessels have no data.

One possible explanation for the lack of Red Throat Emperor catch by some vessels is that the catch may have been recorded as mixed reef A because catches were low and separate packaging of multiple species products was not warranted. A further analysis was therefore carried out in which the Red Throat Emperor catches were adjusted by assuming that for some boats the mixed reef A catch included Red Throat Emperor catch.

The vessels to which this adjustment should be applied were selected by examining the distribution of the ratio of mixed reef A to mixed reef B catch on the assumption that vessels reporting Red Throat Emperor as mixed reef A would show a higher ratio of mixed reef A : mixed reef B. Figure 4.16 shows the distribution of this ratio (arctan transformed to make it finite) grouped by vessels that sometimes recorded Red Throat Emperor catch and those that never recorded it. There is a clear distinction for values above about 0.5, consistent with the hypothesis that that those catches may have been supplemented with Red Throat Emperor. A binary indicator variable of Red Throat Emperor catch (0 if no catch otherwise 1) was fitted to a tree model with $\tan^{-1}$(mxa/mxb) as the only explanatory variable and a cut-off point for considering mixed reef A to contain Red Throat Emperor catch was estimated to be 0.488, which agrees closely with expectations. Finally data consisting of zero Red Throat Emperor catch were replaced with the total mixed A catch if the following conditions were met: 1) the reef was south of 18°S, and 2) the ratio of mixed A to mixed B exceeded tan(0.488). This procedure was likely to have overestimated catches of Red Throat Emperor by an unknown amount, since it was unlikely that all the catch reported as mixed reef A was Red Throat Emperor.

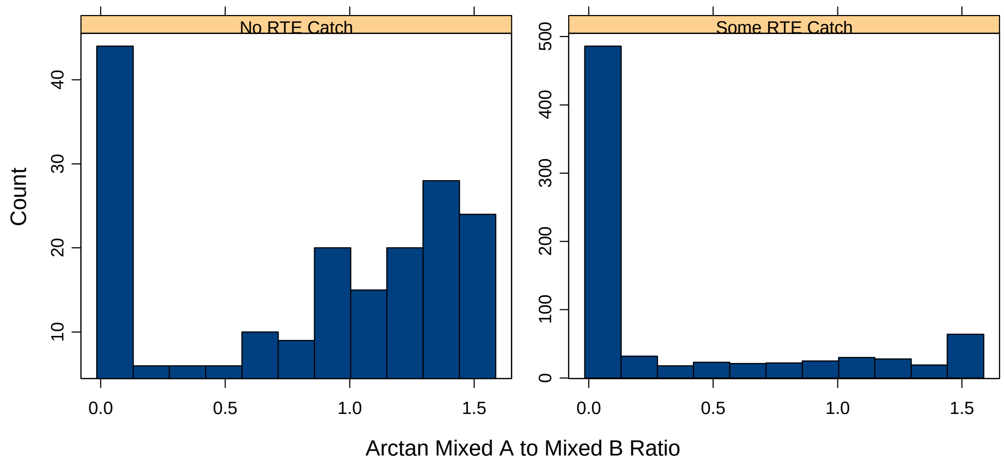


Fig. 4.16. Histograms of $\tan^{-1}$(mxa/mxb) over all vessel-reef combinations grouped by vessels that sometimes recorded Red Throat Emperor catch and those that never recorded it.

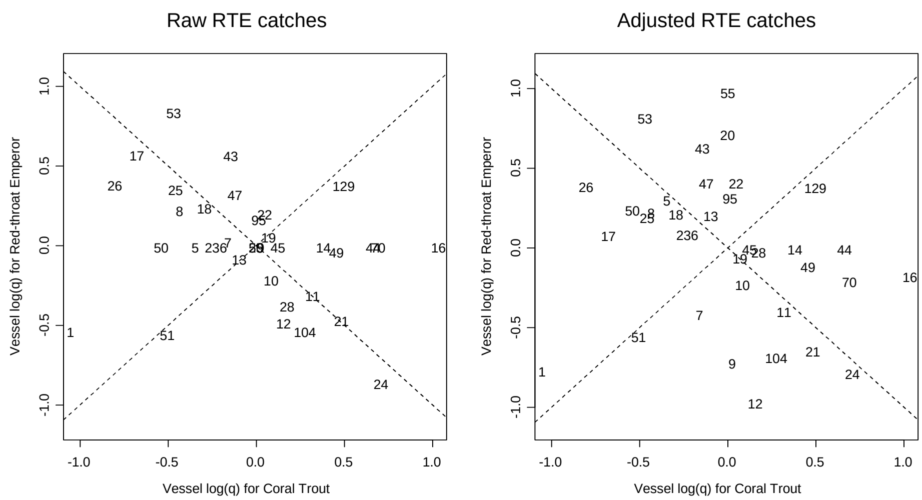


Fig. 4.17. Scatterplots of log Red Throat Emperor (RTE) vessel catchability against log Coral Trout vessel catchability, labelled by vessel ID. Vessels with no raw RTE catch are plotted as 0 along a central horizontal line since there was no estimate of RTE vessel catchability (left-hand panel).

The results of the analysis for the adjusted catches are shown at the bottom of Table 4.4. The vessel standard deviation was somewhat higher than for the earlier random reef model and the residual variation somewhat smaller. The within-vessel residuals are shown in Fig. 4.15.

Inclusion of the surrogate Red Throat Emperor catch (mixed reef A) increased the records available for analysis to 2230 and meant that all but three vessels were considered to have had Red Throat Emperor catch. The vessels did differ slightly in their residuals, however: vessels 20, 9, 55, 236 and 50, whose catches were adjusted, all had slightly smaller-than-typical residuals. This suggests that there was something different about the supposed Red Throat Emperor catch for these vessels, possibly related to the likelihood that it was a mixture of Red Throat Emperor and other species.

It is interesting to compare the catchabilities of the two species for each vessel as in Fig. 4.17. Using the raw catches, a negative correlation between catchabilities might tentatively be claimed, implying that vessels with higher-than-average catchability for one species tend to have lower-than-average catchability for the other. This impression is diluted somewhat when the adjusted catches were included.

On balance, Model B is the preferred model for both Coral Trout and Red Throat Emperor. The outputs from this analysis to be used in the vessel dynamics model are σ, the standard deviation of vessel-specific catchability and τ, the residual standard deviation (Table 4.10). The use of adjusted catches for Red Throat Emperor is perhaps suspect and because the estimates from models with and without the mixed reef A catch are quite similar, we simply used the results from the reported catches of Red Throat Emperor. Figure 4.16 suggests there is a difference in the way some skippers report catch. We would recommend trying to determine from the skippers the nature of this difference so that in future a more informed analysis can be attempted.

Stay/move decision

The vessel dynamics model operates at a daily time step. When a vessel has fished on a reef, it has to decide for the next day whether to move to a new reef or to stay on the same reef. The ELF logbook data showed that about 50% of the time fishers stayed on the same reef from one day to the next. This has been confirmed in conversations with fishers at stakeholder meetings and from the interviews.

Theoretical framework

The decision of whether to stay on a reef was analysed by fitting a statistical model for the probability of staying on the current reef or moving to another reef. Formally, the probability p of staying on the reef is:

$$p = e^{X^T\beta} \Big/ 1 + e^{X^T\beta} \tag{4.5}$$

where, X is a vector of covariates and β is a vector of parameters estimated from analysis of the ELF logbook data. The drivers of the decision whether to stay are based on the size or rate of the day's catch, the size of the reef and the fisher's propensity to stay or move.

This model can also be interpreted in terms of utility. The quantity $X^T\beta$ is the (fixed part of the) utility of staying compared to a utility of 0 for moving. When $X^T\beta > 0$, the fisher is more likely to stay than to move.

The natural way to analyse the data was to estimate the relevant parameters for the vessel dynamics model was using logistic regression. The data consisted of a set of occasions i on which decisions were made, and the outcomes Y_i of the decisions, where $Y_i = 1$ meant the fisher stayed on the same reef and $Y_i = 0$ meant they moved to a different reef. The last decision in each trip was omitted because it typically would be the decision to go back to port. This decision is parameterised and modelled differently (see Trip termination).

The decision to move Y_i was modelled statistically as binomial variates thus:

$$\begin{gathered} Y_i \sim \text{Binomial}(p_i), \\ \text{logit } p_i \equiv \log \frac{p}{1-p} = X\beta, \end{gathered} \tag{4.6}$$

where, X is now a matrix of known covariates, and β is a vector of parameters to be estimated. The logit function transforms probabilities $p \in [0, 1]$ onto the scale of the linear predictor $X\beta \in (-\infty, \infty)$. In this case, positive values of the linear predictor favour decisions to stay and negative values favour decisions to move. The above formulation is known as a generalised linear model (McCullagh and Nelder, 1983). It can be analysed by most statistical software packages. We used the `glm` function of S-Plus.

An exploratory analysis of the data was first performed to look for likely drivers of the stay/move decision. For example, Fig. 4.18 shows the vessels' decisions to move, Y plotted against the day's Coral Trout catch, with each vessel given a separate panel. It is typically quite difficult to detect patterns visually in binary data, so a preliminary fit to the data are plotted, with logit p fit to separate linear functions of catch for each vessel. The solid lines represent the estimated probabilities of staying and aid in the interpretation of the data.

It was first clear that vessel behaviour ranged from a tendency to stay (e.g., vessels 129, 236) to the opposite tendency, to move (e.g. vessels 9, 24, 28). Secondly, some vessels (e.g. 11, 17, 22, 55, 104, 129) had increasing probability of staying with increasing catch. This was the expected behaviour. Some vessels, however, showed the opposite behaviour (e.g. 5, 20, 25, 50, 236). This counter-intuitive result may have been a statistical accident for vessels with few data points (5, 7, 44, 53), especially since the confidence intervals on the fits were very wide. The result may have been accurate, or real, for those vessels with more data, possibly due to factors not included in the statistical model, such as Red Throat Emperor catch or reef perimeter. Interestingly the vessels showing the most convincing negative slope (20, 25, 50, 236) were also those with high Red Throat Emperor catchability compared to Coral Trout catchability (see Section *Fishing the reef*). This suggested that Red Throat Emperor catch might be a possible driver.

A third observation from the data was that for some vessels (e.g., 12, 53, 70) there was a range of catches that perfectly separated the ‘stay’ cases from the ‘move’ cases. This meant that the slope parameter tended to have a very large value and the estimates were unreliable; essentially the model was over-parameterised. An alternative approach was to model the vessel-dependent parameters as random effects, which provided more stable estimates. Instead of estimating separate parameters for each vessel, the parameters were regarded as samples from a gaussian population whose variance could be estimated. The model then became a generalised linear mixed model. Various software exist for such models: we used the S-Plus function `glmmPQL` (Venables and Ripley, 2000), which is based on penalized quasi-likelihood.

Before fitting the mixed model, the model space was first explored using generalised linear models (`glm` in S-Plus). A small set of drivers were considered in the covariate matrix. According to some fishers, the amount of catch determined whether they stayed on a reef; the higher the catch, the more likely they were to stay. If the reef was small, however, they may have decided to move in spite of reasonable catches because they expected the reef may have been fished down and so unlikely to produce good catches the following day. The degree to which these factors come into play may vary among fishers.

A statisitical model was considered of the form:

```
vessel * (ct_catch + rte_catch + perimeter + perimeter_local)
```
(4.7)

where, `perimeter` is the perimeter of the reef and `perimeter_local` is the available reef perimeter within a 5 nm radius, the putative range of a dory from its primary vessel. This model comprised vessel, catch and perimeter main effects and vessel by catch and vessel by perimeter interactions. This model was used as a starting point for a stepwise model selection algorithm.

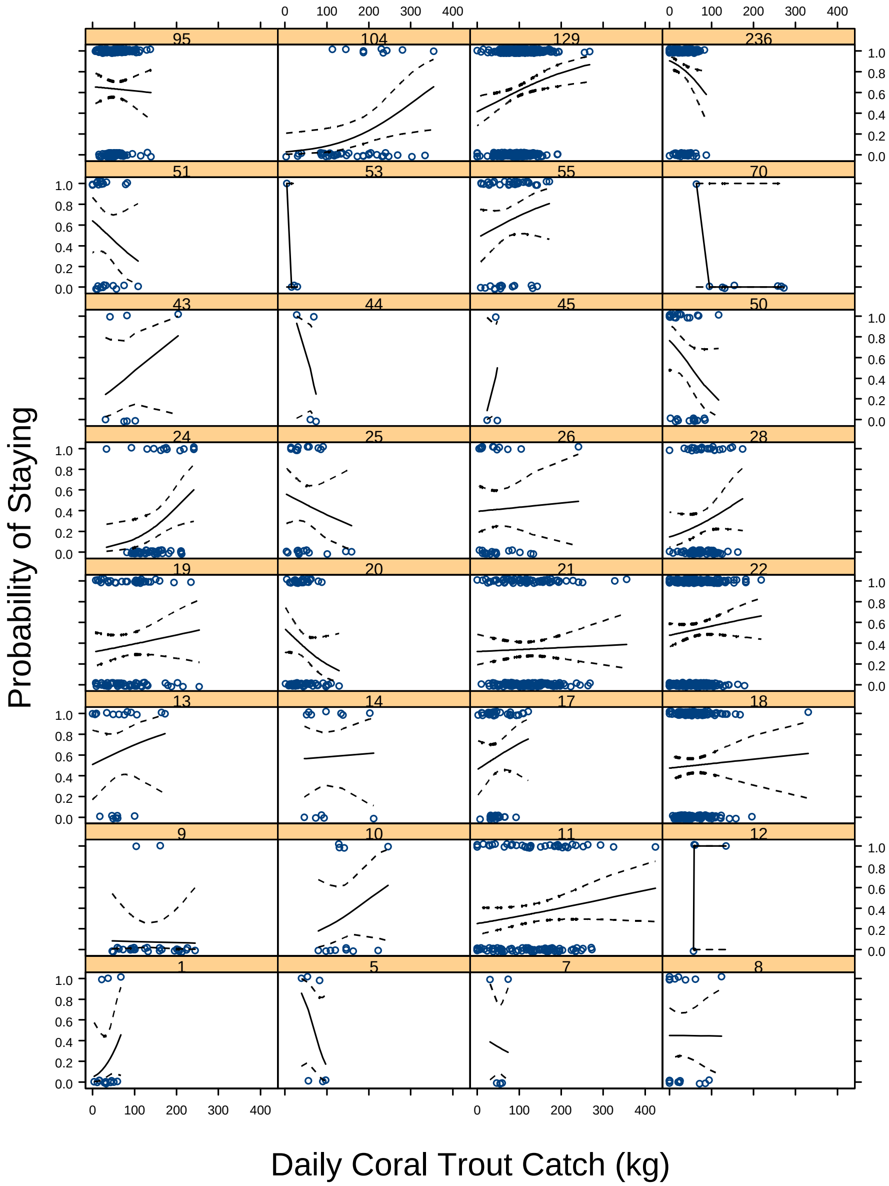


Fig. 4.18. The stay/move data, *Y*, (*small circles*) plotted against total daily catch of Coral Trout for each of 32 vessels (1, 5, 7, …, 236). The *Y* values have been jittered to avoid overplotting. Also shown are the fitted probability (*solid line*) and 95% confidence intervals (*dashed lines*) as fit by the model: logit *p* = catch * vessel.

In stepwise model selection, the current model is fitted to the data as a generalised linear model and a second model with either a single term deleted or a single term added is also fitted. The two models are then compared on their Akaike Information Criterion (AIC) and the model with the lower AIC becomes the current model. This procedure is repeated until no further improvement of AIC can be achieved within the allowed range of models (the model with a single intercept up to the two-way interaction model). The software used was `stepAIC` (Venables and Ripley, 2000).

The resulting model was a simple main effects model in `vessel`, `ct_catch`, `rte_catch` and `perimeter`. The coefficients for `ct_catch` and `rte_catch` were very similar, suggesting that they could be combined into total catch. An analysis of deviance comparison showed that the model with combined catch was preferred, and so was used for a mixed-effect analysis using `glmmPQL`.

Models were also considered in which catch was replaced by CPUE. Catch, however, had slightly more explanatory power than CPUE and so it was retained as a driver. The results of both the fixed-effect and random effect analyses are shown in Table 4.5. The fixed-effect model was fitted after omitting the degenerate cases (vessels 12, 53, 70). The average vessel effect was –1.0277, meaning that on a small reef with small catch the utility for staying would be negative and so the tendency would be to move. This made sense given skipper responses in the interviews. There was quite a sizeable variation in the vessel effect (standard deviation = 0.8186), which encompasses the range of behaviours seen in Fig. 4.18. The coefficients of catch and perimeter were positive (and significant) which also made sense.

The random effects model confirmed the result of the fixed effects model. This model constrained the vessel effects to a normal population whose standard deviation was estimated. Being more parsimonious, its estimates tended to be more accurate and it allowed the degenerate cases to be included, thus exploiting the full data set. The estimates were all very similar to those of the fixed-effect model. The vessel standard deviation was smaller, again because of the shrinkage effect usually seen with mixed-effect models

Table 4.5. Parameter estimates with standard errors for fixed-effect and random effects models.

Model	Parameter	Estimate	Std. Error
Fixed effects	Catch	0.0039	0.0008
	Perimeter	0.0098	0.0015
	Vessel mean	–1.0277	0.1472
	Vessel std. dev.	0.8186	–
Random effects	Catch	0.0032	0.0007
	Perimeter	0.0100	0.0014
	Vessel mean	–0.9306	0.1800
	Vessel std. dev.	0.6871	–

Implications for the vessel dynamics model

The vessel dynamics model has a population of vessels. Each vessel *v* in the population obtains a single random vessel effect γ_v by sampling from a normal distribution with mean 0 and standard deviation 0.6871. When the vessel has fished a reef *r* on day *d* with Coral Trout catch $C^v_{r,CT,d}$ and Red Throat Emperor catch $C^v_{r,RTE,d}$, it then computes the utility *U* given by:

$$U = \gamma_v + 0.0032\sum_s C^v_{r,s,d} + 0.01P_r - 0.9306 \tag{4.8}$$

where P_r is the reef perimeter. The vessel then chooses whether to stay on the reef for day *d*+1 with probability $p_{vrd} = e^U/(1 + e^U)$.

Choosing where to move

The discrete choice model

One of the classical ways to analyse decision behaviour is through discrete choice models. Such models are well established in the econometric literature (Manski and McFadden, 1981) and in the social sciences (Duncombe et al., 2003) and recently have been used to predict trip choice in the Hawaiian longline fishery (Pradhan and Leung, 2004).

The approach can be understood in terms of utility. At the end of every session, the skipper has to make a decision whether to stay at the same reef, move to a new reef or return to port. The idea of utility is that for each decision i, each choice (i.e., reef) j has a utility U_{ij} associated with it; the decision maker then makes the choice that maximises the utility.

Theoretical framework

Utility consists of fixed effects, characterising the systematic effects from known influences (such as distance to reef, bearing, expected CPUE, previous catch, reef perimeter, size of tide, prevailing winds etc), and random effects, representing unknown influences on the decision. Separating these components and writing the fixed effects as a linear predictor, gives:

$$U_{ij} = X_{ij}\beta + \varepsilon_{ij} \tag{4.9}$$

where, X_{ij} is a vector of covariates corresponding to the j-th choice of the i-th decision and β is a vector of choice influencing parameters to be estimated. The random component ε_{ij} is usually assumed to follow an extreme value distribution, so that $\Pr(\varepsilon_{ij} < x) = \exp(-\exp(-x))$.

A remarkable consequence of the utility formulation is that if the decision maker chooses the option that has maximum utility, then, from J_i distinct choices he will make choice j with probability P_{ij}, given by:

$$P_{ij} = \exp\left(X_{ij}\beta\right) \Big/ \sum_{k=1}^{J_i} \exp\left(X_{ik}\beta\right) \tag{4.10}$$

A consequence of this is that choices with similar fixed-effect utility have similar probabilities of being chosen, according with common sense.

By estimating the parameters of this model, the important factors affecting the decision making process can be determined. If the index i represents the decisions, then for each decision the skipper is presented with a set of choices $C_i = \{1, 2, \ldots, J_i\}$. The actual choice made for the i-th decision is $Y_i \in C_i$. If Y_i is multinomially distributed with $\Pr(Y_i = j) = P_{ij}$ given by (4.10), then the likelihood of the data Y, given the parameters β is simply the product of the probabilities:

$$L(Y \mid \beta) = \prod_{i=1}^{n} P_{i,\, j=Y_i} \tag{4.11}$$

The parameters β are estimated by maximizing $L(Y \mid \beta)$ with respect to β. This well-known procedure is called conditional multinomial regression, and can be solved using either the Cox proportional hazards model from survival analysis, the Poisson log-linear model or a non-linear regression model (see e.g. Chen and Kuo, 2001). We found the Poisson log-linear model to be the most convenient because it is a generalised linear model (GLM) and so is readily analysed by most statistical packages. Moreover, the process of model building and comparison is well set up in the GLM framework.

There is also the potential to expand the model to include random effects (over and above the random utility component ε_{ij}) such as vessel-specific behaviour. Random effects allow variation within the vessel population to be parameterised economically.

Example of discrete choice model for a single trip
To show the method in action, it is demonstrated for a single trip with clear directionality. The purpose of this demonstration is to show that the method provides reasonable results for a clear-cut case. The trip (Fig. 4.19) consists of 27 decisions made over 13 days: 7 of these decisions were to stay on the current reef; the remaining 20 decisions resulted in short move generally on a bearing roughly 60°W.

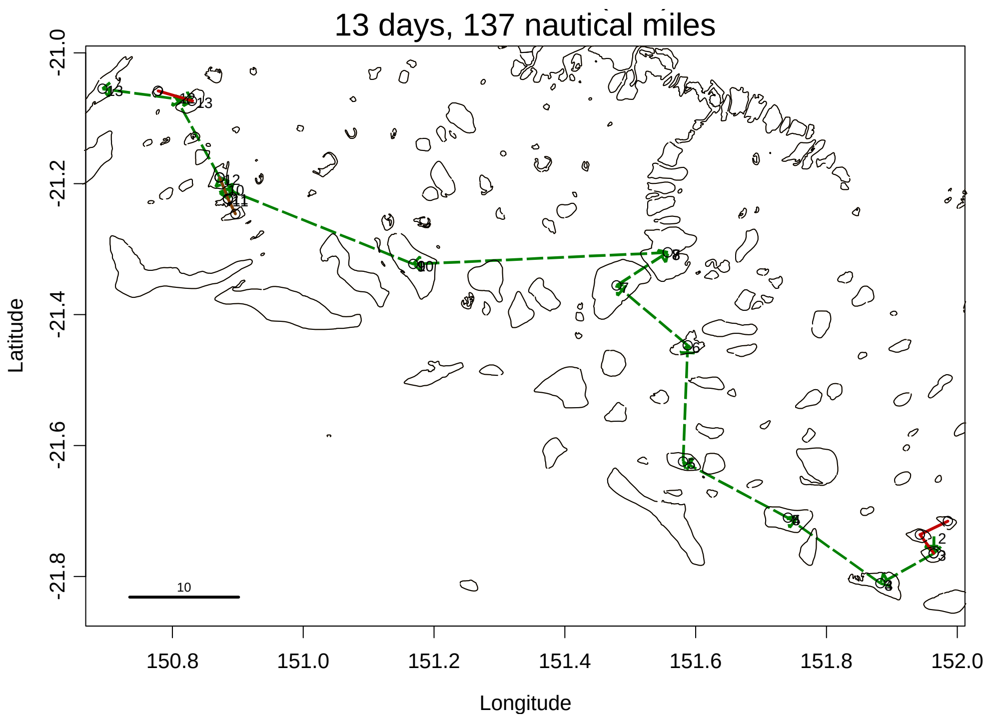


Fig. 4.19. A single trip lasting 13 days with 20 moves. Movement is represented as going from reef centroid to reef centroid. Multiple reefs fished in the same session are linked with red lines.

Since all the distances moved were short, it was natural first to consider distance-to-reef as a predictor, i.e. $X_{ij} = d_j$, distance to *j*-th reef for decision *i*. The coefficient of this term would be expected to be negative, meaning that closer reefs are favoured over more distant reefs, and indeed the estimate was –0.19 with standard error 0.03. This meant in practice that the probability of moving to a reef reduced by a factor exp(–0.19) = 0.83 for every nm more distant that reef was from the current reef.

This first model was isotropic, and would predict a random walk through the reefs. A next step in the modelling was to account for directionality, and so a second model was fitted that included a directional component. The fixed-effect vector thus became $X_{ij} = \left(d_j, d_j \cos\theta_j, d_j \sin\theta_j\right)$, where θ_j was the bearing to reef *j* from the current reef. The resulting estimates are presented in Table 4.6.

Table 4.6. Parameter estimates with standard errors for fixed-effect and random effects models.

Effect	Estimate	Std. Error	P-value
d_j	–0.288	0.051	$<10^{-7}$
$d_j \cos\theta_j$	0.053	0.050	0.29
$d_j \sin\theta_j$	–0.104	0.044	0.017

A likelihood ratio test showed the addition of the directional terms (in combination) was significant at the 5% level, confirming that the trip was not the result of a random walk. The value of the linear predictor was thus written as:

$$X_{ij}\beta = d_j\left[-0.288 + 0.117\cos\left(\theta_j + 63^\circ\right)\right] \tag{4.12}$$

implying that reefs in the direction of 63°W were favoured relative to reefs in the opposite direction. The relative size of the coefficients 0.288 and 0.117 indicated the relative importance of the isotropic and directional components. Direction was important, but distance was the most significant driver of choice of destination reef.

Fig. 4.20 shows the results of simulations using the model estimated from this trip. The simulated trips showed directionality along the reef but they did not exactly retrace the original trip because the outcomes of decisions at each reef were not deterministic.

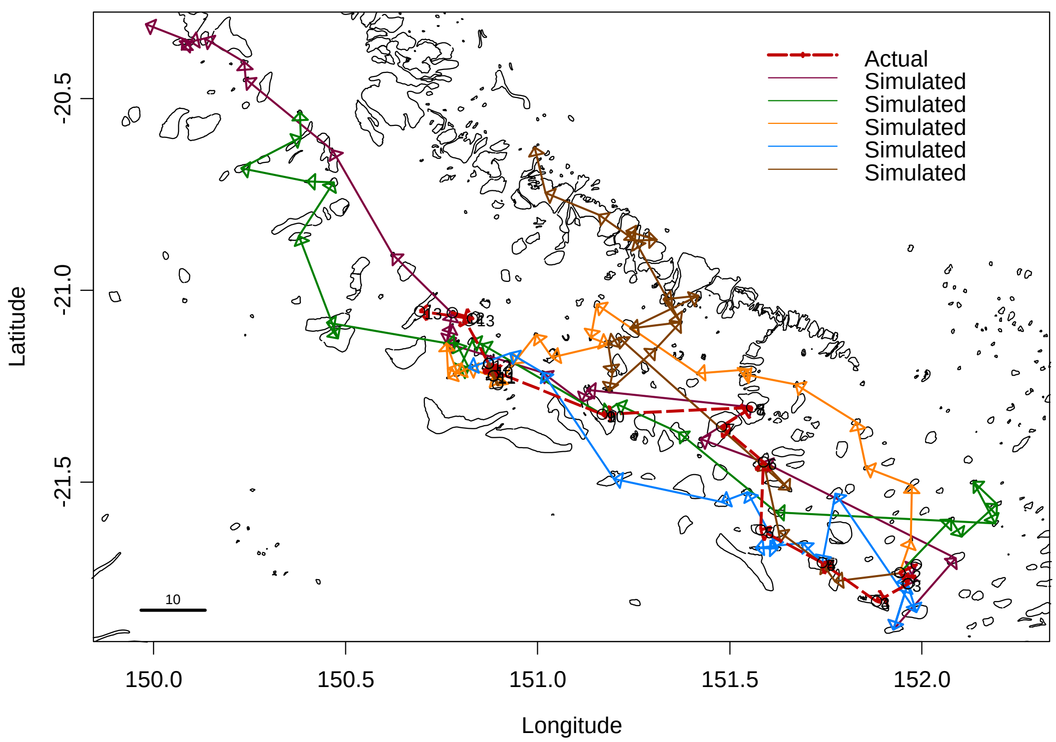


Fig. 4.20. Simulations of 5 trips using distance and bearing parameters from the trip in Fig. 4.19 (shown here as the red dashed line).

Implementation
In order to use the GLM framework a data set was needed consisting not only of the choices that were made (the movements in the ELF logbook data) but also the potential choices that were not made. This augmented data set consisted of sets of decisions labelled by a variable `id`. For each decision there were 10 candidate reefs: the reef that was actually chosen, and 9 other reefs, which were not chosen, randomly sampled from within the horizon *D*. (The estimates did not differ markedly using only 20 candidate reefs.) A logical variable called `chosen` marked those reefs that were actually chosen.

The S-Plus code to implement the above single-trip example looked like this:

```
glm(formula=chosen~dist+dist:cos(bearing)+dist:sin(bearing)+id,
   family=poisson, data=move)
```
(4.13)

The first three terms on the right-hand side of the formula are of interest.

The last term, `id`, called a nuisance parameter must be included in the formula (and therefore be estimated), but is of no interest as it represents a normalizing constant for each decision. In the case of the single trip with 15 decisions, this term adds 15 columns to the design matrix and so 15 parameters were estimated. When doing a combined analysis of all trips, however, the `id` term proves to be a real nuisance because it expands the design matrix to over a 1000 columns.

Model exploration and selection
The above single-trip example indicated that the discrete choice model made sense and produced reasonable results. Rather than describe each trip individually, however, we wanted to make broad statements about the behaviour of the fleet as a whole and generalise behaviour to vessels that were not represented in the ELF logbook data. This was done by fitting each trip to a simple model and looking for broad patterns in the coefficients.

The simple model considered was a main effects model in which three extra terms were introduced: the square root of the reef perimeter, the expected Coral Trout CPUE and the expected Red Throat Emperor CPUE on the candidate reef:

```
glm(formula=chosen~dist+dist:cos(bearing)+dist:sin(bearing)+sqrt.perimeter+CT
    +RTE+id,family=poisson, data=move)
```
(4.14)

This model was fitted to 216 trips. Figure 4.21 is a scatterplot matrix of the *t*-values for the model fits. The number of movement decisions for single trips ranged from 1 to 15 (Fig. 4.22). Because this was an augmented data set consisting of reefs that were chosen by the fisher as well as reefs that were not chosen by the fisher, it was possible to estimate all 6 parameters in a single-decision trip. The *t*-values typically were rather small, however (Fig. 4.21) but show possible effects that could be more precisely defined in an analysis that combined all the trips.

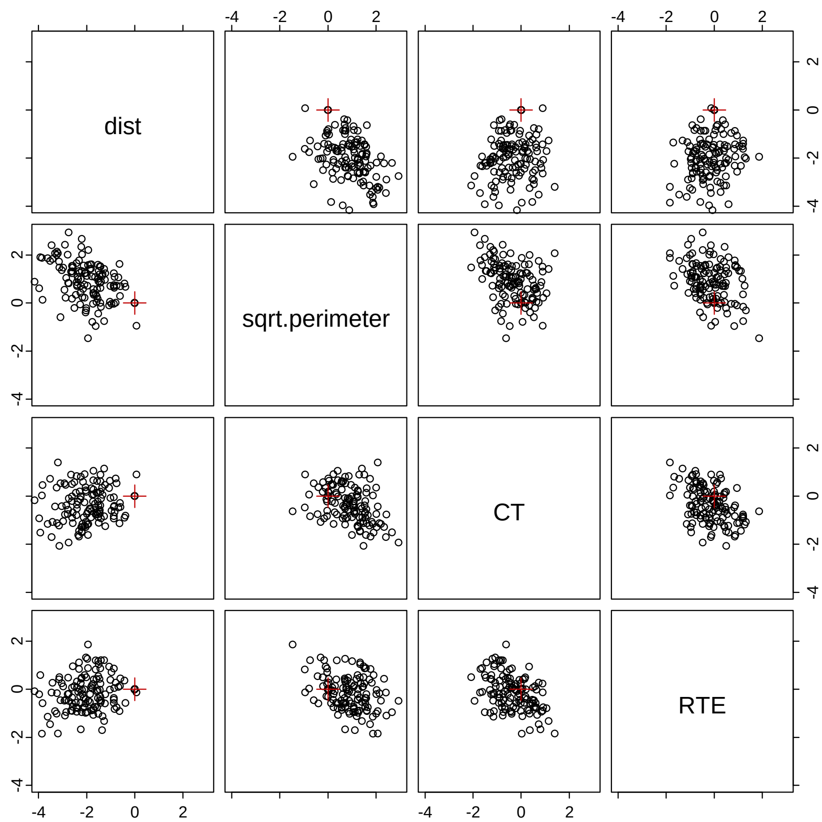


Fig. 4.21. Matrix scatterplot of *t*-values for the 6-parameter main effects model for all trips fitted separately. All axes are on the same scale. The origin is marked by a red cross.

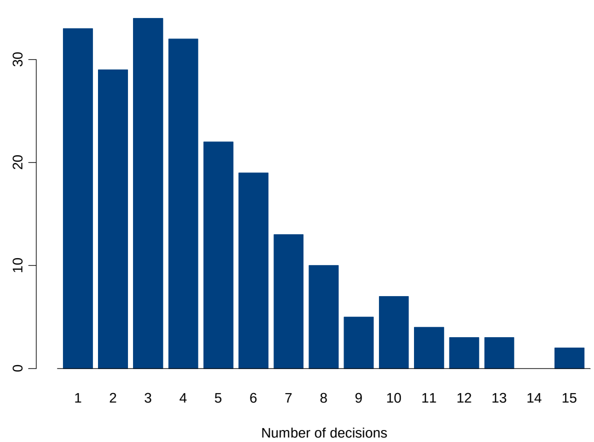


Fig. 4.22. Frequency histogram of the number of movement decisions made per trip.

The scatterplot cloud was centred away from the origin for the distance and perimeter coefficients. This suggests that there was a real distance and perimeter effect whose estimates would be sharpened in a combined analysis. The CPUE terms did not appear to be significant at the individual trip level, although there was a suggestion that they may have been negatively correlated.

The conclusion from Fig. 4.21 was that the distance from the current reef and the destination reef perimeter were important terms that ought to be included in the discrete choice model. Other terms should be explored but may turn out not to have detectable effects.

For the combined analysis, the augmented movement data set (including candidate destination reefs not chosen) was the entire set of decisions for all vessels over all trips meaning that factors such as `vessel` and `trip` and how they interact with other terms had to be considered. It was expected that the directional components depended on trip because a trip may have had a preferred direction, and that different trips may have had different directions, even if they were carried out by the same vessel. The distance component represented the cost of travelling. This could be a global term common to all fishers, perhaps dependent on the price of fuel. Alternatively, it could be a preference of the skipper and so a vessel-dependent term. A model with constant distance coefficient (assuming fixed price of fuel in the absence of economic data) was considered and an alternative with a vessel-dependent distance coefficient was also considered. A comparison of these models using a likelihood ratio test showed that the vessel-dependent model was warranted.

The statistical models explored therefore were of the form:

```
glm(formula=chosen~vessel:dist+sqrt(perimeter)+trip:dist:cos(bearing)+
    trip:dist:sin(bearing)+id+other terms, family=poisson, data=move)
```
(4.15)

The coefficient of the perimeter term was always positive and significant. This implied that fishers preferred to go to larger reefs. The square root transformation of perimeter mitigated this somewhat by diminishing attractiveness of larger reefs, which seemed sensible because beyond a certain size the actual size of the reef should matter less.

The ‘other terms’ we investigated were quarterly CPUE of Coral Trout and of Red Throat Emperor. A significant CPUE effect could not be detected for any of the models that were examined (e.g., distance main effect, distance by vessel interaction, perimeter effect, no perimeter effect, no directional terms). This may have been because the CPUE, being dependent on imputation where no effort data existed, was poorly estimated from the commercial data. Fishers’ CPUE expectations were also hard to quantify, and our computation of CPUE may have been only indirectly related to what was driving their decisions. A reef-tide-wind behaviour was also examined by including perimeter by tide and perimeter by tide by wind interactions, the effects were not significant and were dropped from analyses.

When CPUE was replaced with catch in the model a significant effect was seen for fleet catch in the same month as the movement decision recorded in the ELF logbook data. When the fleet catch from the previous month was also used, the significant effect remained.

Various powers of the catch were tested and again a square root transformation had more explanatory power than the alternatives. Because the catch was assigned to reefs from the gridded commercial data in proportion to perimeter, perimeter and catch terms were highly correlated, and the perimeter term could be dropped from the model.

Vessel dependency was also examined. Because having a separate catch term for each vessel would over-parameterise the model, vessel dependence was introduced through the vessels’ log catchabilities. The rationale was that a ‘good’ Coral Trout catcher might be more influenced by high Coral Trout catches than a ‘poor’ catcher. Therefore an interaction term was included:

```
log(q_v,CT):sqrt(CT_catch)
```
(4.16)

for Coral Trout and a similar term for Red Throat Emperor.

The preferred set of models investigated were of the form:

```
glm(formula = chosen ~ vessel:dist + trip:dist:cos(bearing) +
trip:dist:sin(bearing) + id + other terms, family=poisson, data=move)
```
(4.17)

where the other terms were of the following forms:

```
Model h: sqrt(CT_catch)
Model d: sqrt(CT_catch) + sqrt(RTE_catch)
Model f: sqrt(CT_catch) + log(q_v,CT):sqrt(CT_catch)
Model g: sqrt(CT_catch) + log(q_v,CT):sqrt(CT_catch) + sqrt(RTE_catch)
Model e: sqrt(CT_catch) + log(q_v,CT):sqrt(CT_catch) + sqrt(RTE_catch) +
         log(q_v,RTE):sqrt(RTE_catch)
```

ANOVA sequences of these models showed:

	Resid.Df	Resid.Dev	Test	Df	Deviance
h	7972	1734.993			
f	7971	1731.526	+log(q_v,CT):sqrt(CT_catch)	1	3.466766
g	7970	1731.266	+sqrt(RTE_catch)	1	0.260117
e	7969	1731.264	+log(q_v,RTE):sqrt(RTE_catch)	1	0.002263

meaning adding `log(q_v,CT):sqrt(CT_catch)` was interesting, but adding the RTE terms was not, and:

	Resid.Df	Resid.Dev	Test	Df	Deviance
h	7972	1734.993			
d	7971	1734.063	+sqrt(RTE_catch)	1	0.930194
g	7970	1731.266	+log(q_v,CT):sqrt(CT_catch)	1	2.796689
e	7969	1731.264	+log(q_v,RTE):sqrt(RTE_catch)	1	0.002263

meaning much the same, although the effect of the `log(q_v,CT):sqrt(CT_catch)` was diluted by the RTE term. The AIC was also computed and found Model f had the smallest value, 4589.5, whereas Model h had an AIC of 4591.0. The coefficients for Model f were:

Value	Std.	Error	t-value
sqrt(CT_catch)	0.108531178	0.008133209	13.344201978
log(q_v,CT):sqrt(CT_catch)	0.041126969	0.022001442	1.869285144

and for Model h were:

Value	Std.	Error	t-value
sqrt(CT_catch)	0.111745516	0.007993381	13.979756456

Model h was the more parsimonious model, and the evidence for Model f was slight with a small *t* value (1.869, p=0.156) and only a moderate deviance change (3.466), but the AIC value supported retaining the interaction term. This would mean good Coral Trout catchers (`log(q_v,CT)` = 1) would have a Coral Trout catch coefficient 0.11+0.04 = 0.15 and poor catchers (`log(q_v,CT)` = –1) would have a coefficient 0.11–0.04 = 0.07.

Discounted catch

These models have so far assumed that the total fleet catch was known to each fisher. In reality, each fisher would be uncertain of the total fleet catch and would instead have some kind of estimate of it based partly on his own experience and partly on external, typically historical, information. The vessel dynamics model in ELFSim, which uses the results of these analyses to simulate individual vessel behaviour, assumes that the estimate of total fleet catch is updated as new information is obtained by the fleet. New information is weighted by a discount factor of 0.15; to give what is termed the discounted catch. The discounted catch $C_{y,m}^{\text{dis}}$ for month *m* in year *y* is defined as

$$C_{y,m}^{\text{dis}} = 0.15 \times C_{y,m}^{\text{act}} + 0.85 \times C_{y-1,m}^{\text{dis}} \tag{4.18}$$

where $C_{y,m}^{\text{act}}$ is the actual catch in year *y*, month *m*. Note that the new discounted catch is based on the discounted catch in the same month of the previous year. Since the fishers have access to discounted rather than actual catch, the statistical models used to parameterise the ELFSim vessel dynamics model must be adjusted to use discounted catch. In consideration of the different ways discounted catch could be calculated, both previous month's and year's discounted catch were included in the utility.

The models investigated now had 'other terms' of the following forms:

```
Model f1:  sqrt(DCT_catch_y) + log(q_v,CT):sqrt(DCT_catch_y)
Model f2:  sqrt(DCT_catch_m) + log(q_v,CT):sqrt(DCT_catch_m)
Model f12: sqrt(DCT_catch_y) + log(q_v,CT):sqrt(DCT_catch_y) +
           sqrt(DCT_catch_m) + log(q_v,CT):sqrt(DCT_catch_m)
```

with `_y` denoting previous year and `_m` denoting previous month. The coefficients for these models were

Model	Parameter	Value	Std. Error	*t*-value
F1	sqrt(DCT_catch_y)	0.180	0.026	6.96
	log(q_v,CT):sqrt(DCT_catch_y)	0.160	0.064	2.49
F2	sqrt(DCT_catch_m)	0.188	0.027	7.07
	log(q_v,CT):sqrt(DCT_catch_m)	–0.011	0.060	–0.19
F12	sqrt(DCT_catch_y)	0.116	0.029	3.97
	sqrt(DCT_catch_m)	0.142	0.030	4.72
	log(q_v,CT):sqrt(DCT_catch_y)	0.183	0.071	2.56
	log(q_v,CT):sqrt(DCT_catch_m)	–0.028	0.063	–0.45

These results suggested that both previous month's and year's discounted catches were important drivers, but that the interaction with catchability was only important for the previous year's catch. That is, 'good' Coral Trout catchers weighted last year's catch higher than 'poor' Coral Trout catchers. Likelihood ratio tests showed that model `f12` was strongly preferred to both the simpler models, implying that the model captured behaviour that neither `f1` nor `f2` would capture alone. It was interesting that the coefficients for the catch term in models `f1` and `f2` were very similar (about 0.18), perhaps because the two catch terms were fairly highly correlated ($\rho = 0.5$). Note, however, that the sum of the coefficients in the combined model (0.26) was greater than 0.18, again indicating that the model explained more than either `f1` or `f2` could alone.

Another important observation was that the strength of the response in these discounted catch models was stronger than in the non-discounted catch models (`f`, `h`), i.e. the coefficients were higher, although the evidence was weaker (the *t*-values smaller). Since the discount factor for the current month's catch was quite small (0.15), discounted catch was effectively a long-term average. The relatively large coefficient therefore suggested some conservatism in behaviour, in which fishers tended to visit reefs that historically had high catches. The smaller *t*-values indicated the presence of contingent or short-term behaviour not captured by the model due to the lack of a sufficiently responsive covariate.

Geographic terms

Many skippers reported that they have a tendency to keep travelling in a general direction during a trip. This is additionally supported by reports, especially from 'live' boats, that they will head upwind at the start of a trip so as to catch and return to port with the wind (and waves) behind them to increase survival of their catch. The geographic terms considered for reef selection involved distance and bearing. A separate coefficient of distance γ_{1v} was estimated for each vessel *v*. These coefficients were always negative. The two (trip-level) directional coefficients γ_{2t} and γ_{3t} could be interpreted as a preference for going east and north and could be combined more conveniently into a preferred direction ϕ_t, and a magnitude of preference δ_t, where

$$\gamma_{2t} = \delta_t \cos(\phi_t), \gamma_{3t} = \delta_t \sin(\phi_t) \tag{4.19}$$

The ratio δ_t/γ_{1v} determined how marked was the directional preference on a trip. Fig. 4.23 shows the estimates δ_t *vs* $|\gamma_{1v}|$ on the log scale. The distributions were fairly irregular, partly because some parameters were very poorly estimated, had very small *t*-values and so were considered unreliable. These are indicated by the smallest circles in the graph. The more reliable estimates form a cluster in the lower left part of the graph. These were characterised by taking their median and *mad* (median absolute deviation) estimators (the robust counterparts of the mean and standard deviation). The values for the median were (–1.38, -2.10) and for the mad (0.47, 0.78). The correlation between them on the log scale was 0.63. The crosses show a sample from a bivariate normal distribution with the properties given by the above robust estimators. In the vessel dynamics model, the geographic parameters would be generated from such a distribution.

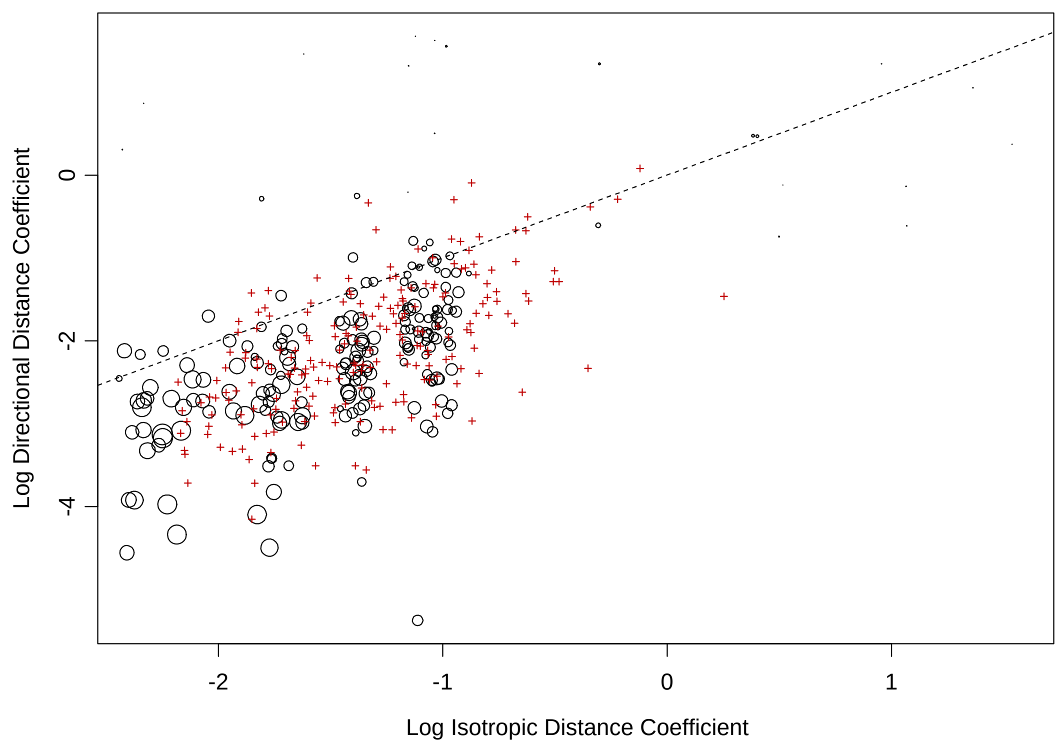


Fig. 4.23. Scatterplot of directional (δ) *vs* absolute distance (γ_{1v}) coefficients on the log scale (*circles*). The area of the circles is inversely proportional to the standard error of the directional estimate. The γ_{1v} values are jittered for clarity. The red crosses are a random sample from a bivariate normal distribution with properties similar to the estimated parameters. The dashed line corresponds to $\delta = \gamma_{1v}$.

Implications for the vessel dynamics model

The probability $P_{ij,vtd}$ that vessel *v* on trip *t* to move from reef *i* to reef *j* on day *d* (given that a decision to move has been made) is:

$$P_{ij,vtd} = \exp\left(Z_{ij,d}^{T}\gamma_{vt}\right) \Big/ \sum_{k=1}^{J(i,v)} \exp\left(Z_{ik,d}^{T}\gamma_{vt}\right) \tag{4.20}$$

where, $Z_{ij,d}$ is a vector of covariates, γ_{vt} is a vector of estimated parameters influencing the choice of destination reef, and *J*(*i*,*v*) is the set of candidate reefs.

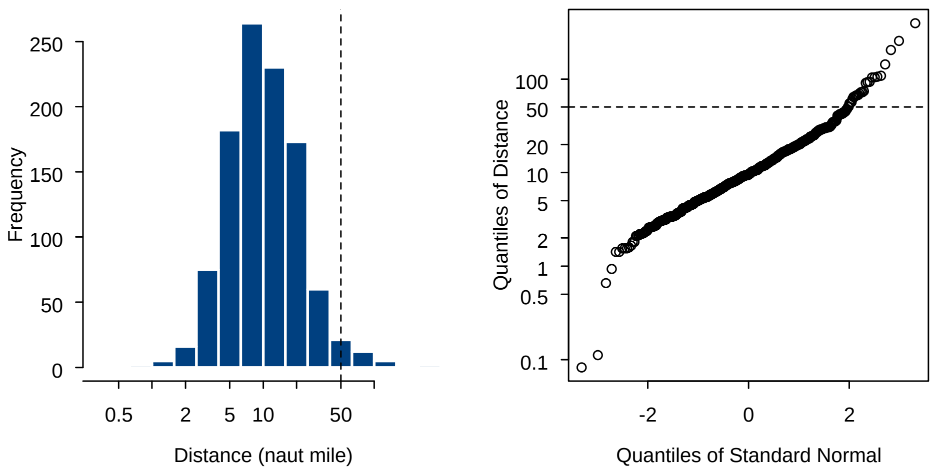


Fig. 4.24. Histogram and q-q plot of daily distance (excluding zero distance). The dashed line indicates the chosen cut-off horizon of 36 nm.

The set of candidate reefs *J*(*i*,*v*) depends on reef *i* (the current reef) with the potential destination reefs (*j*) filtered through a simple distance threshold (*D*) with reefs further away than some fixed distance being excluded. The destination distance cut-off conceptually relates to the expected limit that a skipper would be expected to steam to a new reef during normal operations. The value *D* = 36 nm was used and obtained by looking for the beginning of the 'tail' of the distribution of daily movement distances, as indicated by a kink in the quantile-quantile plot (see Fig. 4.24). *J*(*i*,*v*) also depends on vessel *v* through avoidance behaviour gleaned from the interview data since some reefs would be avoided if the number of competing vessels h_r already on that reef exceeded a threshold H_v. Formally, the candidate set is defined as follows:

$$J(i,v) = \left\{ r : d_{ir} < D \text{ and } h_r < H_v \right\} \tag{4.21}$$

The preferred utility term for vessel *v*, in trip *t*, on reef *r* and day *d* to move from reef *i* to reef *j* on day *d*+1 is:

$$\begin{aligned} Z_{ij,d}^{T}\gamma_{vt} = {} & \gamma_{1,v}\, d_{i,j} + \delta_v d_{i,j}(\cos\phi_{v,t}\cos\theta_{i,j} + \sin\phi_{v,t}\sin\theta_{i,j}) + \\ & \sum_s \left(\gamma_{4,s}\sqrt{\tilde{C}^{\text{dis},v}_{y-1,m,j,s}} + \gamma_{5,s}\sqrt{\tilde{C}^{\text{dis},v}_{y,m-1,j,s}} + \gamma_{6,s}\ln(q_{v,s})\sqrt{\tilde{C}^{\text{dis},v}_{y-1,m,j,s}} + \gamma_{7,s}\ln(q_{v,s})\sqrt{\tilde{C}^{\text{dis},v}_{y,m-1,j,s}} \right) \end{aligned} \tag{4.22}$$

where

d_{ij} is the distance from reef *i* to reef *j*;

θ_{ij} is the bearing from reef *i* to reef *j*;

$\tilde{C}^{\mathrm{dis},v}_{y-1,m,j,s}$ is the discounted catch of species *s* in the previous year on reef *j* for vessel *v;*

$\tilde{C}^{\mathrm{dis},v}_{y,m-1,j,s}$ is the discounted catch of species *s* in the previous month on reef *j* for vessel *v*; and $q_{v,s}$ is the catchability of species *s* for vessel *v*.

The parameters of Equation 4.22 were estimated (Table 4.7) using the fleet wide discounted catch (Equation 4.18). Operationally, in the vessel-specific simulation context, the discounted catches used are derived from the simulation model. Although our previous analyses showed that catches of Red Throat Emperor did not have a discernible contribution to the utility, we chose to retain this species effect because of the multi-species nature of the fishery, and because our interactions with fishers, including from the interviews, indicated that catch, including of Red Throat Emperor, influenced their decision-making. The directional parameters were more conveniently expressed in the vessel dynamics model using δ_v and ϕ_t (see Table 4.7), and log $-\gamma_{1v}$ and log δ_v were set to be bivariate normal. The parameter ϕ_{vt} is the preferred bearing for the trip *t*. This generally should be along the coast in the north and mid sections of the GBR, but in the south of the GBR the directions are more isotropic, depending on the starting point of the trip.

Table 4.7. The covariates and parameters for reef choice decision. Coefficient 1 depends on vessel *v*; coefficients 2 and 3 depend on trip *t*; and coefficients 4, 5, 6 and 7 are constants for all vessels and trips. See also Table 4.10.

	Covariate X_i	Units	Form	Parameter Estimates	
1	d_{ij}	naut mile	γ_{1v}	log $-\gamma_{1v}$ ~ $N(-1.37, 0.53)$ log δ_t ~ $N(-2.42, 0.90)$	
2	$d_{ij}\cos\theta_{ij}$	naut mile	$\gamma_{2t} = \delta_t \cos\phi_{vt}$	Corr(log $-\gamma_{1v}$, log δ_t) = 0.72 ϕ_{vt} along coast in north and	
3	$d_{ij}\sin\theta_{ij}$	naut mile	$\gamma_{3t} = \delta_t \sin\phi_{vt}$	mid, isotropic in south	
				CT	RTE
4	$\sqrt{C^{\mathrm{dis}}_{y-1,m,j,s}}$	$Kg^{0.5}$	$\gamma_{4,s}$	0.032467	0.004509
5	$\sqrt{C^{\mathrm{dis}}_{y,m-1,j,s}}$	$Kg^{0.5}$	$\gamma_{5,s}$	0.032316	0.028214
6	$\log(q_{v,s})\sqrt{C^{\mathrm{dis}}_{y-1,m,j,s}}$	$Kg^{0.5}$	$\gamma_{6,s}$	0.025259	-0.039765
7	$\log(q_{v,s})\sqrt{C^{\mathrm{dis}}_{y,m-1,j,s}}$	$kg^{0.5}$	$\gamma_{7,s}$	0.038902	0.033773

Termination of a trip

Trip lengths in the vessel dynamics model are determined by random selection from a set of candidate trip lengths (in days) at the beginning of each simulated trip. The range of candidate trip lengths was estimated from interviews, ELF logbook and QDPI&F compulsory logbook data. Each simulated trip is terminated simply when it finishes the last day of its designated duration.

4.4 Vessel dynamics model

A vessel dynamics module, TRIPSim (fishing Trip Simulator), was developed to operate within ELFSim and simulate the movement, reef selection processes, and fishing activities of individual vessels in the commercial reef line fishery of the GBR. The basic approach is to simulate vessel behaviour and hence effort dynamics using an agent-based model. Agent-based models attempt to determine the combined behaviour of a collection of individuals (Uchmański and Grimm 1996, Grimm 1999, Lempert 2002). Individual vessels within TRIPSim operate based on their own perspective and accumulated knowledge using models of their decision-making processes parameterised from interview, ELF voluntary logbook and QDPI&F compulsory logbook data. Agent-based models are particularly effective when the number of agents is small, agents show non-uniform behaviours and the combined behaviour of individuals exhibits characteristics that are not easily identified by more aggregated models. The agents in the TRIPSim model are primary vessels, each with fishing power (effort) that takes into account their associated dories. These agents:

- have heterogeneous characteristics;
- have different spatial, efficiency and behavioural attributes;
- make decisions based on rules;
- interact with other agents;
- learn from past experiences; and
- use information from a range of external sources.

TRIPSim operates on a daily time-step within each monthly time-step at which the remainder of ELFSim operates. Through TRIPSim, effort, measured as the number of dory-days (one fisher per dory), has the ability to dynamically respond to daily changes in fishing conditions (e.g. CPUE on individual reefs) and management arrangements (e.g., area and seasonal closures). It incorporates the facility for fishers to exchange information and learn from past experience, as well as overcomes some of the criticisms levied at earlier attempts at ecologic-economic modelling described by Nijkamp (1987) by not constraining future effort to historical patterns and by concentrating on individual fisher behaviour.

At present, only the commercial reef line fleet is modelled using this model as it has not yet been feasible to parameterise the model for either the charter or recreational fleets. The effort dynamics of the latter two fleets are therefore managed using the original Effort Allocation module in ELFSim (see Section 4.1, Mapstone et al. 2004).

Consistent with previous work on effort dynamics, the vessel dynamics model is based on the concept of utility, as specified by an objective function constructed using the results of analyses of the historical QDPI&F catch and effort data and additional information about fishing behaviour, motivation and information sharing obtained from previous and ongoing ELF Project tasks and the interviews (see Section 4.2 above). Fishers are assumed to distribute their effort to maximise their perceived utility. This utility is not based on *a priori* assumptions (such as fishers are rational and optimally maximise their profits), but rather on observed and survey-elucidated behaviour. At each daily time step after a vessel has left port and started fishing a decision is made whether to stay on the currently occupied reef for another day or move to another reef. Whether a vessel stays on a reef is related to the size of the reef and the catch realised from that reef during the current day. If not staying, the key elements for selecting the next reef are: (1) travel time (or its surrogate travel distance); (2) bearing to the next reef relative to the general direction of travel within a trip; (3) size of the potential destination reef; (4) presence of other commercial vessels on a potential destination reef (which also depends on reef size); and (5) catch expected at each potential destination reef based on prior experience by the vessel and the fleet. TRIPSim incorporates data sharing among vessels and progressive discounting of historical catches, with more recent experiences and personal information being more important than historical information or fleet-wide experience when making decisions. Catch expectations therefore are specific for each vessel for each reef for each month of the year and are ‘learnt’ by the fishers or ‘forgotten’ if a reef is not visited for some time.

Figure 4.25 gives an overview of the decision processes and interaction between TRIPSim and the other components of ELFSim. ELFSim provides the outer framework controlling the simulations into the projection period, maintaining the biological populations on individual reefs, and supervising management strategies under examination. When the program is started, raw data are read from background database tables and GIS shape files and variables are initialised. In the projection period, ELFSim runs the biological operating model and reef management model in accordance to the management strategies being investigated. At the end of each month ELFSim passes control to TRIPSim with the current status of the populations on each reef. TRIPSim then runs through its daily cycles, selects reefs on which to fish, catches fish, and provides, as feedback, a measure of the amount of effort the fleet expended on each reef for the month.

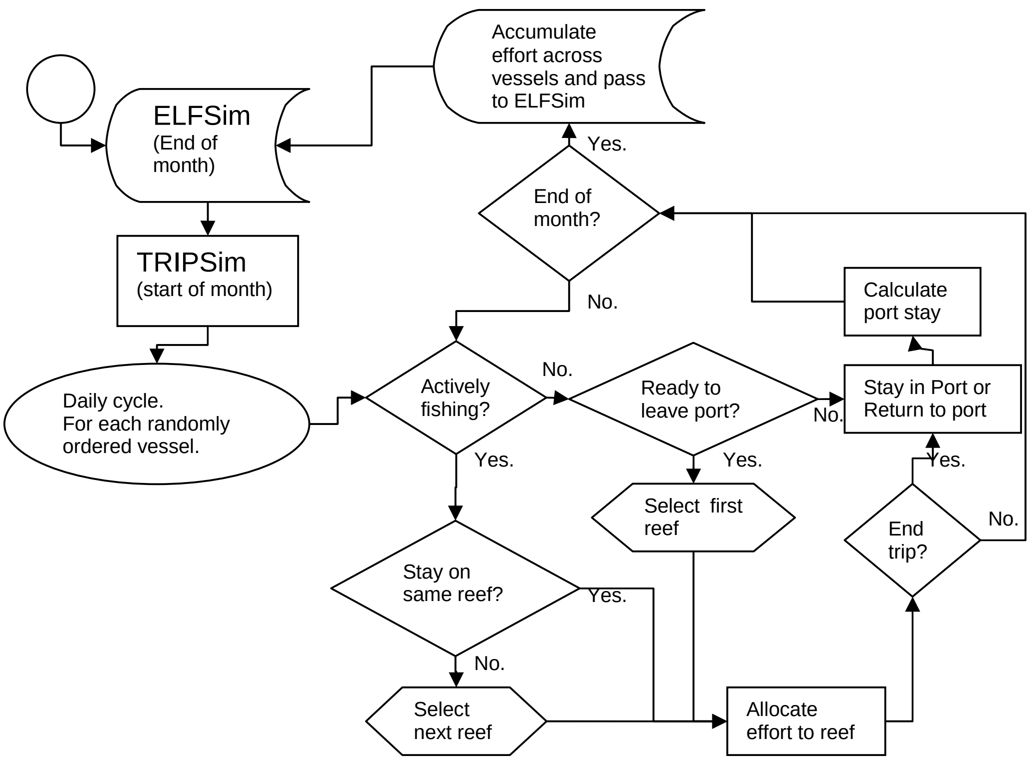


Fig. 4.25. Decision processes within the vessel dynamics module.

Give a total amount of effort to allocate the vessel dynamics model involves the following steps:

1. Determine the number of vessels and assign them characteristics;
2. Schedule trips for each vessel, accounting for the known seasonal pattern of effort and possible seasonal closures;
3. Determine the first reef to be fished for each trip and how each vessel’s movements respond to behavioural factors and abundance.

4.4.1 Data sources

Three primary data sources were used to develop and parameterise the model: (1) compulsory logbook records from the commercial fleet; (2) ELF voluntary logbooks from the commercial fleet; (3) fisher interviews (Section 4.2). The commercial and ELF experimental logbook data were the primary sources of data for model parameterization (see Section 4.3).

4.4.2 Vessel characterisation

Vessel characteristics

The characteristics of the boats that were in the fishery in 2005 following the implementation of the catch quota system by QDPI&F were used to define the simulated fleet for inclusion in TRIPSim. As a result, the fleet for the ELFSim simulations consisted of 411 commercial reef line fishing vessels. The effort expended during 1996 by the fleet (~80,000 dory-days) was used as a benchmark for the MSE evaluations. Fishing trips were scheduled based on historical monthly trip data contained in the database to capture the seasonal distribution of fishing effort, as specified in detail below.

The QDPI&F registration data also provided information on the number of dories attached to a licence, vessel size, and some detail regarding frequency of using ports (including ports other than the home port) for offloading catch. Other attributes such as trip length and number of days fished per year were obtained for 406 anonymous vessels from CFISH data on trip schedules. This data set was used to calculate the average trip lengths per vessel per year and the average number of days fishing per year based on the assumption that trips were demarcated by 2 or more days on which no catch was recorded in the compulsory logbooks. (Most available logbook records from the CFISH database were for days when catch was reported and so days in port were not identified explicitly.) Dummy identification numbers were randomly assigned to the 406 vessels and their trip and fishing characteristics then transferred to 406 of the 411 vessels to be used in the model. The remaining five vessels were each assigned the averages of the statistics. The trip length, home port, number of trips per year and average number of days in port between trips all were vessel specific parameters. The number of dories assigned to a vessel was adjusted prior to initialisation to ensure that the effort under average conditions equalled that for 1996. The resultant vessel characteristics are summarised in Table 4.8

Table 4.8 Characteristics of the commercial reef line fishing fleet used in TRIPSim.

Number of vessels	411
Average yearly effort per vessel (line days)	189.8
Average number of dories	2.0
Average dory units (includes dories and mother boat)	2.6
Average trip length (days)	5.4
Average days at sea (per year)	75.5
Average trips per year	14.1
Average vessel length (m)	10.5

It should be noted that there is no direct link between individual ‘vessels’ in the model and the actual vessels in the fishery. The vessels in the model are simply agents used to manipulate fishing effort, parameterised to reflect the range of vessel types and behaviours in the CRFFF. Thus, correctly parameterised, the results will provide insights to the likely implications of actual management arrangements.

Ports and port associated fishing grounds

Commercial reef line fishing vessels operate from ports, rivers and estuaries along most of the Queensland coast and indeed some (in the far north) operate from mother vessels. However, the available data do not include reliable information on vessel transit details such as from what port vessels operated, when they departed and returned to port (i.e., steaming data) or the total number of vessels actually fishing over the historical period.

The 411 vessels implemented in the vessel dynamics model are associated with 10 fishing ports which were selected as being major ports and which have a representative geographic spread along the Queensland coast. The 10 ports (from north to south) are Cooktown, Port Douglas, Cairns, Innisfail, Townsville, Bowen, Mackay, Yeppoon, Gladstone and Bundaberg. Each port has an associated fishing 'ground' with a north and south latitude boundary that was primarily based on the fisher interviews (Fig. 4.26). The latitude boundaries of these port-associated fishing grounds overlap because each may be accessed by vessels from neighbouring ports. We elected not to use all 14 ports reported in the interviews (Table 4.1 in Section 4.2) as they included some minor ports (e.g. Kurrimine, Ayr) and also did not include some of the major ports (e.g. Cooktown). The port-associated fishing grounds are modelling objects created to manage the latitudinal placement of effort and spatial behaviour of vessels (via their associated vessels) such that patterns in effort generated by the vessel dynamics model under historical management arrangements reflect the patterns shown in the historical commercial logbooks (e.g., Mapstone et al. 1996b).

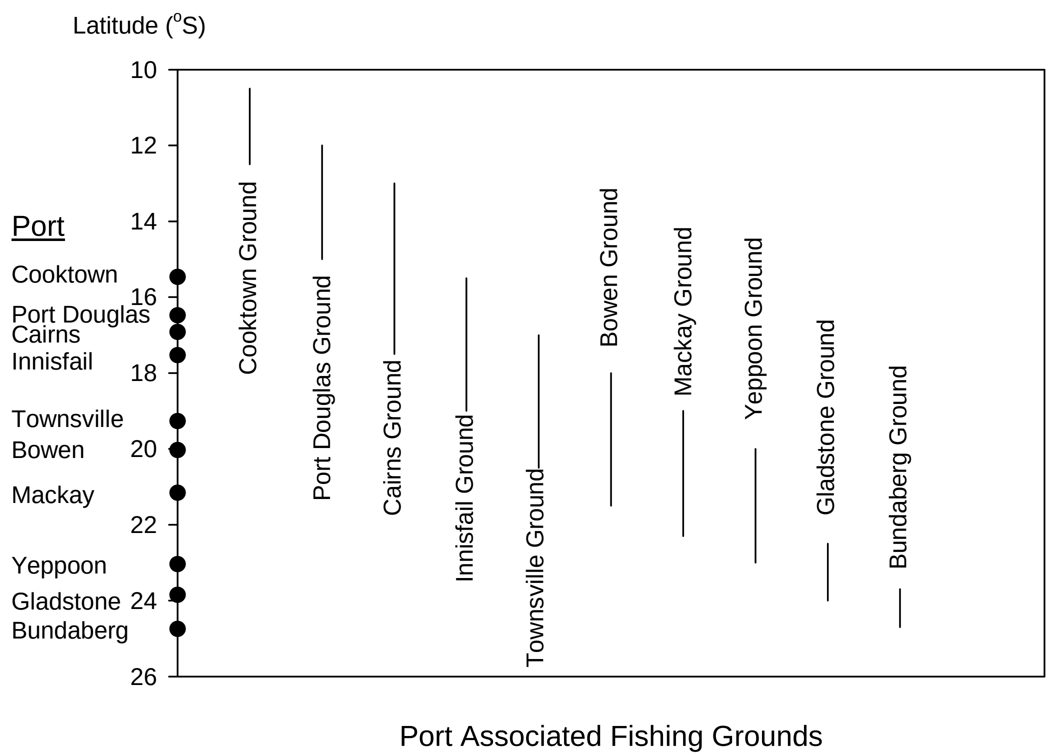


Fig 4.26. Ports (dots) and port-associated fishing grounds (vertical lines) indicating their northern and southern latitudinal boundaries.

Home port information was available for 307 of the 411 vessels identified in QDPI&F licence data, although 57 of those were registered as outside the GBR region (e.g., from Brisbane, Southport, Torres Strait). Using supplementary data on landing points it was possible to associate 269 vessels to eight major ports (or more correctly to port-associated fishing grounds), that were initially selected for use in the model. The remaining 142 vessels, including the non-GBR vessels, were initially randomly assigned to one of these eight ports in the same proportions as the 269 vessels.

Vessels commence each fishing trip during model execution by selecting their first reef based in part on the historical frequency of visitation (from commercial logbook data) to the reefs associated with their port of operation. A vessel may extend its trip outside the latitude bands of a fishing ground after it has started a trip but most trips are completed within the home port ground. Each port, through its associated vessels with their fishing strategies, generates a spatial pattern of effort that is partly dependent on historical data, especially in the early stages of model execution.

Initially, the 411 vessels were allocated to port-associated fishing grounds using data from QDPI&F records of port fish landing records and our interviews (see Section 4.2). This led to a pattern of effort allocation, as measured by average annual units of effort assigned to each 1-degree latitude band, that differed considerably from that recorded historically (Fig 4.27). The total discrepancy in effort (i.e. sum of the absolute differences between observed and expected effort for each degree of latitude) was 21,575 units, or 27% of the total effort allocation of units.

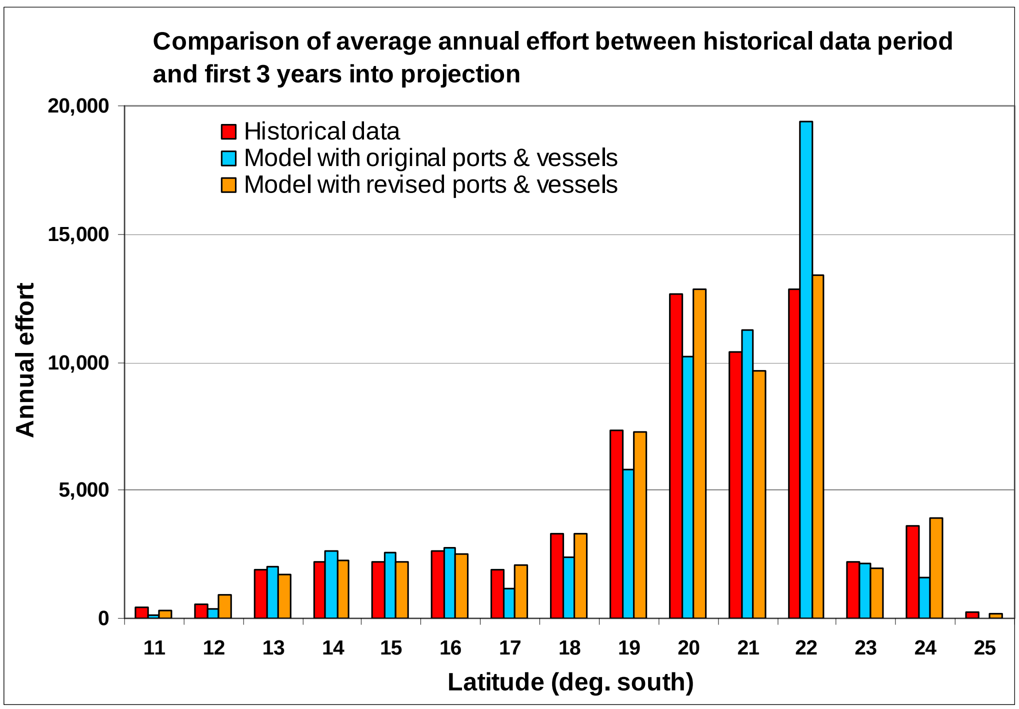


Fig 4.27. Comparison of commercial fishing effort by latitude band and that predicted using the initial and revised vessel-port associations. Effort comparisons are between the average over year of the historical data (1989-2000) and the corresponding average for 2001-2003. The latter have been adjusted to have the same total annual effort as in the historical period; only the first three years of the projection period have been used to reduce the effect of changing catch histories over time.

The initial allocation of vessels to ports was modified to increase the concordance between the historical pattern in effort and that generated by the model in the first years of the projection period under historical management conditions. A revised allocation of vessels to ports was obtained by minimizing a utility function involving the absolute weighted discrepancy between the historical effort and the effort assigned from the distribution of vessels among ports while maintaining constant the total effort over all ports and total number of vessels:

$$\sum_{l=10}^{25} \frac{\left|E_l - \hat{E}_l\right|}{\hat{E}_l} \qquad (4.23)$$

where E_l is the assigned effort by latitude band from the distribution of vessels among ports,

$\hat{E}_l$ is the historical effort allocated to latitude band

The minimization of Equation 4.23, subject to a maximum proportional discrepancy for any latitude band of 0.5, provided an indication, or starting point, for assigning model vessels to ports such that the resultant effort distribution that approximated historical data of the total annual effort by latitude (Fig 4.28).

The match between TRIPSim generated effort distribution and that derived from historical logbook records was further tuned by moving vessels (with their accompanying annual effort as measured by trip length times number of dories times number of trips per year) among port-associated fishing grounds and adjusting slightly the boundaries of the grounds to produce an acceptable distribution of total annual effort compared with the historical data. Running the model with these revised vessel-port allocations (Fig. 4.28) led to a total discrepancy in effort across latitude bands of only 2,557 units (i.e., less than 4% of the total effort allocation of 80,000 units; see Fig. 4.27).

The descriptions of the final 10 port-associated fishing grounds including the numbers of vessels associated with each port are listed in Table 4.9, where it can be seen that most of the adjustment was between neighbouring ports within the mid-northern and southern areas of the GBR. One should not place much credence on the actual number of vessels associated with a port because it is the vessels' total combined effort that is important. For example the 64 vessels originally associated with Mackay produced more annual effort (14,424 dory days) than the 102 vessels associated with Gladstone (10,864 dory days).

Table 4.9 Number of vessels associated with ports before and after revising port allocations to obtain better concordance of effort between modelled and historical data.

<table>
<tr><th rowspan="2">Homeport</th><th rowspan="2">original</th><th rowspan="2">revised</th><th colspan="2">Grouped</th></tr>
<tr><th>original</th><th>revised</th></tr>
<tr><td>Cooktown</td><td>14</td><td>11</td><td>14</td><td>11</td></tr>
<tr><td>Port Douglas</td><td>Nil</td><td>18</td><td rowspan="3">118</td><td rowspan="3">115</td></tr>
<tr><td>Cairns</td><td>90</td><td>36</td></tr>
<tr><td>Innisfail</td><td>28</td><td>61</td></tr>
<tr><td>Townsville</td><td>28</td><td>26</td><td>28</td><td>26</td></tr>
<tr><td>Bowen</td><td>76</td><td>79</td><td>76</td><td>79</td></tr>
<tr><td>Mackay</td><td>64</td><td>91</td><td rowspan="4">175</td><td rowspan="4">180</td></tr>
<tr><td>Yeppoon</td><td>9</td><td>38</td></tr>
<tr><td>Gladstone</td><td>102</td><td>28</td></tr>
<tr><td>Bundaberg</td><td>nil</td><td>23</td></tr>
</table>

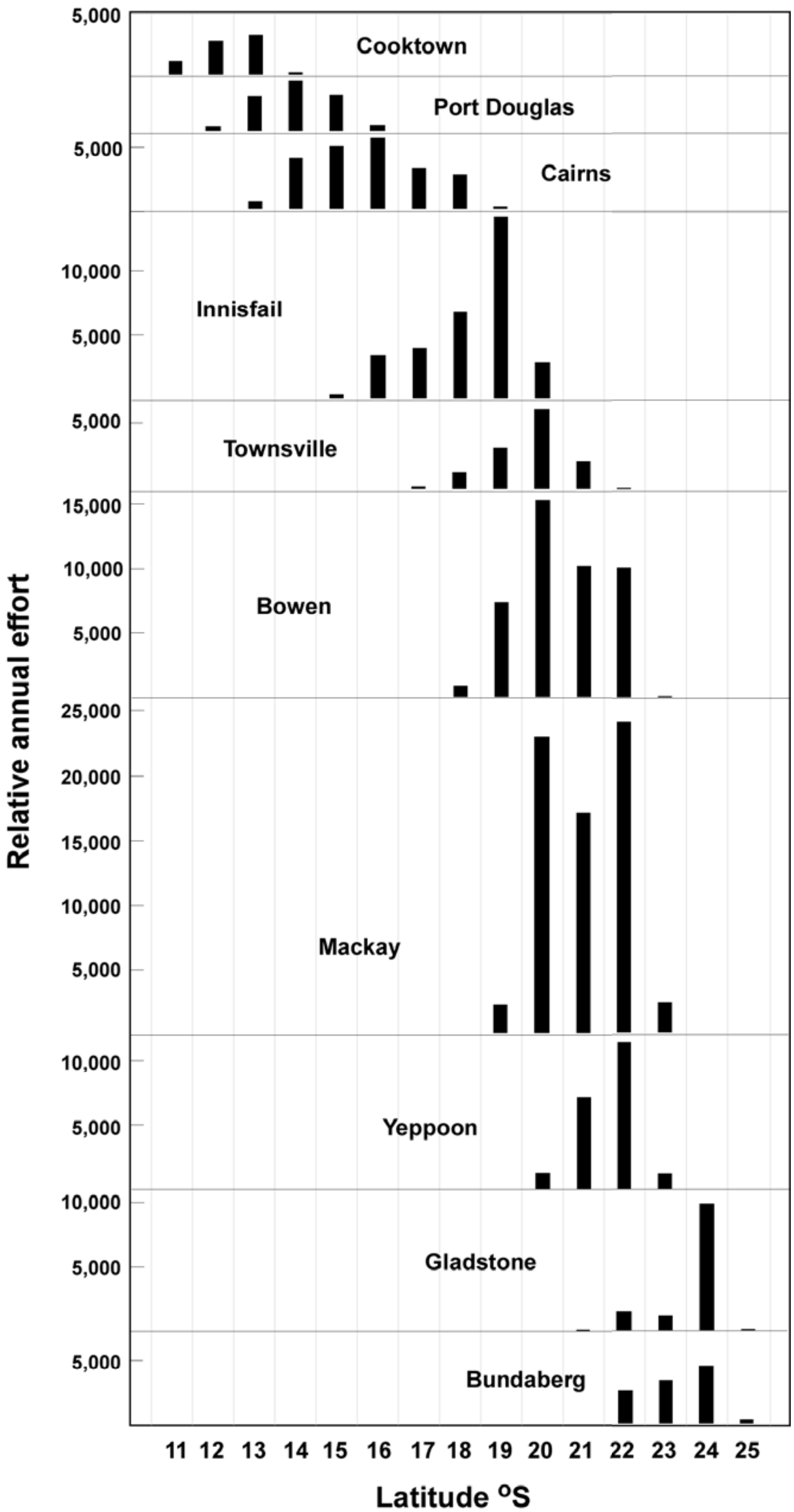


Fig 4.28. Total annual effort produced for each latitude band by the vessels assigned to the various port-associated fishing grounds.

Determining the number of dories per vessel for the benchmark level of effort

The total amount of annual effort to be allocated during the projection period of the simulations is pre-specified when using ELFSim. The basic unit of fishing in the vessel dynamics model is a single hooked line, with one line associated with each dory attached to a primary vessel plus one line associated with the primary vessel. This allocation is based on the most common situation in the fishery where a single fisher works from each dory and often the skipper will fish from the primary vessel. The basic unit of effort is therefore a line-day; one day's fishing by one person from a dory or primary vessel. The dories are directly associated with their primary vessel, and it is the movement of this vessel (with its attendant dories and effort) that is modelled in TRIPSim.

Trip data from the QDPI&F compulsory logbook database consisting of monthly trip lengths, trip frequency, and intervals between trips were used to schedule the trips that a vessel will take during a year. The vessel characteristics of the simulated fleet were first altered (by manipulating vessels' time in port) so that the total effort equaled the 1996 effort, i.e. the amount of effort generated during a year for the commercial reef line fishing fleet under benchmark conditions must satisfy:

$$\sum_{v} L_v N_v l_v = 80{,}000 \qquad (4.24)$$

where

L_v is the mean trip length in days for vessel *v*,

N_v is the mean number of trips per year for vessel *v* (trip frequency), and

l_v is the number of line-day effort units used by vessel *v*.

The 411 vessels, with characteristics as described above, initially produced some 86,000 units of effort. This was reduced to 80,000 units by randomly selecting a vessel (without replacement) and removing a unit of effort (which might represent either a dory or primary vessel) and recalculating the total annual effort over all vessels until the 80,000 baseline was reached. This mechanism of reduction can be justified by the fact, as elucidated during the interviews, that not all fishing operations always use their complete licensed dory allocation, and not all vessels fish from the primary vessel.

Management scenarios that change the total annual effort

The number of trips each vessel makes each year is adjusted for those scenarios in which the total annual effort differs from the baseline (1996) level of effort. This adjustment involves scaling the number of trips each vessel makes in a year by the ratio of the intended effort to the effort for 1996. However, simply scaling up trips can result in unrealistic outcomes if this results in some vessels undertaking too many trips and thus having no time remaining to return to port, unload, perform maintenance etc. The following rules, therefore, were implemented:

1. All vessels must spend at least one day in port between trips;
2. A vessel cannot engage in more trips than will fit (together with a day in port at end of each trip) into 365 days, although;
3. The number of trips in a year does not need to be an integer as the last trip can cross the end of year boundary and occur, in part, in the following year.

This has been implemented as follows:

1. The number of trips per year for each vessel is increased in the same proportion as the required total effort compared with the baseline effort;
2. All vessels are checked to determine whether any of the rules above are violated;

3. The number of trips for any vessels that violated the rules above are reduced so all rules are satisfied and the excess effort is accumulated;
4. Excess effort is re-allocated to the remaining vessels that did not violate the above rules;
5. If re-allocated effort is greater than 25 line units, repeat the reallocation process from step 2.

Trip scheduling

Scheduling is controlled by three variables: (1) number of trips during a year; (2) trip duration; and (3) port stay. In reality, when conditions are favourable and catches are good, some vessels can offload catch, reprovision and head back out to the reef to fish in less than a day. However, vessels generally spend from 3-4 days, and up to several weeks, in port between trips. Additionally, all vessels spend extended periods in port for annual maintenance and overhauls or due to adverse weather. Interviews with fishers indicate that fishing effort is not evenly distributed throughout the year and this was supported by data from commercial logbook records that showed distinct increases in effort from July to November (Fig 4.29, Mapstone et al. 1996b). The seasonal pattern of fishing effort is captured in TRIPSim by shrinking or expanding the port stay of vessels between trips, i.e. when fishing effort is higher, the average length of time in port must be concomitantly reduced. The number of days spent fishing in month *m* each vessel, $d^{f}_{v,m}$ is given by:

$$d^{f}_{v,m} = \min(L_v N_v I_{y,m}, n_m) \tag{4.25}$$

$$I_{y,m} = E_{y,m} / \sum_{m} E_{y,m} \tag{4.26}$$

where y is a year selected at random from 1989-2000, and

$I_{y,m}$ is the proportion of the (total) effort during year *y* that was expended in month *m*,

n_m is the number of days in month *m*

$E_{y,m}$ is the observed effort (in line days) for month *m* of year *y*.

L_v, N_v are as defined in equation 4.24 (Fig. 4.29).

The number of days in port between consecutive trips $d^{p}_{v,m}$ is then calculated as

$$d^{p}_{v,m} = \frac{n_m - d^{f}_{v,m}}{N_v I_{y,m}} \tag{4.27}$$

A vessel's port stay is applied at the end of each trip. At the start of the projection period, the state of the fleet is set with vessels randomly assigned to be fishing or in port.

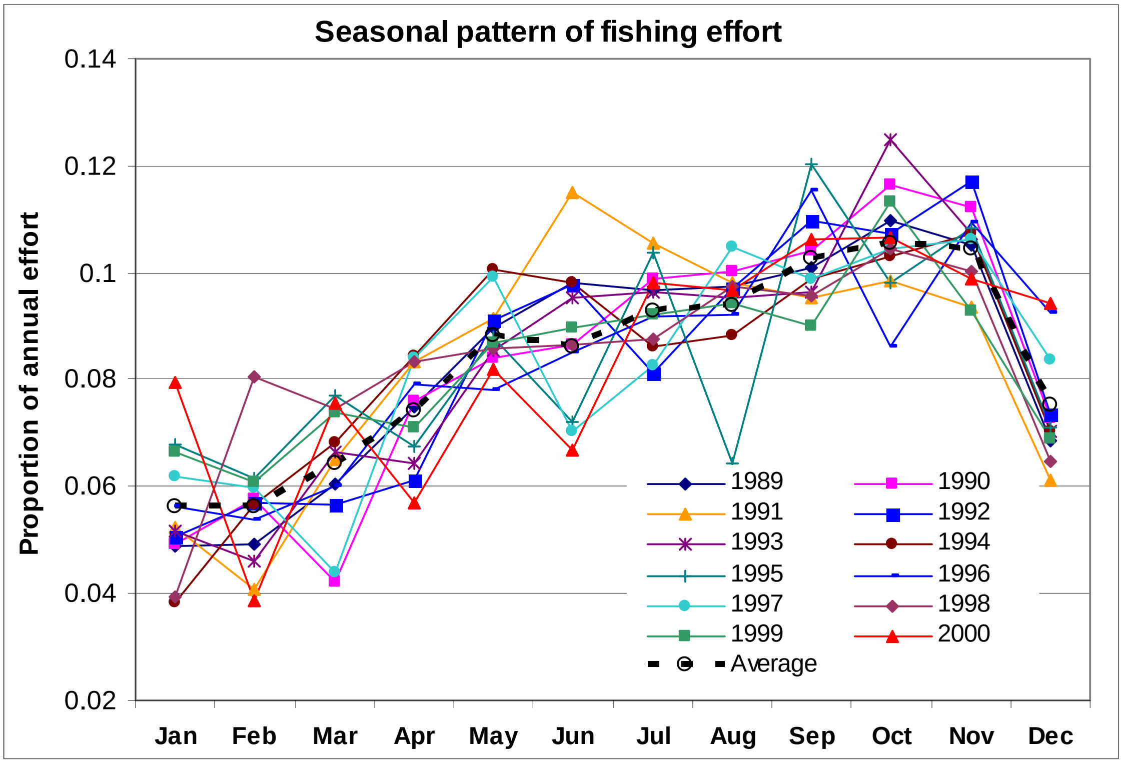


Fig. 4.29 Seasonal (monthly) variation in effort. Solid lines show the proportional monthly fishing intensity for 1989 -2000. The dotted line is the average over these 12 years.

Seasonal closures

Fishery regulations introduced in 2003 impose seasonal fishing restrictions on the fishery. No fishing is permitted for 9 days around the new moon in October, November and December each year. Seasonal closures may be imposed as one of the management options in ELFSim to prohibit vessels fishing during these periods which may result in fishing being reduced during the lead-up to a closure period because vessels are forced to cancel a trip if it would extend into or continue through a closure period. This anticipatory loss is somewhat counterbalanced by a build-up of potential fishing activity when the fishing season opens again. The model allows a proportion of the effort that would have taken place during the closure periods to be either lost or displaced to other times of the year. Effort displaced to other times of the year is done in proportion to the seasonal distribution of effort indicated by the data.

4.4.3. Modelling effort

Area of fishing: first reef selection

The first reef visited by a vessel at the start of a fishing trip is selected from the reefs within its port-associated fishing ground. Specifically, a seed reef is selected at random from the reefs within the latitude range of its home port, with probability proportional to the effort distribution observed from the commercial logbook data. The vessel does not necessarily fish on this reef, but rather fishes on a reef selected from within the 'neighbourhood' (36 nm from this 'seed' reef) of this reef using the algorithm for selecting reefs based on analysis of the ELF logbook data, except that the effect of distance and bearing are ignored when calculating the utility for the first reef visited. The seed reef is itself in the neighbourhood, so it can be selected. Note that the travelling time between port and fishing ground, a non-fishing activity, is not modelled explicitly but is implicitly included in the vessel's port stay.

Applying a daily time step effort model

In order to implement a vessel dynamics model in ELFSim that operates at a daily time step, a method of reconciling such models with the monthly time step of the biological component of ELFSim has been developed. The issues in dealing with vessels operating at a daily time step include their ability to get an accurate or realistic daily catch on a given reef, when the biological dynamics, viz growth and mortality, operate at a coarser monthly time step. Vessel-specific, reef-specific and daily variability in catchability is used to address these issues.

The interface between the biological model, which operates at a monthly timestep and the vessel dynamics model which operates at a daily time step maintains an estimate of each reef population at a daily level based on initial conditions set by the biological model at the beginning of each month. The vessels fish, obtaining a catch based on the daily estimates, until the end of the month when an aggregate effort is returned to the operating model. This effort is then applied to the reef populations within the operating model, which calculates fishing mortalities and catches by reef, and updates the populations on each reef. The reef populations are then used to initialise the daily cycle for the next month.

The reef populations that are passed to the interface and used by the vessel dynamics model are, a) the available biomass of species *s* on reef *r* at the start of month *m* of year y, $B_{r,y,m,s}$, and *b)* $\varepsilon_{q^r_{y,m,f,s}}$, the catchability of vessels of class *f* on fish of species *s* that are on reef *r* during month *m* of year *y*, i.e., $\varepsilon_{q^r_{y,m,f,s}} = q^r_{f,s}\exp(\varsigma^r_{y,m,s}\sigma_{q^r_{f,s}} - (\sigma_{q^r_{f,s}})^2/2)$ where $\varsigma^r_{y,m,s} \sim N(0;1^2)$, and $q^r_{f,s}$, and $\sigma^2_{q^r_{f,s}}$ determine the extent and variability in catchability on reef *r*, for species *s*, and fleet *f*, calculated from Equations 3.20 and 3.21.

At a daily time step, the vessel dynamics model calculates catch of fish of species *s* on reef *r* by vessel *v* on day *d*, month *m* and year *y*, $C^{v,r}_{y,m,d,s}$, using the equation:

$$C^{v,r}_{y,m,d,s} = E^{v,r}_{y,m,d}\, B_{r,y,m,s}\varepsilon_{q^r_{y,m,f,s}}\varepsilon_{q^v_{y,m,d,s}} q_{v,s} \tag{4.28}$$

where $B_{r,y,m,s}$ is the available biomass of species *s* on reef *r* at the start of month *m* of year *y* *y*, specified in the biological model of ELFSim and not modified within the month by the vessel dynamics model

$E^{v,r}_{y,m,d}$ is the effort by vessel *v* on reef *r* on day *d*, month *m*, and year *y*,

$\varepsilon_{q^r_{y,m,f,s}}$ is the monthly variation in catchability for fleet *f*, species *s* on reef *r* during month *m* of year *y*,

$\varepsilon_{q^r_{v,m,d,s}}$ $\varepsilon_{q^v_{y,m,d,s}}$ is the variation in catchability for vessel *v* fishing on reef *r* for species *s* on day *d*, month *m* and year *y*, $\varepsilon_{q^v_{y,m,d,s}} = \exp(\xi_{y,m,d,s} - \sigma^2_\xi/2)$ where $\xi_{y,m,d,s} \sim N(0,\sigma^2_\xi)$,

σ^2_ξ determines the extent of variation in catchability at the daily level,

$q_{v,s}$ is the vessel-specific catchability coefficient, defined according to the equation:

$$q_{v,s} = n_v\, q'_{v,s} / \sum_{v'} q'_{v',s}\ ;\ \ q'_{v,s} = \exp(\eta_{v,s} - \sigma_{v,s}/2)\,;\ \eta_{v,s} \sim N(0,\sigma^2_{v,s}) \tag{4.29}$$

$\sigma^2_{v,s}$ determines the extent of among-vessel variation in catchability,

n_v is the number of vessels in the vessel-class in which vessel v is located, and
$q_{s,d}$ is the daily variation in species-specific CPUE (Coral Trout: $e^{N(0,0.671)}$; Red Throat Emperor $e^{N(0,0.941)}$ (Table 4.4).

The calculation of daily catch is required to inform decision making by vessels (e.g., stay/move decisions) but is not kept to update each vessel's catch history.

At the end of the month, the total effort is aggregated across all days and vessels and passed to the biological model, after taking account of the inter-vessel differences in efficiency, and daily variation in catchability:

$$E^r_{y,m,s} = \sum_v q_{v,s} \sum_d E^{v,r}_{y,m,d} \ \varepsilon_{q^v_{y,m,d,s}} \tag{4.30}$$

The model thus incorporates estimates of species-specific fishing efficiency for vessels and daily stochasticity in catchability. The effort passed to ELFSim (Equation 4.31) is used to calculate the total catch for the month given that effort. It is important that this calculation is done by ELFSim so that the catches are correctly reconciled with the monthly updating of the biological model. ELFSim then passes the corrected monthly catch back to TRIPSim, where it is allocated among the vessels of the vessel dynamics model:

$$C^{v,r}_{y,m,s} = C^r_{y,m,s} \frac{q_{v,s} \sum_d E^{v,r}_{y,m,d} \ \varepsilon_{q^v_{y,m,d,s}}}{\sum_{v'} \left(q_{v',s} \sum_d E^{v',r}_{y,m,d} \ \varepsilon_{q^{v'}_{y,m,d,s}} \right)} \tag{4.31}$$

It is this vessel catch that captures the fishing experience of the vessel and is added to the vessel's catch history, and so in turn influences subsequent fishing behaviour and decisions.

Move or stay?

Vessels decide whether to stay on the current reef or move to another at the end of each day unless the trip is terminated. The probability of a vessel v staying on its present reef, *r,* is $e^{U^v_r}/(1+e^{U^v_r})$ where U^v_r is defined as in Equation 4.8. The catch by vessel v of species s on reef r during day d is calculated internally to the vessel dynamics model using Equation 4.28.

Move to which reef?

Given the decision to move from one reef to another, the choice of the next reef depends on a) its expected catch, b) its distance from the current reef, c) the bearing of the reef relative to the vessels current direction of travel, and d) whether fishers are already fishing the reef (avoidance). All reefs within the (36 nm) neighbourhood are considered when deciding where to fish next, except that a reef cannot be fished twice on the same trip, which is a general practice of fishers documented from skipper interviews. The model of where to move next does not explicitly include travel time because the distance travelled between reefs is relatively small; the mean distance travelled per day from ELF logbook data is 10 nm (Fig 4.11), and, for the purposes of the model, travel is considered to be accomplished over-night between fishing sessions. Other factors have been mentioned as affecting the choice of reef (e.g. reef size, big-reef-big-tide practices, moon phase), but either the utility function captures these issues using other factors implicitly or the data available to us were not sufficiently sensitive to estimate their effects quantitatively above the effects of other variables.

The probability of being on reef i and selecting reef j is $e^{U_{i,j}} / \sum_k e^{U_{i,k}}$ where $U_{i,j}$ is defined according to Equations 4.20 and 4.22, where the reef with the highest value of U is most likely to be selected with less desirable reefs also retaining a chance if being visited. This method allows for exploration and visiting new reefs and recognises that skippers do not always act with perfect knowledge. The utility function describing reef selection is shown in Fig. 4.22 and the values of the components are shown in Table 4.10.

Table 4.10 Table of parameter values utilised in TRIPSim.

Parameter	Description/use	Value
Utility function for selecting next reef (Equation 4.30):		
$\gamma_{4,CT}$	Coral Trout expected catch for same month previous year	0.032467
$\gamma_{4,RTE}$	Red Throat Emperor expected catch for same month previous year	0.004509
$\gamma_{5,CT}$	Coral Trout expected catch for previous month same year	0.032316
$\gamma_{5,RTE}$	Red Throat Emperor expected catch for previous month same year	0.028214
$\gamma_{6,CT}$	Interaction of vessel-q and catch for Coral Trout for same month previous year	0.025259
$\gamma_{6,RTE}$	Interaction of vessel-q and catch for Red Throat Emperor for same month previous year	-0.039765
$\gamma_{7,CT}$	Interaction of vessel-q and catch for Coral Trout for previous month same year	0.038902
$\gamma_{7,RTE}$	Interaction of vessel-q and catch for Red Throat Emperor for previous month same year	0.033773
$\log -\gamma_{1v}$	Vessel parameter for distance	$\sim N(-1.37, 0.53)$
$\log \delta_v$	Vessel parameter for direction	$\sim N(-2.42, 0.9)$
$\text{Corr}(\log -\gamma_{1v}, \log \delta_t)$	Correlation between distance and bearing parameters	0.72
	Fishing mortality (Equation 4.29):	
$\sigma_{v,s=CT}$	Std dev of vessel catchability for Coral Trout	0.494
$\sigma_{v,s=RTE}$	Std dev of vessel catchability for Red Throat Emperor	0.508
$\varepsilon_{Q^v_{s=CT,d}}$	Std dev of daily variability in catchability for Coral Trout	0.671
$\varepsilon_{Q^v_{s=RTE,d}}$	Std dev of daily variability in catchability for Red Throat Emperor	0.941
	Stay or move decision (Equation 4.28):	
-	Catch contribution	0.0032
-	Reef size (perimeter) contribution	0.0100
-	Intercept	-0.9306
γ_v	Std ddev for the vessel-specific propensity to stay or move	0.6871

Expected catch

Some skippers prefer some reefs to others. These impressions may be based on different experiences and catch histories and they change over time. Results from the interviews demonstrated that past catches on a reef were influential in decision-making, and the resultant effort allocation process. As a result, a continuously updated record is kept of each vessel's catch history by reef. Initially, all vessels, as well as the fleet, are assigned identical catch histories for all reefs for each calendar month. This catch history is based on average monthly catch records for each reef from the historical data records for 1989–2000. The expected catch used in the utility function is then imputed from a vessel's catch history for each species and reef, updated with that vessel's catch calculated during execution of the model. A component is incorporated in each vessel's catch history that captures information shared from other vessels in the fleet, consistent with advice from skippers during interviews. Thus, the expected catch for each reef and vessel is calculated within the vessel dynamics model using the vessel's own catch history and that of the fleet:

$$\tilde{C}^{\text{dis},v}_{y,m,r,s} = \pi_v C^{\text{dis},v}_{y,m,r,s} + (1-\pi_v) C^{\text{dis},f}_{y,m,r,s} \tag{4.34}$$

where $C^{\text{dis},v}_{y,m,r,s}$ is the catch history of vessel *v* for species *s* on reef *r* during month *m* of year *y*,

$C^{\text{dis},f}_{y,m,r,s}$ is the catch history of the fleet for species *s* on reef *r* during month *m* of year *y*, and

π_v is the parameter that determines the extent to which vessel *v*'s catch history depends on its own catch history compared to that of the fleet.

For the current simulations we assumed a value of π_v equal to 0.9 to reflect the strong reliance that a vessel places on their own historical fishing experiences and the relatively slight dependence on information from others.

The catch history records for all vessels are updated at the end of each month as is the fleet catch history. This updating takes the form:

$$C^{dis,v}_{y,m,r,s} = \begin{cases} \alpha C^{dis,v}_{y-1,m,r,s} + (1-\alpha) C^{v}_{y,m,r,s} & \text{if reef } r \text{ was visited by vessel } v \text{ during month } m \text{ of year } y \\ \beta C^{dis,v}_{y-1,m,r,s} & \text{otherwise} \end{cases} \tag{4.35}$$

where α is a time-weighting discount factor (assumed to be 0.85), and

β is a discount or 'forgetting' factor (assumed to be 0.85).

The fleet catch history, $C^{\text{dis},f}_{y,m,r,s}$, is also updated monthly, except that it is based on the monthly catch of a species taken by all vessels in the fleet for the month concerned.

This updating mechanism is equivalent to expressing the current catch history as a weighted average of all prior observed catches, with progressively smaller discounted weight given to those further in the past. This continuous updating on a monthly basis also maintains any seasonality in expectations of catch.

Vessel efficiency

The utility function incorporates a vessel's species-specific catchability $q_{v,s}$ as a measure of vessel-specific efficiency taken as a surrogate for different fishing abilities among fishers or crews of different vessels. These species-specific, vessel-*q*'s are assigned to each vessel during model initialization. As with the expected catch, the terms of the utility function that involve the vessel-specific *q*'s have associated, species-specific, gamma coefficients ($\gamma_{6, s}$ and $\gamma_{7, s}$) that were derived from the logbook analyses (Section 4.3), and which also have time-partitioning components for the previous month and for the same month in the previous year.

Bearing and direction of travel

During model execution, once a vessel selects the first reef on a trip, it is 'coerced' to follow a general path back towards its home port for the remainder of a trip. This is done with the bearing coefficient $\phi_{v,t}$. Thus, if a vessel starts at the northern end of its port associated fishing ground, it subsequently favours reefs that lie towards the south-east and the vessel tends to move in a south-easterly direction. Trips are set to run in line with the major axis of the reef in a north-westerly or south-easterly direction (Fig. 4.8).

The bearing parameter also incorporates distance, because going a short way in the wrong direction is more acceptable than having to backtrack over a greater distance. The utility function includes an interaction term involving distance between reefs in combination with bearing between reefs and direction of travel within a trip, together with a vessel-dependent parameter value for the influence of bearing and direction.

Vessel avoidance

The vessel dynamics model also considered vessel avoidance of other vessels because results from skipper interviews indicated a consistent response to avoiding other commercial reef line fishing vessels on the same reef (Table 4.11). An overarching trend was that avoidance (i.e., bypassing a reef) was less likely if the reef was large. Other factors considered included whether the skipper of the other vessel was 'good' (in which case they were more likely to avoid it); or whether they were targeting similar product (for example deep water fishers were not so concerned with the presence of reef line fishers).

Two factors were considered in setting the values for the parameters for avoidance behaviour: what is a big or little reef, and what is the range in number of other vessels tolerated. We asked fishers in the interviews to indicate the diameter of what they consider a small or large reef, or give examples of typical small or large reefs which we could subsequently measure on a chart. This gave an average size (perimeter) of 'small' reefs as 7 nm and an average for 'large' reefs as 31 nm. For modelling purposes we have taken the mid-point of 19 nm as being the discriminator for large and small reefs.

Skippers were also asked how many other vessels would need to be on a big or little reef before they would avoid it. Vessels were assigned an avoidance characteristic for small and large reefs randomly based on the distribution of respondents (Table 4.11). Each vessel was assigned one of these levels of avoidance at random during vessel initialization at the beginning of a run., At each daily time step during model execution, the order in which vessels are processed is randomised and a record of the number of vessels currently fishing on each reef is maintained. When a vessel is considering moving to another reef, all reefs within its selection horizon are first checked for the number of vessels already present. Reefs are excluded from selection (i.e. no utility is calculated) for reefs that already contain an equal or greater number of primary vessels than the avoidance criterion for that vessel.

Table 4.11 Results from skipper interviews when asked "how many other vessels would need to be on a reef before you would avoid it". The response was different for small and large reefs. For instance 46 respondents indicated that they would avoid a small reef with another vessel already there, while only 12 would avoid a large reef with 1 vessel. The 'zero' vessel does not mean they would avoid a reef with no vessels on it, but that these respondents would not avoid a reef regardless of the number of vessels there.

Reef Size	Number of other vessels	Frequency of respondents
Small	0	4
Small	1	46
Small	2	13
Small	3	6
Small	4	1
Small	5	0
Large	0	6
Large	1	12
Large	2	20
Large	3	19
Large	4	8
Large	5	5

Infringement and management

Some fishers do fish in protected areas or during seasonal closures, and this behaviour is likely to change when area closures are increased. The decision-making routines followed by the fishers take into consideration the management or zoning status of reefs, and modify the likelihood of visiting that reef. Specifically, the zoning and management status of a reef can range from 0 (open for fishing) to 1 (completely closed). Values between 1 and 0 indicate a probability of infringement (which may be a function of the distance from the edge of a protected area, or some function of the probability of detection). To account for reef closures and different levels of infringement, during model execution, prior to randomly selecting the next reef in which to move, the utility value of each reef in the vessel's selection horizon is modified as,

$$P_{v,t,d,i,j} = \alpha(1 - L_j)\exp(Z_{ij,d}^T \gamma_{vt}) \tag{4.36}$$

where $P_{v,t,d,i,j}$ is the probability that vessel *v* in trip *t* on day *d*, moves from reef *i* to reef *j*

$Z_{ij,d}^T \gamma_{vt}$ is the utility calculated in Equation 4.22 that vessel *v* in trip *t* on day *d*, derives in moving from reef *i* to reef *j*

α is a scaling factor that ensures the probabilities sum to unity

L_j is the 'management status' of reef *j,* which ranges between 0, indicating the reef is open to fishing, to 1 indicating the reef is closed to fishing and receives no infringement.

Closing a reef to fishing effectively re-scales the probability that the vessel will fish that reef. We assumed a management status of 0.95, which implied that the modified probability of infringing a closed reef was 5% of the unmodified probability of selecting a reef.

5. Management strategy evaluation

Management strategy evaluation (MSE) is a process that attempts to evaluate the effects of management actions in a computer simulation framework, to identify the consequences of alternative management strategies as trade-offs among stakeholder-derived management objectives (Smith 1994, Smith et al. 1999). Consequently, MSEs are comparative rather than prescriptive, seeking to compare likely outcomes from a range of management strategies rather than to prescribe optimal strategies or decisions that should be taken under an existing regulatory framework (Smith 1994, Mapstone et al. 2004). An MSE approach provides a simulation-based framework within which harvest strategies and performance indicators can be compared (as in this project), as well as different stock assessment methods and research and monitoring programs (Punt et al. 2002).

A key element of an MSE involves turning broad conceptual objectives into quantifiable and measurable operational management objectives and related performance indicators (Smith 1994). Multiple and conflicting objectives, although inherent in fisheries management, are dealt with in an MSE framework by demonstrating the trade-offs in performance of alternative management strategies against such objectives (Smith et al. 1999). Fundamental to this approach, therefore, is the identification and representation of diverse stakeholder objectives (conservation to sustainable use). Stakeholder engagement in an MSE approach is essential to the acceptance of credible management objectives and strategies that represent the divergent interests of the different user-groups (Mapstone et al. 2004).

Another key element of an MSE is the operating model which represents the underlying stock and fishery dynamics of the system being evaluated. The operating model simulates the characteristics of the harvested stock or stocks (biological model; see Chapter 3), the fishery (effort model; see Chapter 4) and the interactions between them (Mapstone et al. 2004). Through this process, the MSE deals explicitly with a range of sources of uncertainty in predicting the consequences of alternative management strategies, including structural and parameter uncertainty in the models, errors in data, estimation uncertainty and management implementation uncertainty (Smith 1994, Smith et al. 1999). Transparency in trade-offs in performance of alternative strategies and recognition of sources of uncertainty is essential to the approach and acceptance of outcomes from stakeholders.

In this Chapter, we build on the single species MSE developed for Coral Trout (ELFSim) to include Red Throat Emperor (FRDC 1997-124; Mapstone et al. 2004). ELFSim provides the MSE framework to examine the trade-offs associated with the performance of alternative management strategies, which to date have focused on area closures and effort controls for Coral Trout (see Mapstone et al. 2004 for further details). Previously, our capacity to address the multi-species nature of the CRFFF was limited by a paucity of information for the target species and fishing practices, and the lack of a formal MSE framework to do so. Therefore, we extend the biological model in ELFSim to include Red Throat Emperor (Chapter 3) and the effort model component to include an individual-vessel based model (Chapter 4). The newly developed models within ELFSim were used to formally evaluate stakeholder-derived management strategies for both common Coral Trout and Red Throat Emperor in the multi-species CRFFF. Specific operational management objectives, performance indicators and management strategies were defined for both species and formally evaluated. The process was facilitated by a series of stakeholder workshops and extension activities similar to those undertaken for the single species MSE as part of the ELF Project (Mapstone et al. 2004; see Appendix G).

5.1. Management objectives

Following the protocols used in the initial Coral Trout MSE (Mapstone et al. 2004), we sought input from a range of stakeholders in the CRFFF to identify relevant management objectives and feasible management strategies by which those objectives may be attained. Two stakeholder workshops were held to both familiarise stakeholders with the modelling approach and identify and refine specific operational management objectives, performance indicators and alternative management strategies for both Coral Trout and Red Throat Emperor (see Appendix G for minutes from these workshops). Throughout this process our intention was not to seek consensus among the different stakeholders, but to capture their diversity of views (Mapstone et al. 2004), emphasising the benefits of an MSE approach which effectively examines the trade-offs amongst these views.

A revision of the initial MSE for Coral Trout was provided to stakeholders with an opportunity to determine if the management objectives, performance indicators and management strategies, previously agreed to in December 1999 and November 2000, were still relevant (see Mapstone et al. 2004). A total of 43 management objectives were identified for Coral Trout and varied across stakeholders from aspects of conservation to exploitation and reflecting the changing management arrangements within the fishery (Table 5.1). Similar objectives to those identified for Coral Trout were also considered appropriate for Red Throat Emperor, although only 37 management objectives were specified (Table 5.1). The objectives for Coral Trout identified at the previous stakeholder workshops in 1999 and 2000 were accepted as still appropriate but were supplemented with management objectives, predominantly related to the charter and recreational sectors (e.g., recreational CPUE >80% 1998-2000 levels). Importantly, the objectives were specified in terms of quantifiable and measurable indicators that could be evaluated within the ELFSim modelling framework (Table 5.1).

Some objectives appear to be unreasonable for an exploited fishery. For example, the spawning biomass was expected to be above pre-fished (virgin) levels 100% of the time. The reason that such hopeful objectives for the fishery were formulated at the stakeholder workshops was due to rather high expectations resulting from the recently implemented RAP management arrangements.

Clarification was also sought on the time periods over which the management objectives were to be assessed, and the spatial division between the northern and southern GBR for two of the management objectives related to the magnitude of the undersize catch. Two time periods were agreed upon: 1) 2010-2015; and 2) 2020-2025. These were considered to represent both short- and mid- to long-term time frames. The spatial division for the northern and southern GBR was agreed to occur at 22°30', thereby capturing the natural division between the inshore Capricorn-Bunkers reefs in the southern GBR and the more offshore northern reefs of the GBR (see Fig. 1.2). Growing evidence from fisher’s reports and independent scientific studies supports this division, with changes in fish population structure and fishing practice across the Capricorn Channel.

Table 5.1. Management objectives and performance indicators for Coral Trout (CT) and Red Throat Emperor (RTE) identified at the MSE stakeholder workshops. These objectives were evaluated using the ELFSim models and form the basis of the multi-species MSE. "Retain" refers to fish caught above MLS (minimum legal size: 38 cm TL). "Total" = kept plus discards. CPUE = catch per unit effort. Total biomass represents fish > 20 cm. The northern and southern GBR regions are separated at 22°30'. Virgin refers to population levels in 1965, assumed to be unexploited. Time periods evaluated were 2010-2015 and 2020-2025.

Management objective	Indicator	Species	Stakeholder
Spawning Biomass			
Spawning biomass (SB) ≥ SB_{virgin} 100% of the time	$P(SB/SB_{virgin} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) ≥ SB_{virgin} 50% of the time	$P(SB/SB_{virgin} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on closed reefs ≥ SB_{virgin} 100% of the time	$P(SB/SB_{virgin} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on closed reefs ≥ SB_{virgin} 50% of the time	$P(SB/SB_{virgin} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on open reefs ≥ SB_{virgin} 100% of the time	$P(SB/SB_{virgin} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on open reefs ≥ SB_{virgin} 50% of the time	$P(SB/SB_{virgin} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) ≥ SB_{2000} 100% of the time	$P(SB/SB_{2000} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) ≥ SB_{2000} 50% of the time	$P(SB/SB_{2000} > 1.0)$	CT, RTE	DPI&F
Spawning biomass (SB) on closed reefs ≥ SB_{2000} 100% of the time	$P(SB/SB_{2000} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on closed reefs ≥ SB_{2000} 50% of the time	$P(SB/SB_{2000} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on open reefs ≥ SB_{2000} 100% of the time	$P(SB/SB_{2000} > 1.0)$	CT, RTE	Research
Spawning biomass (SB) on open reefs ≥ SB_{2000} 50% of the time	$P(SB/SB_{2000} > 1.0)$	CT, RTE	Research
Available Biomass			
Available biomass (AB) ≥ AB_{virgin} 100% of the time	$P(AB/AB_{virgin} > 1.0)$	CT, RTE	Research
Available biomass (AB) ≥ AB_{virgin} 50% of the time	$P(AB/AB_{virgin} > 1.0)$	CT, RTE	Research
Available biomass (AB) on closed reefs ≥ AB_{virgin} 100% of the time	$P(AB/AB_{virgin} > 1.0)$	CT, RTE	Research
Available biomass (AB) on closed reefs ≥ AB_{virgin} 50% of the time	$P(AB/AB_{virgin} > 1.0)$	CT, RTE	Research
Available biomass (AB) on open reefs ≥ AB_{virgin} 100% of the time	$P(AB/AB_{virgin} > 1.0)$	CT, RTE	Research
Available biomass (AB) on open reefs ≥ AB_{virgin} 50% of the time	$P(AB/AB_{virgin} > 1.0)$	CT, RTE	Research
Available biomass (AB) ≥ AB_{2000} 100% of the time	$P(AB/AB_{2000} > 1.0)$	CT, RTE	Research
Available biomass (AB) ≥ AB_{2000} 50% of the time	$P(AB/AB_{2000} > 1.0)$	CT, RTE	Research
Available biomass (AB) on closed reefs ≥ AB_{2000} 100% of the time	$P(AB/AB_{2000} > 1.0)$	CT, RTE	Research
Available biomass (AB) on closed reefs ≥ AB_{2000} 50% of the time	$P(AB/AB_{2000} > 1.0)$	CT, RTE	Research
Available biomass (AB) on open reefs ≥ AB_{2000} 100% of the time	$P(AB/AB_{2000} > 1.0)$	CT, RTE	Research
Available biomass (AB) on open reefs ≥ AB_{2000} 50% of the time	$P(AB/AB_{2000} > 1.0)$	CT, RTE	Research
Total Biomass			
Total biomass (TB) ≥ TB_{virgin} 100% of the time	$P(TB/TB_{virgin} > 1.0)$	CT, RTE	Research
Total biomass (TB) ≥ TB_{virgin} 50% of the time	$P(TB/ TB_{virgin} > 1.0)$	CT, RTE	Research
Total biomass (TB) ≥ TB_{2000} 100% of the time	$P(TB/TB_{2000} > 1.0)$	CT, RTE	GBRMPA
Total biomass (TB) ≥ TB_{2000} 50% of the time	$P(TB/TB_{2000} > 1.0)$	CT, RTE	DPI&F
Total biomass (TB) > 40% TB_{virgin} 80% of the time	$P(TB/TB_{virgin} > 0.4)$	CT, RTE	DPI&F

Table 5.1. continued.

Management objective	Indicator	Species	Stakeholder
CPUE			
Commercial CPUE >80% 1993-1996 levels 90% of the time	$P(CPUE/CPUE_{1993\text{-}1996} > 0.8)$	CT	Commercial
Commercial CPUE >120% 1993-1996 levels 90% of the time	$P(CPUE/CPUE_{1993\text{-}1996} > 1.2)$	CT	Commercial
Commercial CPUE >150% 1993-1996 levels 90% of the time	$P(CPUE/CPUE_{1993\text{-}1996} > 1.5)$	CT	Commercial
Commercial CPUE >80% 1994-1996 levels 90% of the time	$P(CPUE/CPUE_{1994\text{-}1996} > 0.8)$	RTE	Commercial
Commercial CPUE >120% 1994-1996 levels 90% of the time	$P(CPUE/CPUE_{1994\text{-}1996} > 1.2)$	RTE	Commercial
Commercial CPUE >150% 1994-1996 levels 90% of the time	$P(CPUE/CPUE_{1994\text{-}1996} > 1.5)$	RTE	Commercial
Charter CPUE >80% 1996-2000 levels 90% of the time	$P(CPUE/CPUE_{1996\text{-}2000} > 0.8)$	CT	Charter
Charter CPUE >120% 1996-2000 levels 90% of the time	$P(CPUE/CPUE_{1996\text{-}2000} > 1.2)$	CT	Charter
Charter CPUE >150% 1996-2000 levels 90% of the time	$P(CPUE/CPUE_{1996\text{-}2000} > 1.5)$	CT	Charter
Recreational CPUE >80% 1998-2000 levels 90% of the time	$P(CPUE/CPUE_{1998\text{-}2000} > 0.8)$	CT	Recreational
Recreational CPUE >120% 1998-2000 levels 90% of the time	$P(CPUE/CPUE_{1998\text{-}2000} > 1.2)$	CT	Recreational
Recreational CPUE >150% 1998-2000 levels 90% of the time	$P(CPUE/CPUE_{1998\text{-}2000} > 1.5)$	CT	Recreational
Discards			
In northern GBR <30% of catch is <MLS 90% of the time	P(discard/total < 0.3)	CT	Commercial
In southern GBR <5% of catch is <MLS 90% of the time	P(discard/total < 0.05)	CT	Commercial
In northern GBR <5% of catch is <MLS 90% of the time	P(discard/total < 0.05)	RTE	Commercial
In southern GBR <30% of catch is <MLS 90% of the time	P(discard/total < 0.3)	RTE	Commercial
Harvest			
9 in 10 fish caught >MLS 60% of the time	P(retain/total > 0.9)	CT, RTE	Charter
To catch the quota that is available 100% of the time	P(retain/quota > 1.0)	CT, RTE	Commercial
Big fish			
50% of common Coral Trout caught > 50 cm	$P(CCT_{> 50\ cm}/ CCT_{all} > 0.5)$	CT	Recreational
50% of Red Throat Emperor caught > 50 cm	$P(RTE_{> 50\ cm} /RTE_{all} > 0.5)$	RTE	Recreational

5.2. Management strategies

A range of alternative management strategies were also identified and agreed upon by the stakeholders at the workshops. A total of 18 management strategies were identified, combining area and temporal spawning closures, effort restrictions, and legal sizes (Table 5.2). These strategies were considered by the stakeholders to be the most appropriate considering the management regime under which the fishery operated prior to 2004 (when the workshops were held), while acknowledging the time constraints of evaluating multiple management strategies.

Four levels of area closures were identified: 1) current closures under the new GBRMPA RAP (RAP in Table 5.2); 2) closures in place immediately prior to the implementation of RAP (Pre-RAP in Table 5.2); 3) 50% of all reefs closed to fishing (50% in Table 5.2); and 4) 100% of all reefs closed to fishing (the latter being included for model validation and for testing trends) (100% in Table 5.2).

Three levels of effort restrictions were also identified: 1) 1996 fishing effort; 2) 50% of 1996 fishing effort; and 3) 150% of 1996 fishing effort. The 1996 fishing effort level was assumed to best represent historical exploitation patterns, although it was acknowledged that fishing patterns would likely change with the introduction of the total allowable commercial catch system.

Three levels of spawning closures were identified: 1) 9-day closures in October, November and December under the new QDPI&F CRFFF Management Plan; 2) total closures from September to November; and 3) no spawning closures. The three month total closure between September and November was considered by stakeholders to better capture the peak spawning periods of both common Coral Trout and Red Throat Emperor, rather than the current closures which were designed only around common Coral Trout.

There were several ways to consider seasonal spawning closures within ELFSim. Spawning closures can be implemented either by removing or preventing effort from being allocated during the time period, in which case, the closures act as an effort reduction mechanism. The alternative is to have the effort, or some portion of it, that was to be allocated during the closure period redistributed to some other time period. ELFSim is capable of re-allocating a portion of the effort that would be allocated during a seasonal closure to other times in proportion to the historical seasonal effort distribution. We treated spawning closures strictly as an effort reduction for most of the strategies reported here but also included a management strategy where all of the effort removed from the spawning closure period was redistributed to other times of the year for comparison with the simple effort reduction option (Table 5.2).

Six levels of size restrictions on harvest were identified: 1) current minimum legal size of 38 cm; 2) a minimum legal size of 35 cm; 3) minimum and maximum legal sizes of 28 cm and 45 cm respectively based on biological principles of first maturity, protogyny and protection of larger males; and 4) no size limits. We also considered that if size restrictions were reduced, and fishers were allowed to catch smaller fish, they might employ different gear to better select the smaller fish that would not be selected with currently favoured gear. We therefore examined two of the strategies with reduced size restrictions of 35 cm, and 28 cm – 45 cm, and shifted the selectivity curve (Table 3.2) so that proportionally the same amount of fish of the minimum legal size were selected as that which is selected under the 38 cm MLS (Table 5.3).

Table 5.2. Management strategies for Coral Trout and Red Throat Emperor identified at the MSE stakeholder workshops. These strategies were evaluated using the ELFSim models and form the basis of the multi-species MSE. RAP = GBRMPA Representative Areas Program (current closures). Base case refers to current management strategy under which the CRFFF is operating.

Area closure	Effort restriction	Spawning closure	Legal size	Comment
RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	Base case – current (2004) strategies
RAP	0.5x 1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
RAP	1.5x 1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
Pre-RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
Pre-RAP	0.5x 1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
Pre-RAP	1.5x 1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
50%	1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
50%	0.5x 1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
50%	1.5x 1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 38 cm	
RAP	1996	None	Min – 38 cm	
RAP	1996	Sep-Nov (effort reduction)	Min – 38 cm	
RAP	1996	3x 9 days (Oct-Dec) (effort redistribution)	Min – 38 cm	This strategy tests the effect of effort that is redistributed to other times of the year, instead of being lost.
RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	None	
RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 35 cm	Previous size limit
RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	28 - 45 cm (Min – Max)	Slot size limits based on biological analysis; minimum to reflect size at first maturity; maximum to reflect sex ratios and size at sex change
RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	Min – 35 cm	Selectivity curve reduced to account for targeting smaller fish (Table 5.3)
RAP	1996	3x 9 days (Oct-Dec) (effort reduction)	28 - 45 cm (Min – Max)	Selectivity curve reduced to account for targeting smaller fish (Table 5.3)
100%	Zero effort	NA	NA	No fishing – control strategy

Table 5.3. Selectivity parameters implemented for different size limit strategies.

Size Limit	Parameter	Coral Trout	Red Throat Emperor
35 cm MLS	Length-at-50%-selectivity	30.2 cm	37.5 cm
	Length-at-95%-selectivity	35.5 cm	46.5 cm
28 cm – 45 cm	Length-at-50%-selectivity	22.2 cm	29.5 cm
Min. – Max.	Length-at-95%-selectivity	27.5 cm	38.5 cm

5.3. Model projections

Management strategies are implemented during the projection period by varying annual effort, access to areas for fishing, and the values of the parameters determining the interaction between the biological and effort models, such as selectivity and minimum legal sizes. Management strategies can be fully implemented at the start of the projection period or, if they include time-varying measures, during the projection period. However, management strategies are always pre-specified, i.e., there is no dynamic feedback between management strategies and stock dynamics. Evaluations proceed by running the operating model from 1965 to the end of the period for which real data are supplied (2000) (the initialisation period) and then introducing the desired changes in the parameters that define the management strategy. Random processes in the population dynamics mean that each initialisation will lead to different starting conditions for the projections. The model is then run for a defined projection period (in this case 25 years). Repeating runs with the same management strategy allows an evaluation of the effect of variation in population dynamics and effort allocations on the results for that management strategy. Running the same management strategy with different parameters for the underlying operating model allows an assessment of the robustness of the results to uncertainties or errors in model assumptions. A wide range of reef-specific data can be collected at each time step, including catch and effort for each fleet (commercial, charter and recreational), available biomass, spawning biomass, fishing mortality and size and age measures for the population and catch.

For the purposes of this report we performed initialisations from 1965 to 2000 for the two species, Coral Trout and Red Throat Emperor, under two habitat scalars. The Coral Trout population dynamics were governed by larval migration and settlement, whereas the Red Throat Emperor dynamics had the added feature that post-settlement fish migrated in a northerly direction. The two habitat scalars represented our uncertainty regarding the pre-exploitation state of the reef populations, and consequently the uncertainty in the effect of the historical catches and levels of depletion at the end of the historical period. The two habitat scalars, therefore, represented two depletion levels for the start of the projection period: (1) a high level of depletion where the total available biomass was approximately 40% of the pre-exploitation level; and (2) a low depletion level where total available biomass was approximately 50% of the pre-exploitation level. Although we had two levels of depletion for each species, and conducted projections fully crossing each species with each depletion level, for ease of presentation we present only one combination here, that in which both the available biomass of Coral Trout and Red Throat Emperor was depleted to approximately 40% of the pre-exploitation level. The results are qualitatively similar when the higher depletion of 50% pre-exploitation level is used. Ten of these replicate initialisations were performed for each species.

For each of the 18 management strategies, the 10 initialisations were each followed by 10 replicate projections, resulting in 100 replicate projections for each management strategy. Lastly, all 1800 (18 X 10 X 10) projected simulations were performed under two commercial effort models. The first was the vessel dynamics model (Section 4.4) and the second was the effort allocation model (Section 4.1). The effort dynamics of the charter and recreational fleets were modelled as in Mapstone et al. (2004).

5.4. Analysis of simulation data

The simulation results were analysed and portrayed as follows:

1. The biomass performance indicators (spawning biomass, available biomass) were totalled across all reefs (or by open/closed status) for each year. The average of these totals (and standard deviation) were calculated from 2011-2015 and 2021-2025 for each replicate simulation and divided by either the unfished biomass (1965) or

2000 level biomass calculated from the same replicate simulation. The number of these 100 relative biomasses that satisfied the management objective defined the probability that the objective was met.

$$X'_{sim} = \frac{\frac{1}{n_y}\sum_{y}\sum_{r} X_{sim,y,r}}{\sum_{r} X_{sim,ref,r}} \qquad (6.1)$$

where X'_{sim} is the relative biomass (spawning, available or total) in replicate simulation *sim,*

$X_{sim,y,r}$ is the biomass (spawning, available or total) in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r.*

2. The CPUE indicators were similarly calculated by totalling catch and effort across all reefs for all years, and then dividing the total catch by the total effort to obtain an annual CPUE. The average and standard deviation of the annual CPUE was calculated across the years from 2011-2015 and 2021-2025 for the projection period, and across the relevant historical reference years for the different fleets (i.e., 1994-1996 commercial, 1996-2000 charter, 1998-2000 recreational). Relative CPUE was calculated by dividing the average historical CPUE into the average projected CPUE from 2011-2015 or 2021-2025. Of the 100 relative CPUEs the number that satisfied the management objective defined the probability that the objective was met:

$$CPUE'_{sim} = \frac{\frac{1}{n_{y_1}}\sum_{y_1} \frac{\sum_r C_{sim,y_1,r}}{\sum_r E_{sim,y_1,r}}}{\frac{1}{n_{y_2}}\sum_{y_2} \frac{\sum_r C_{sim,y_2,r}}{\sum_r E_{sim,y_2,r}}} \qquad (6.2)$$

where $CPUE'_{sim}$ is the relative CPUE in replicate simulation *sim*

$C_{sim,y,r}$ is the catch in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r*

$E_{sim,y,r}$ is the effort in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r*

y_1 is the summation interval for the projection period

y_2 is the summation interval for the historical period

3. The discard indicators were reported by calculating the total amount of fish released across all reefs and the total amount of fish retained across all reefs in the respective regions (north or south of 22°30') for each year, and dividing the number of released fish by the total amount of fish caught (released plus retained). These discard rates were then averaged across the years from 2011-2015 and 2021-2025. Of the 100 replicated simulations, the number that satisfied the management objective defined the probability that the objective was met:

$$C'_{sim} = \frac{\frac{1}{n_{y_1}}\sum_{y_1}\sum_{r} C^R_{sim,y_1,r}}{\frac{1}{n_{y_1}}\sum_{y_1}\sum_{r} C^R_{sim,y_1,r} + C_{sim,y_1,r}} \qquad (6.3)$$

where C'_{sim} is the relative harvest indicator in replicate simulation *sim*

$C_{sim,y,r}$ is the retained catch in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r*

$C^{R}_{sim,y,r}$ is the released catch in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r*

4. The harvest indicators were calculated by adding the amount of fish released and the amount of fish retained across all reefs. These values were averaged across the years 2011-2015 and 2021-2025. The performance indicator that concerned legal retentions was calculated by dividing the average amount of fish retained across all reefs during the respective interval (2011-2015 or 2021-2025) by the average amount of fish caught (released plus retained) during the respective interval. Similarly, the performance indicator that concerned quota was calculated by dividing the average amount of fish retained across all reefs during the respective interval by the relevant quota level., The proportion of the 100 replicated simulations that satisfied the management objective defined the probability that the objective was met.

$$C'_{sim} = \frac{\frac{1}{n_{y_1}}\sum_{y_1}\sum_{r} C_{sim,y_1,r}}{K^*} \qquad (6.4)$$

where C'_{sim} is the relative harvest indicator in replicate simulation *sim*

$C_{sim,y,r}$ is the retained catch in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r*

K^* is either the quota level or the average total amount of fish caught $\frac{1}{n_{y_1}}\sum_{y_1}\sum_{r} C_{sim,y_1,r} + C^{R}_{sim,y_1,r}$

$C^{R}_{sim,y,r}$ is the released catch in replicate simulation *sim*, in year *y* (*ref* is reference year) on reef *r*

5. The big fish indicator was calculated by averaging the proportion of big fish (>50 cm) in the catch across all reefs for each year of the projection period. These were then averaged across the years 2011-2015 and 2021-2025:

$$B^*_{sim} = \frac{1}{n_{y_1}}\sum_{y}\sum_{r} B^*_{sim,y,r} \qquad (6.5)$$

where B^*_{sim} is the size indicator for fish >50 cm in replicate simulation *sim*

$B^*_{sim,y,r}$ is the proportion of fish >50 cm on reef *r*, in year *y* and replicate simulation *sim*

6. Results

6.1. Vessel dynamics model (TripSim)

6.1.1. Spawning biomass

One of the objectives concerning spawning biomass (mature female biomass) of both Coral Trout and Red Throat Emperor was that it should be above unfished, pre-exploitation, levels 100% of the time. An additional objective was that it should be above unfished, pre-exploitation, levels 50% of the time. Figure 6.1 shows that no management strategy came close to achieving either of these objectives. This result is hardly surprising because stochastic processes in the biological model mean that even in the absence of fishing the population fluctuates around its unfished value, and so the probability that the spawning biomass exceeds the unfished level is unlikely to exceed 50%. The reason that such hopeful objectives for the fishery were formulated at the stakeholder workshops was due to rather high expectations resulting from the recently implemented RAP management arrangements.

An alternative objective, analogous to previous objectives (Mapstone et al. 2004) was to expect spawning biomass to be above 90% of the unfished level, either 100% of the time, or 50% of the time. The results of the simulations as they apply to this objective are shown in Fig. 6.2. It is apparent that these objectives are closer to being achieved. Reducing fishing effort to 50% of 1996 levels achieved the second of these objectives for Coral Trout, but not quite for Red Throat Emperor. No other strategy achieved either of these objectives, mainly because a large portion of the Marine Park is still fished.

Figure 6.3 shows the average spawning biomass relative to the unfished level over the whole Marine Park for the different management strategies. The values in Fig. 6.3 range between about 0.6 to 0.9. The same results are shown in Fig. 6.4, except instead of referencing the spawning biomass to a year (e.g., the unfished level) they are instead referenced to a management strategy. This management strategy is that closest to that which was operating when the simulations were run, i.e. RAP closures, 1996 Effort, three 9-day spawning season closures that remove effort, and a 38 cm minimum legal size (MLS), and is referred to as the current management strategy. Figure 6.4 shows that the management strategies that reduce effort, including the three month spawning closure (September – November) which effectively stops fishing in these months, resulted in more spawning biomass than the current management strategy. The only other management strategy to result in higher spawning biomass than the current strategy, although only marginally, was increasing the area closures to 50% while keeping the effort at 1996 levels. In contrast, strategies that increase the accessibility of smaller fish to the fishery lead to notably less spawning biomass than the current management strategy.

Other objectives pertained to specific partitions of the reefs (i.e., into closed and open areas) and addressed the different values (e.g., conservation or stock) with which they are associated. The closed reefs address the conservation imperative, and Fig. 6.5 shows the probability of the management strategies achieving the objective of attaining unfished spawning biomass levels on the closed reefs, while Fig. 6.6 shows the probabilities of the management strategies achieving 90% of the unfished levels on the closed reefs. It is more likely that either of these objectives is achieved for Coral Trout than for Red Throat Emperor. The main reason for this is that Red Throat Emperor that are protected in areas closed to fishing, do not stay protected since it is assumed that adult Red Throat Emperor migrate among reefs.

Figure 6.6 shows that changes in effort have the greatest effect on getting the probability of leaving the spawning biomass on closed reefs above 90% of the unfished level. The management strategies that came closest to achieving this objective for Red Throat Emperor were those with effort reductions. The actual spawning biomass on closed reefs relative to unfished levels ranged between 0.6 and 0.9 for both species (Fig. 6.7); not surprisingly, more areas closed to fishing meant more spawning biomass on those reefs compared to the current management strategy (Fig. 6.8).

Other objectives expressed by stakeholders concerned the spawning biomass on the open reefs. The reference point and expected likelihood were similar to other objectives, and are shown in Figures 6.9 and 6.10. Since the open reefs are exploited, it is not surprising that the chance of the spawning biomass on these reefs approaching 100% (Fig. 6.9) or 90% (Fig. 6.10) is not very high. The actual average spawning biomass on the open reefs, relative to the unfished levels ranged between 0.5 and 0.9 (Fig. 6.11). Although these levels may seem high, and relatively unaffected by fishing for an exploited population, much of the spawning biomass is protected by the selectivity and size restrictions on both species. As a result, the spawning component on the exploited reefs would be reduced by up to 30% by reducing the MLS or selectivity (Fig. 6.12). We introduced the strategy of reduced size selectivity with changed retention lengths because we judged it plausible that fishers would change gear to target smaller animals if they were allowed to keep them.

The 3 month spawning closure from Sept-Nov, under RAP closures increased the spawning component on the open reefs, mainly because this strategy resulted in an effort reduction. Our approach to modelling spawning closures was to simply remove the associated effort during the closure period. We addressed variations on this by redistributing effort to other months, instead of removing it, and by having no spawning closure at all. Under these management strategies, the spawning component on the open reefs was marginally smaller than under the comparable current management strategy.

The management objectives concerning spawning biomass related not only to the pre-exploitation or unfished levels, but also to the levels that might have been experienced, namely the spawning biomass levels in 2000. The results of the simulations concerning the management objective of achieving the levels of spawning biomass in 2000, across all reefs in the Marine Park (i.e., reefs open and closed to fishing) are shown in Fig. 6.13. Almost all of the strategies for both species led to spawning biomasses above the 2000 level more than 50% of the time. The exception was the combined effect of reduced selectivity and the slot size restriction (which had a MLS of 28 cm). The strategies with the current spawning closure, MLS and selectivity, and even the reduced effort seasonal closure (Sept–Nov seasonal closure) approached having spawning biomass above 2000 levels 100% of the time. The actual spawning biomass in the simulations over the whole Marine Park ranged between 0.8 and 1.4 of the 2000 level, depending on management strategy and species (Fig. 6.14).

All strategies achieve the easier objective of maintaining the spawning biomass on closed reefs above the 2000 levels 50% of the time (Fig. 6.15). Most strategies also come close to achieving above the 2000 levels of spawning biomass on closed reef 100% of time. Only the reduced gear selectivity strategy with the slot limit did not achieve either of these objectives for Red Throat Emperor (Fig. 6.15). Once again the vulnerability of the migratory Red Throat Emperor on closed reefs is apparent since the chance of achieving the 2000 level of spawning biomass on the closed reefs is lower for Red Throat Emperor than for Coral Trout (Fig. 6.15). This is shown most clearly in Fig. 6.16, which shows the actual spawning biomass on the closed reefs relative to their 2000 levels, and that increasing the amount of area closed to fishing to 50% had a greater effect for Coral Trout than Red Throat Emperor.

The chances of the spawning biomass on the open reefs exceeding the 2000 spawning biomass are shown in Fig 6.17. Increasing the closure levels (decreasing the areas open to fishing) lead to slightly reduced chances of achieving the objectives, presumably because increasing the amount of closures without changing the total amount of effort leads to increasing fishing mortality on the open reefs. The actual spawning biomass on the open reefs relative to their 2000 levels (Fig. 6.18) is higher for Coral Trout than for Red Throat Emperor.

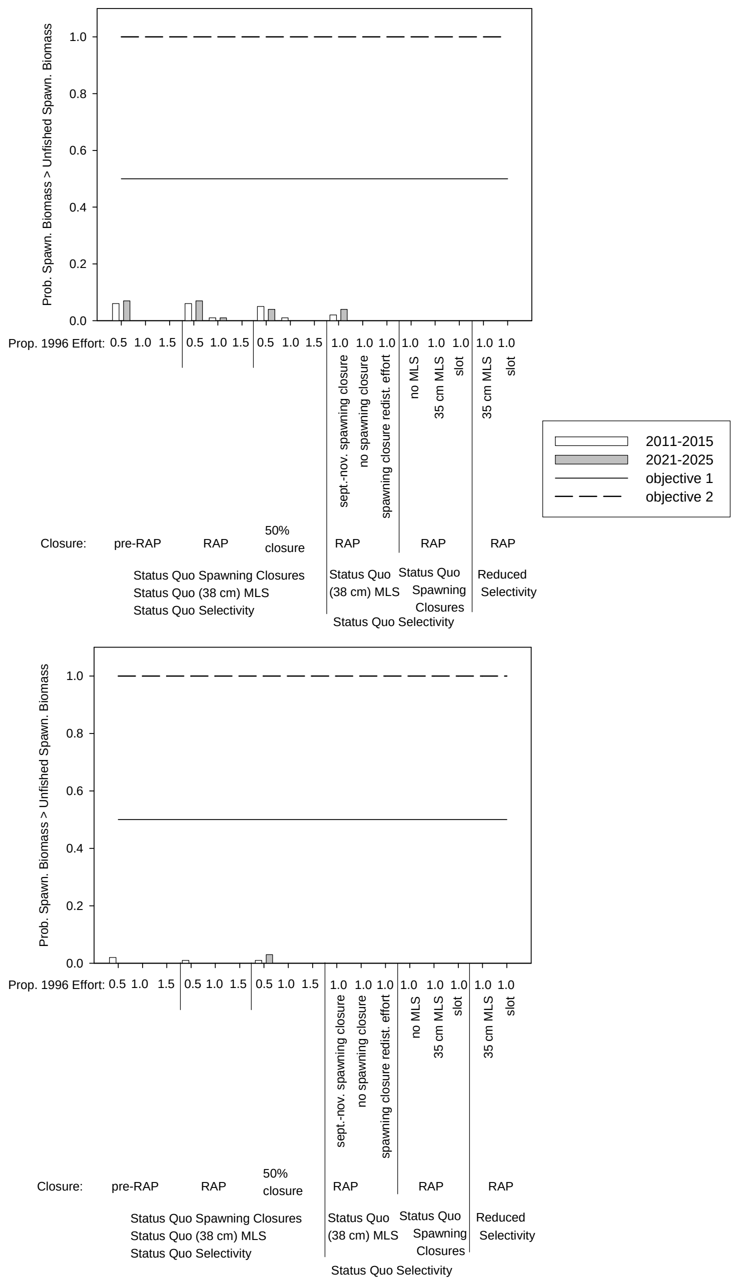


Fig. 6.1. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) exceeds the unfished spawning biomass

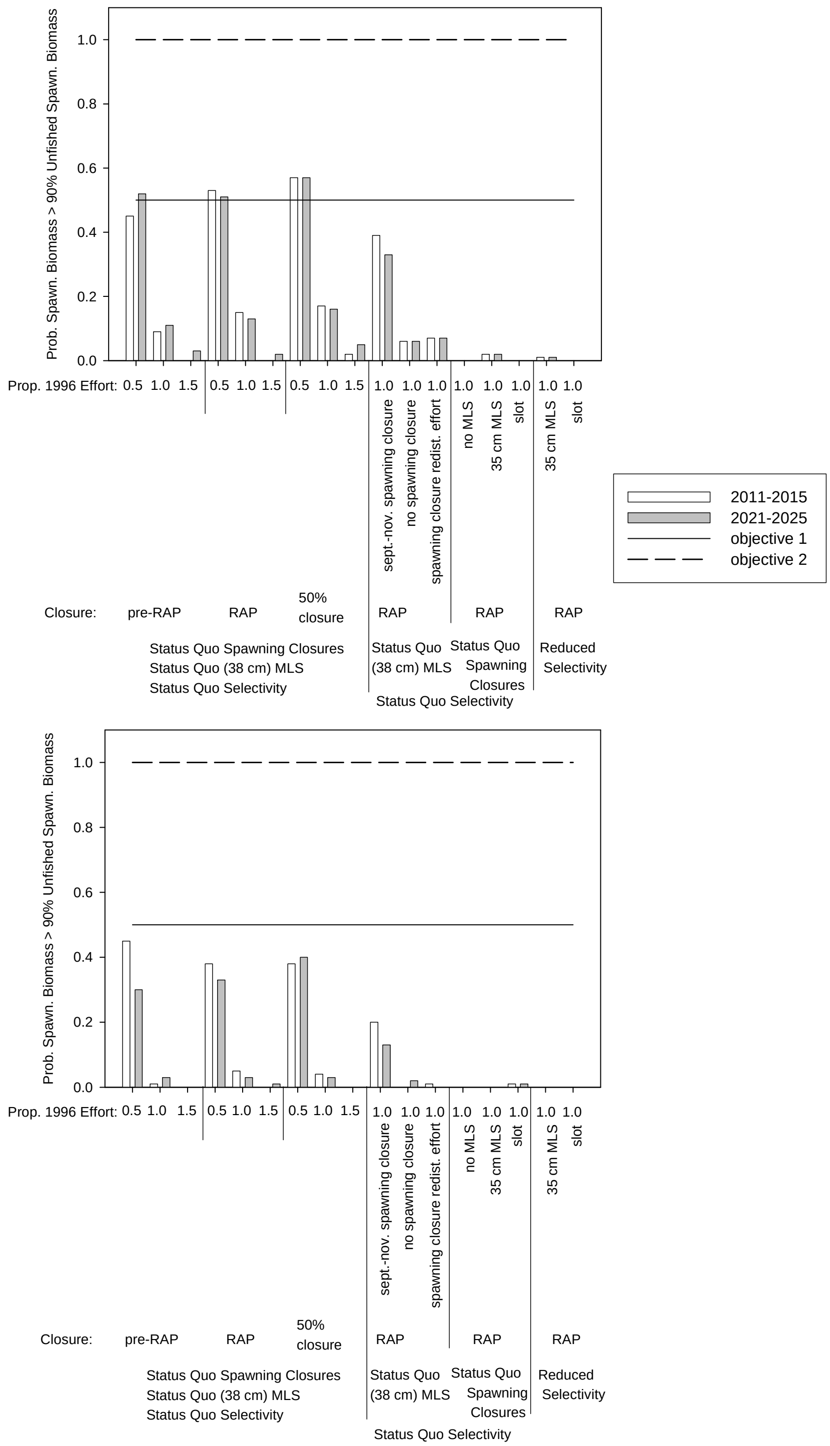


Fig. 6.2. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) exceeds 90% of the unfished spawning biomass.

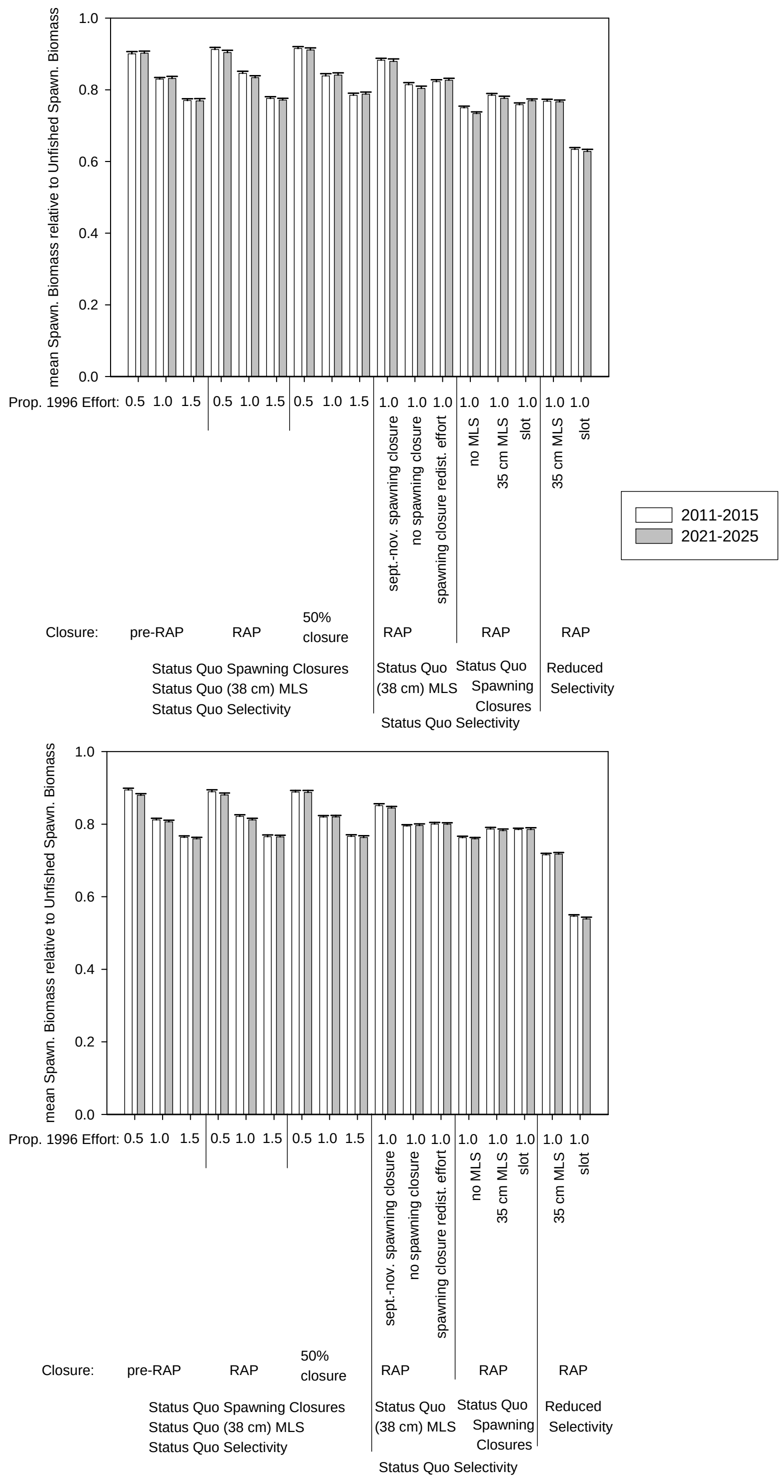


Fig. 6.3. Average (+SE) spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to unfished levels under the vessel dynamics model.

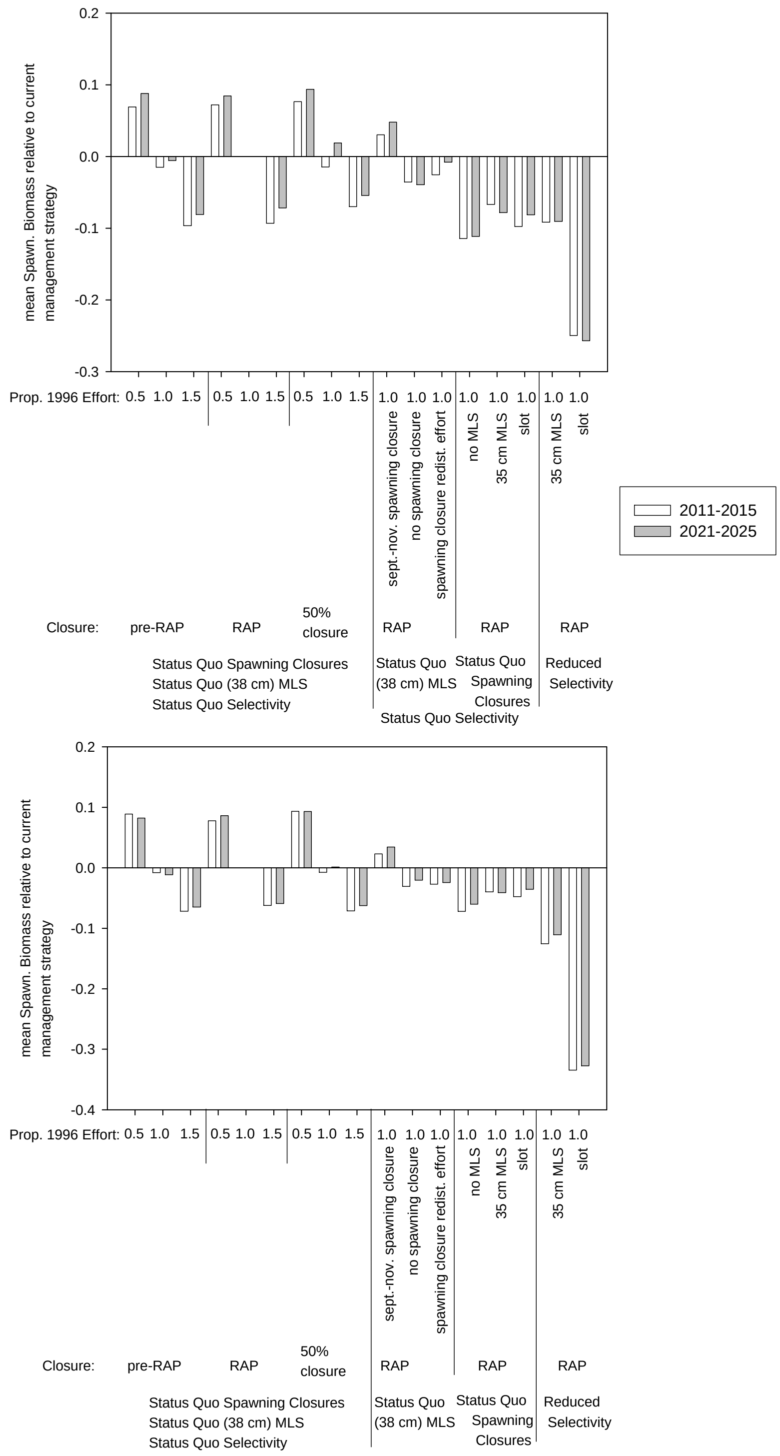


Fig. 6.4. Average spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the current management strategy, under the vessel dynamics model.

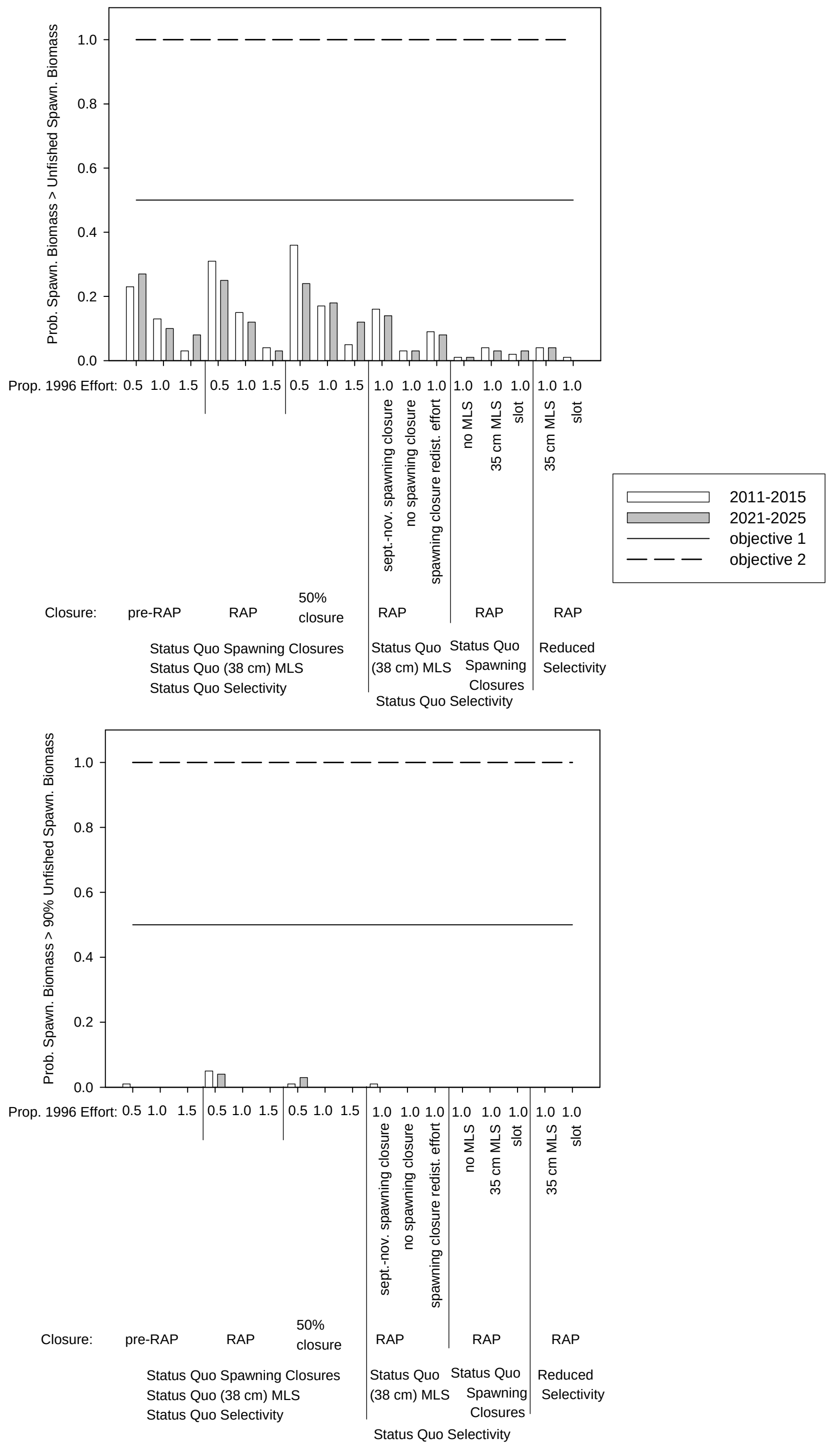


Fig. 6.5. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) on the closed reefs is greater than the unfished spawning biomass on these reefs.

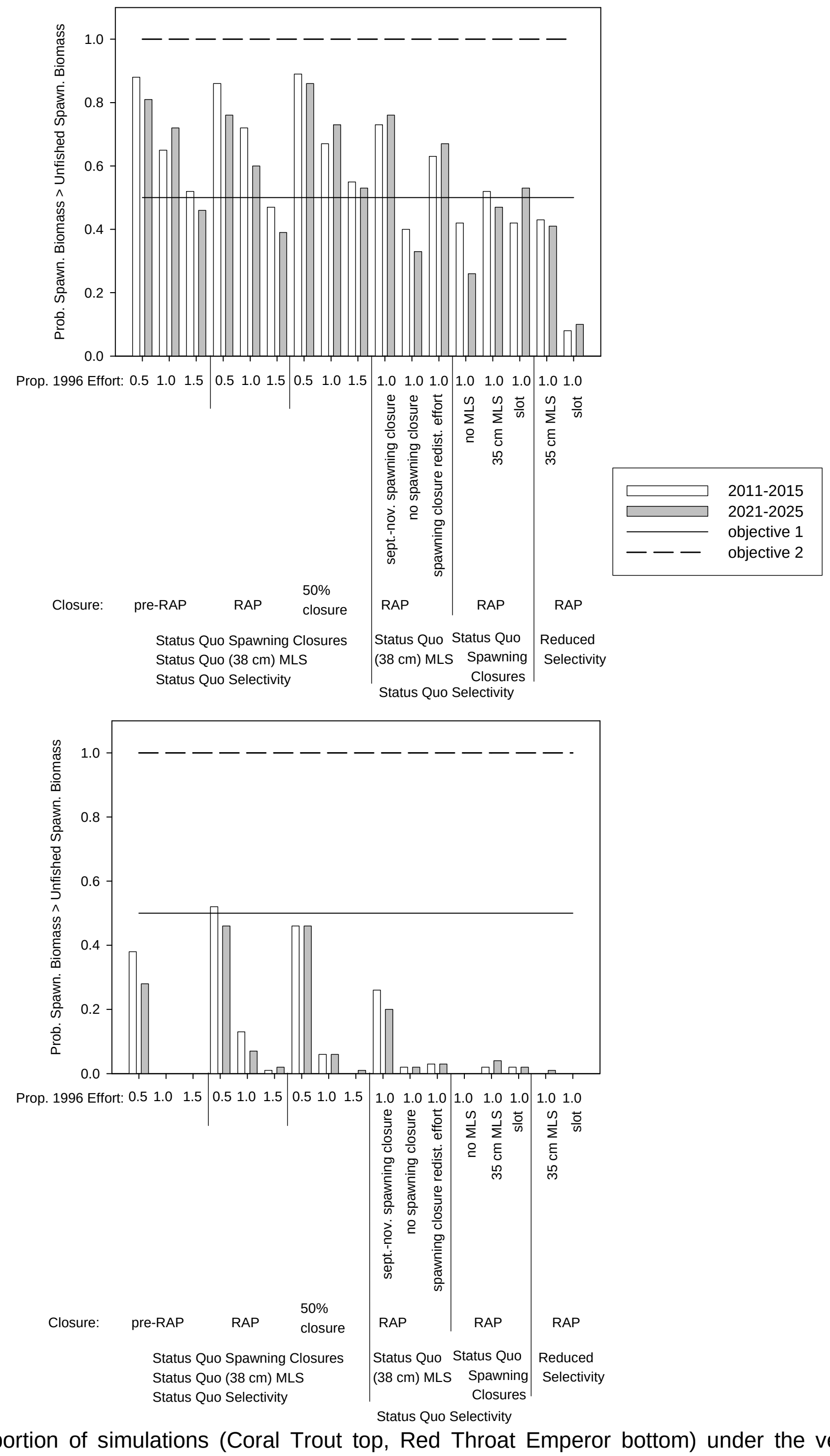


Fig. 6.6. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) on the closed reefs is greater than 90% of the unfished spawning biomass on these reefs.

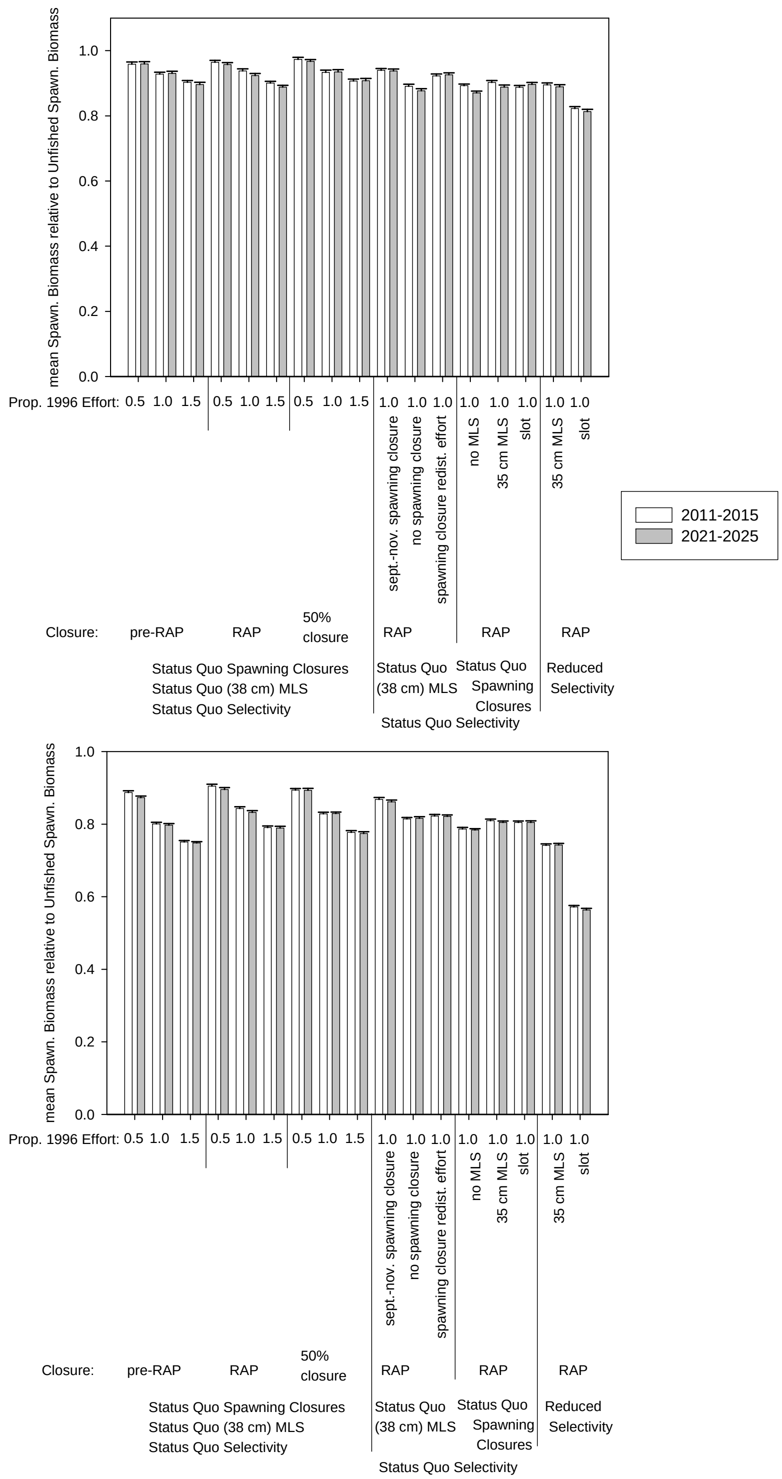


Fig. 6.7. Average (+SE) spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the closed reefs relative to unfished levels, under the vessel dynamics model.

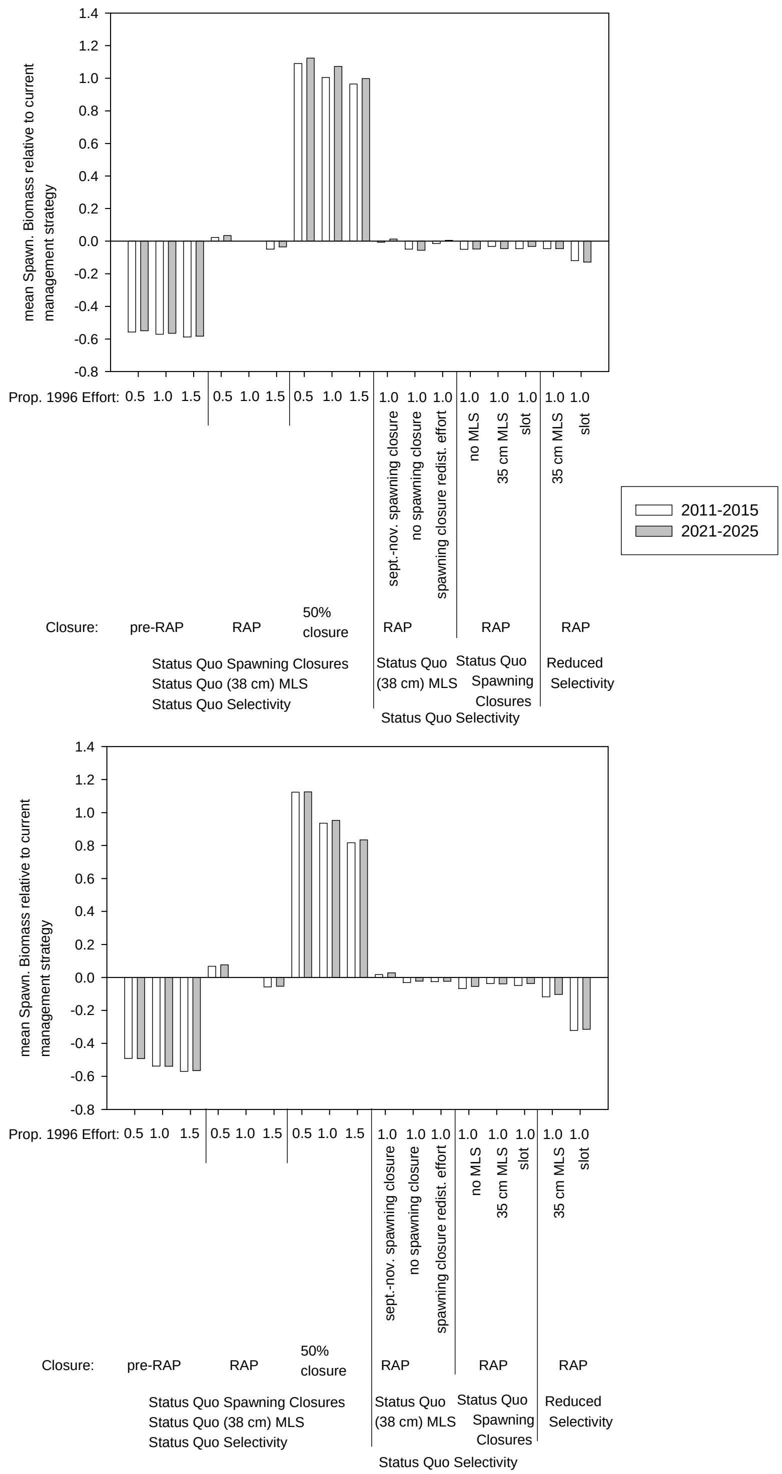


Fig. 6.8. Average spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the closed reefs relative to the current management strategy, under the vessel dynamics model.

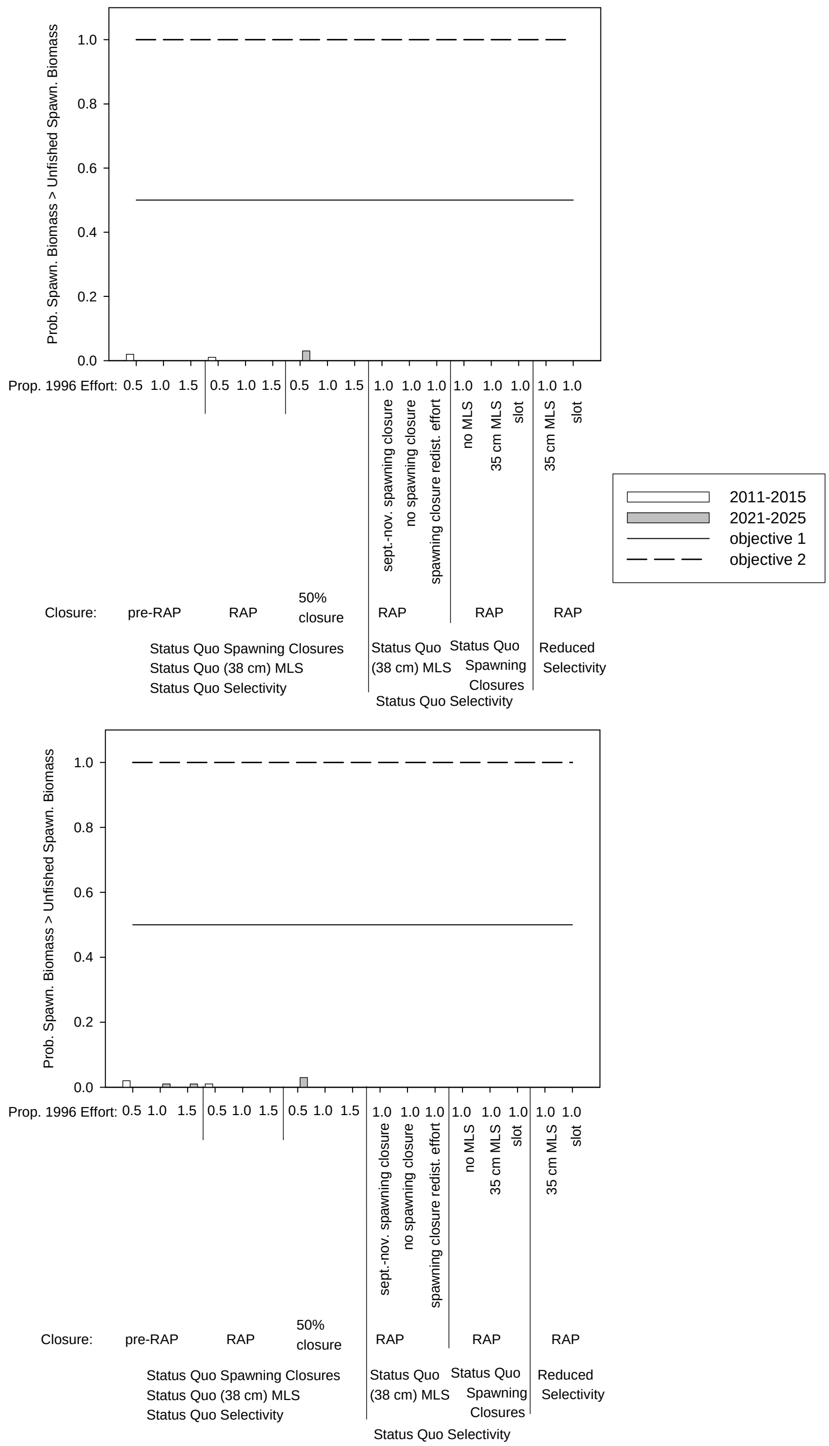


Fig. 6.9. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) on the open reefs is greater than the unfished spawning biomass on these reefs.

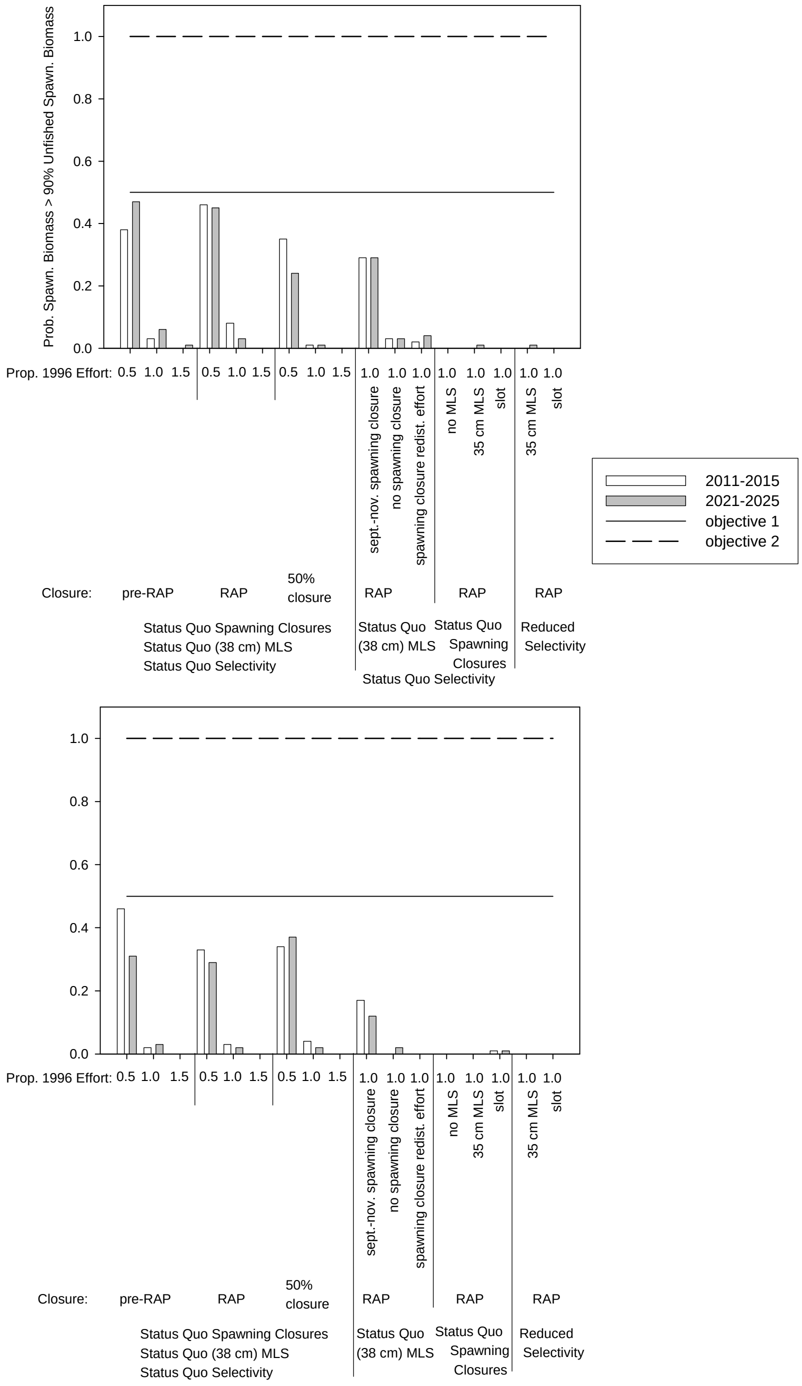


Fig. 6.10. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning Biomass (2011-2015 and 2021-2025) on the open reefs is greater than 90% of the unfished spawning biomass on these reefs.

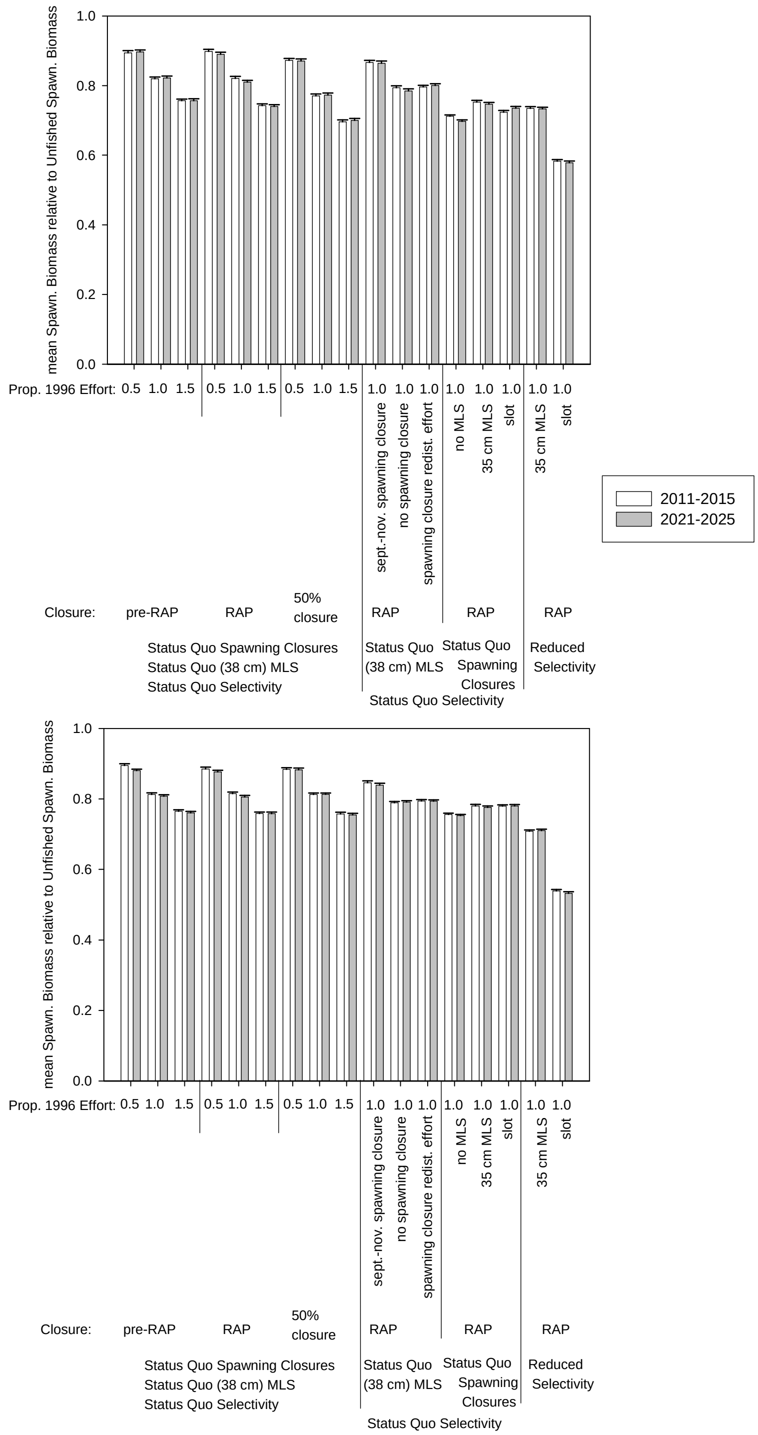


Fig. 6.11. Average (+SE) spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the open reefs relative to the unfished spawning biomass on these reefs, under the vessel dynamics model.

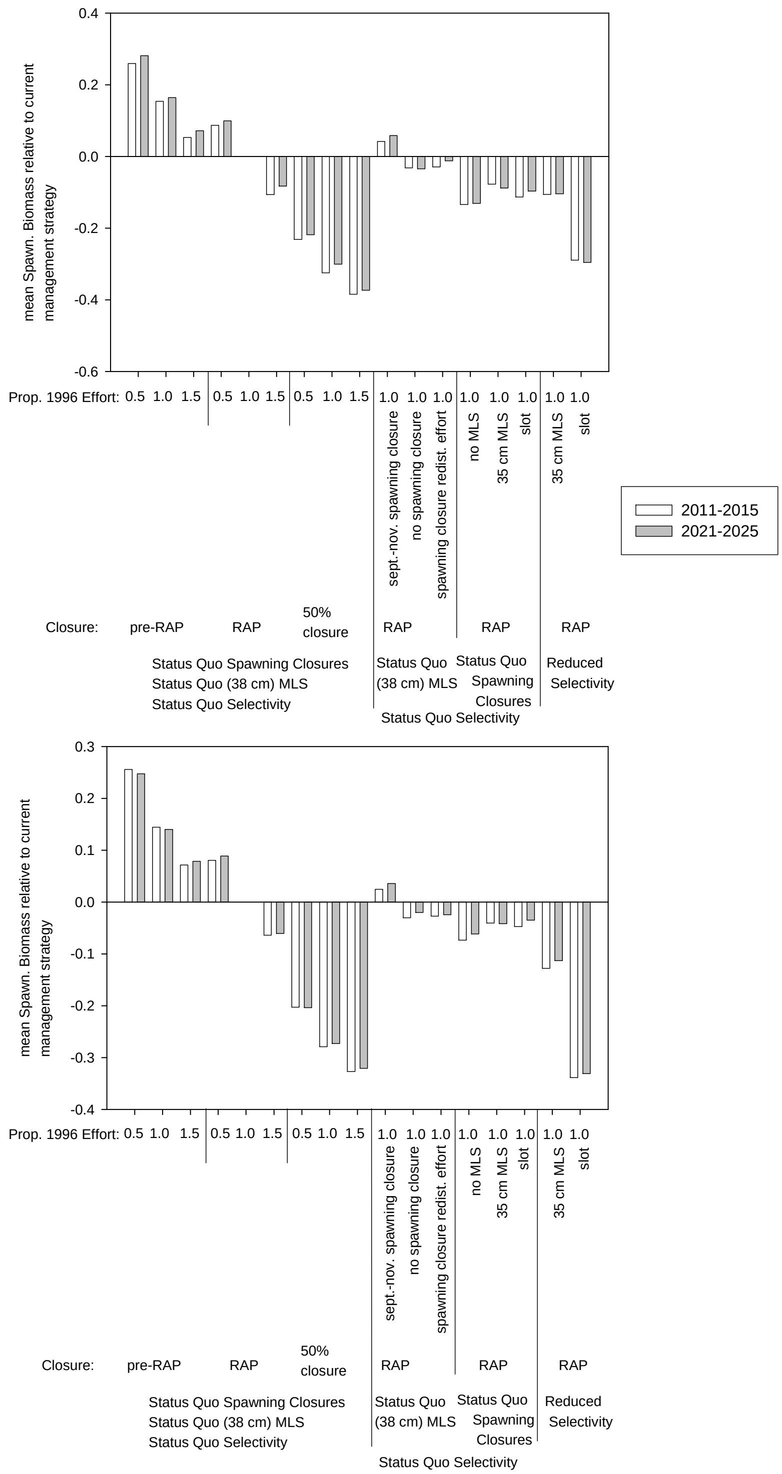


Fig. 6.12. Average spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the open reefs relative to that under the current management strategy, under the vessel dynamics model.

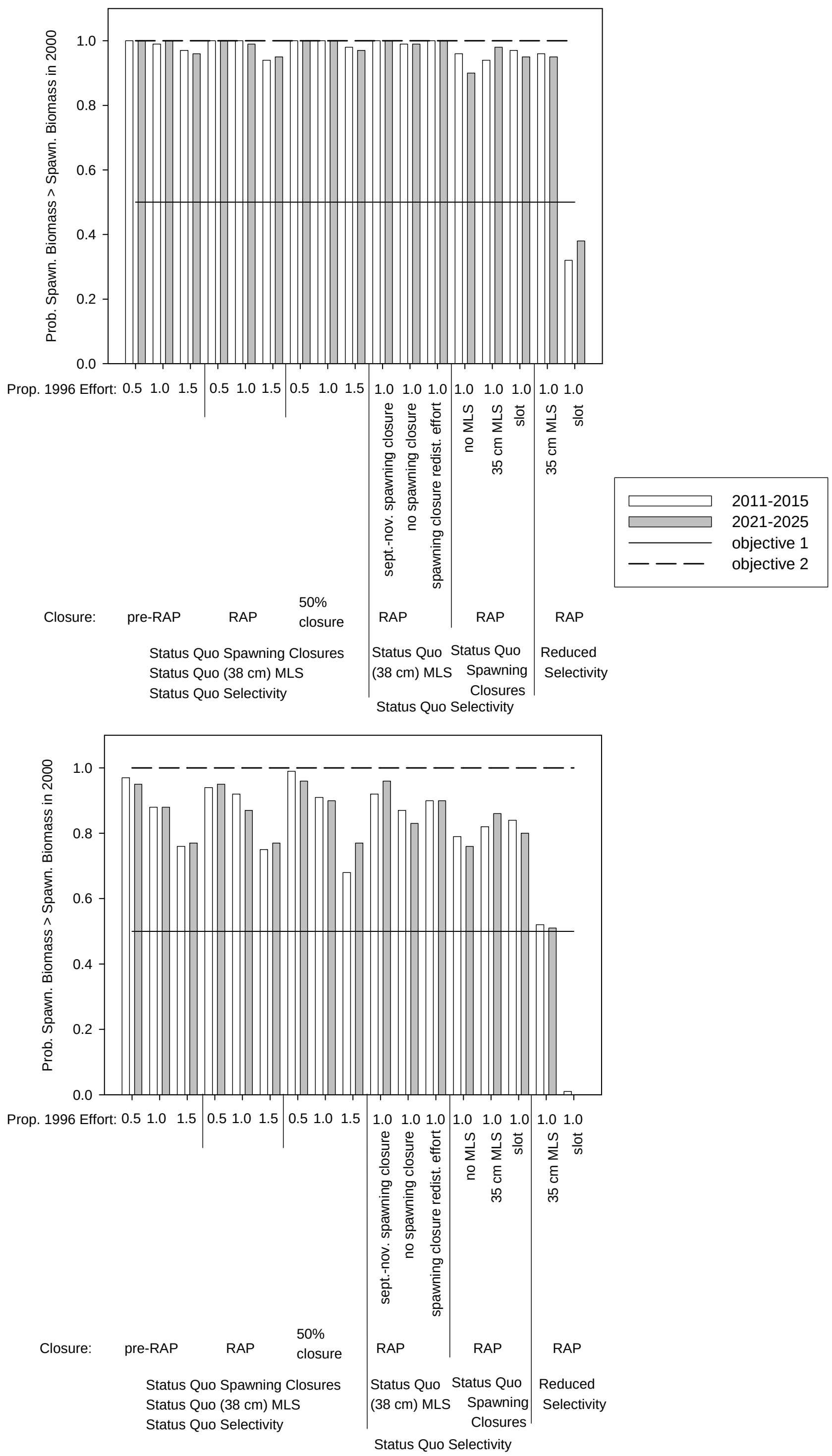


Fig. 6.13. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) is greater than the 2000 spawning biomass.

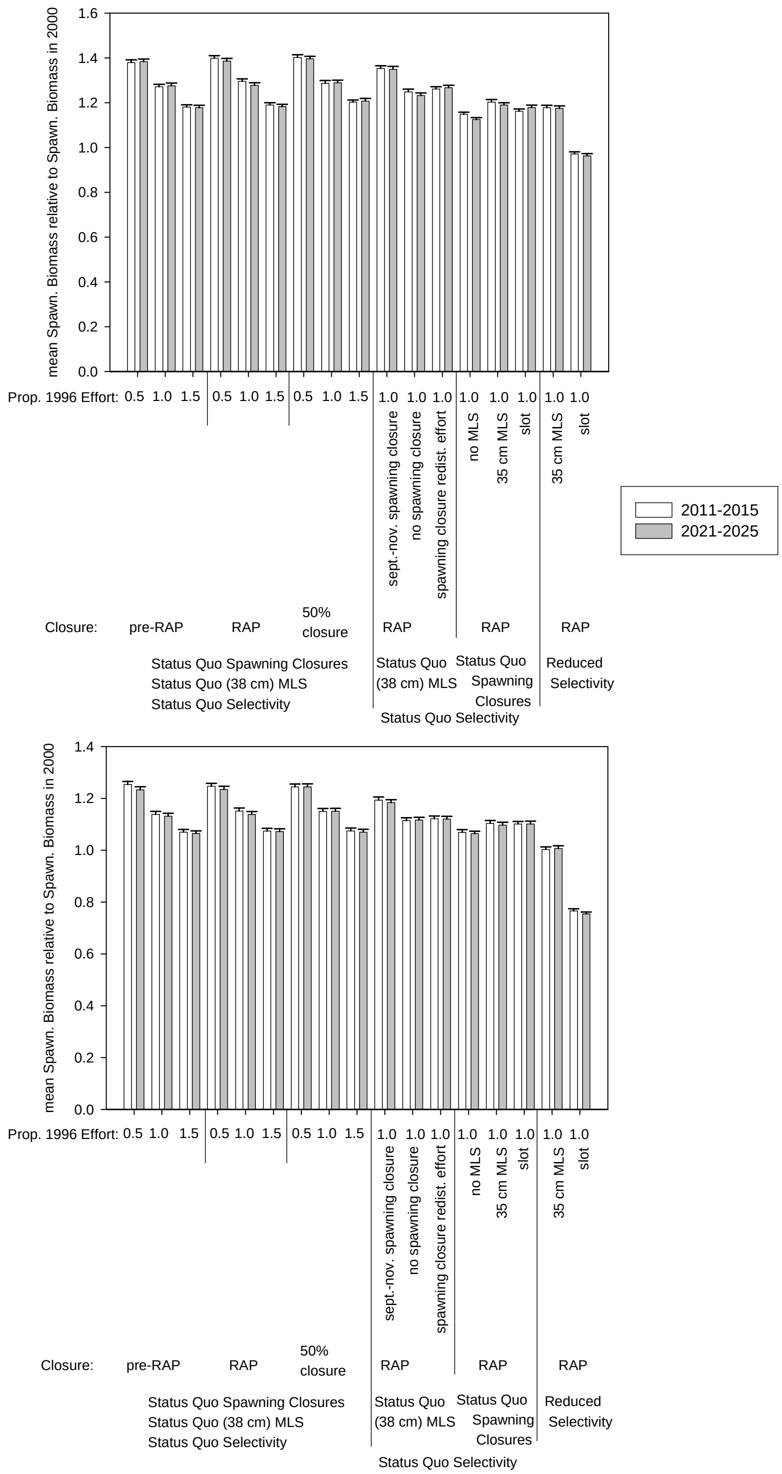


Fig. 6.14. Average (+SE) spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the 2000 spawning biomass, under the vessel dynamics model.

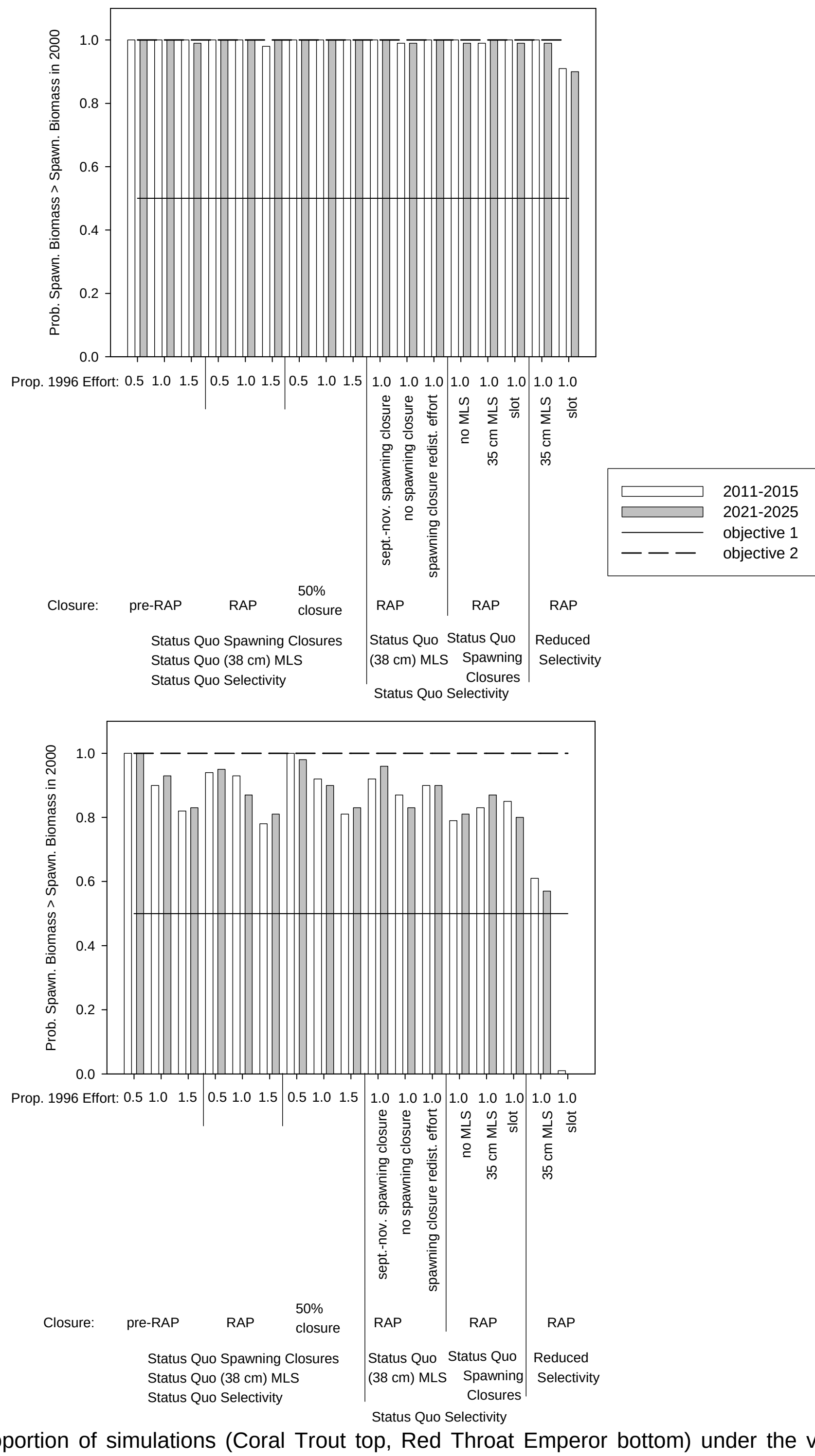


Fig. 6.15. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) on the closed reefs is greater than the spawning biomass on these reefs in 2000.

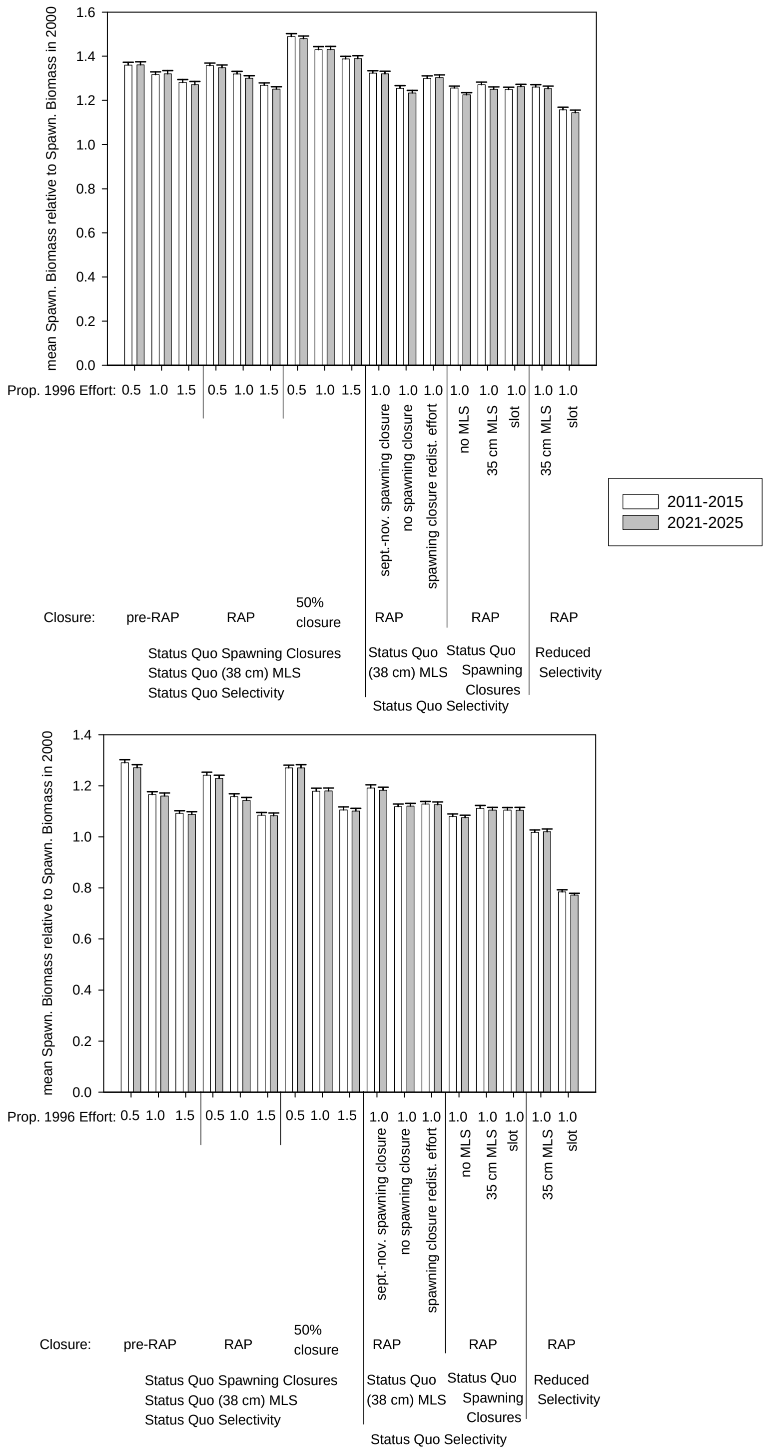


Fig. 6.16. Average (+SE) spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the closed reefs relative to the spawning biomass on these reefs in 2000, under the vessel dynamics model.

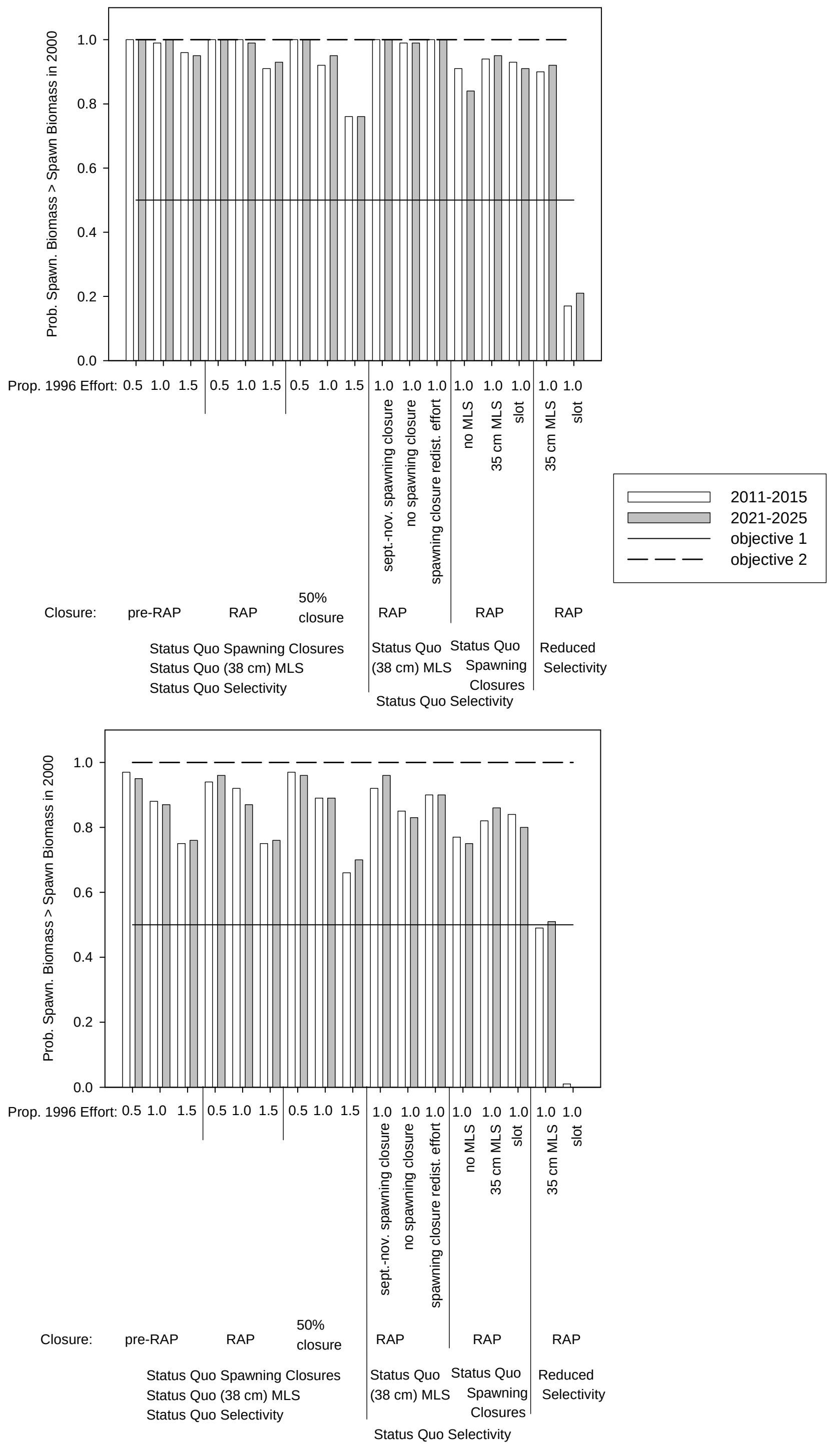


Fig. 6.17. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average spawning biomass (2011-2015 and 2021-2025) on the open reefs is greater than the spawning biomass on these reefs in 2000.

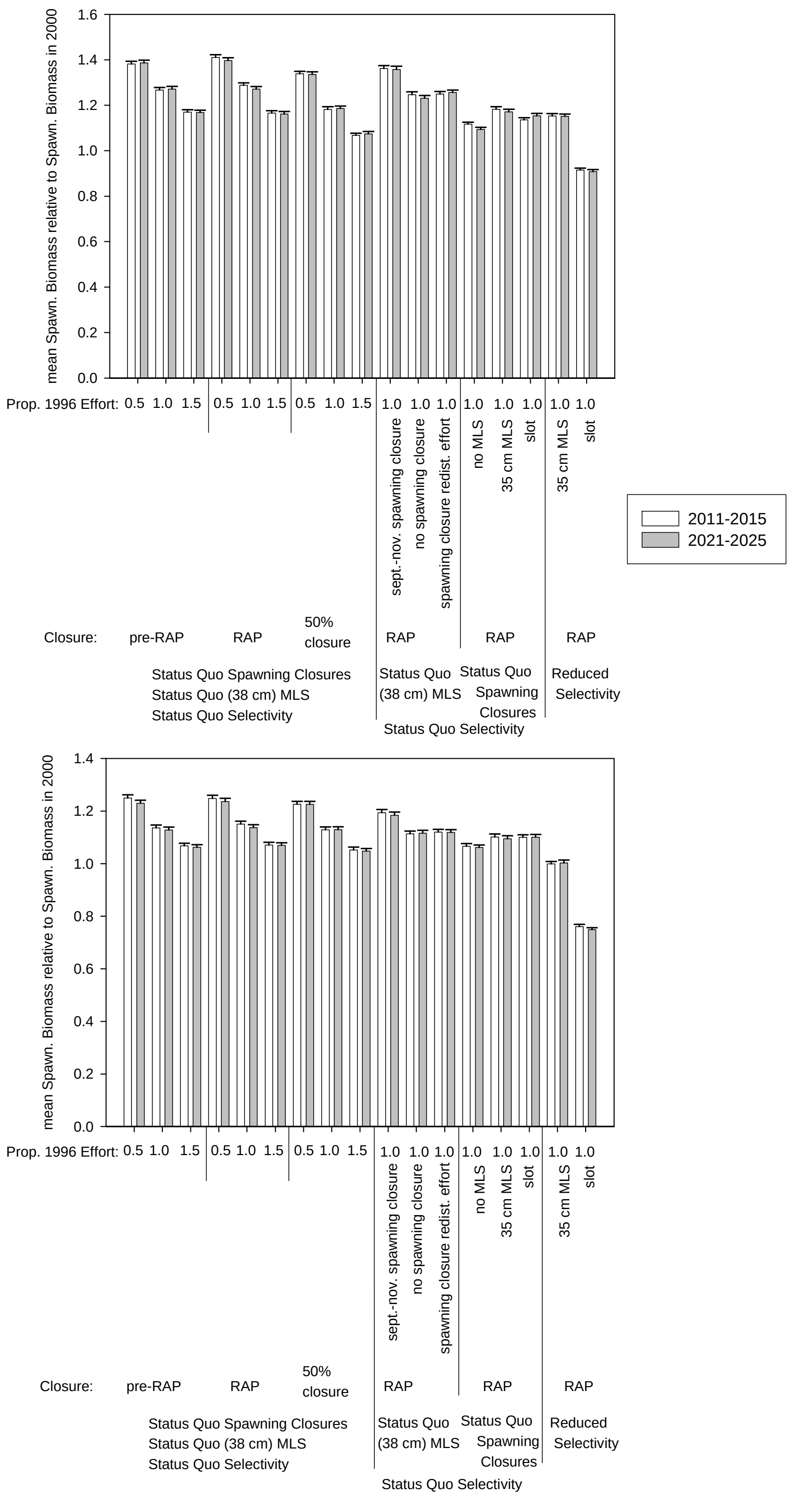


Fig. 6.18. Average (+SE) spawning biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the open reefs relative to the spawning biomass on these reefs in 2000, under the vessel dynamics model.

6.1.2 Available biomass

In common with the objectives for spawning biomass, those concerning available biomass (the biomass that could be selected by the gear and, if caught, legally retained by the fishery) specified that, for both Coral Trout and Red Throat Emperor, available biomass should be above unfished, pre-exploitation, levels 100% of the time, or alternatively 50% of the time. Figure 6.19 shows that, as for spawning biomass, no management strategy came close to achieving either of these objectives. The reason again was that the available biomass would not be above the average unfished level all or most of the time even in the absence of exploitation. The alternative objective, analogous to previous objectives (Mapstone et al. 2004), would be to expect available biomass to be above 30% of the unfished level, either 100%, or 50% of the time; all of the management strategies achieve these two objectives (Fig. 6.20) The ratio of the average available biomass to the unfished average available biomass ranges from 0.55 to 0.8 for Coral Trout, and from 0.5 to 0.75 for Red Throat Emperor (Fig 6.21).

A comparison of performance relative to the current management strategy (see Fig. 6.4 for spawning biomass) was not made for the available biomass because the definition of available biomass differs among the management strategies. For example, the current management strategy defines available biomass as all fish that could be selected by the current gear (Status Quo selectivity) and of legal size, i.e., above the 38 cm MLS. The available biomass under the No MLS management strategy, however, is all fish that could be selected by the current gear, irrespective of their size. When comparisons are made relative to another point in time, it is necessary to calculate the available biomass in the reference year as it is calculated for that management strategy. This was done for the current results. What is needed when comparing management strategies to a reference strategy like the current management, therefore, is a common definition of biomass (e.g. spawning biomass). Thus, to compare among strategies we use total biomass, defined independently of MLS and arbitrarily as all fish > 20 cm since almost no fish under 20 cm would be selected by any of the gears we modelled.

When the reefs are partitioned into closed and open areas, the probability of the management strategies achieving the objective of leaving the available biomass on the closed reefs above its unfished level, was slightly higher for Coral Trout than for Red Throat Emperor, but nevertheless fairly low (Fig. 6.22). Figure 6.23 shows the probabilities of the management strategies leaving the available biomass on the closed reefs above 30% of the unfished levels. This objective was met with 100% probability by all strategies. This is hardly surprising given the result shown in Fig. 6.21 which suggests that the total available biomass (over all reefs) exceeds 30% of the unfished level. The ratio of the available biomass on closed reefs relative to the corresponding unfished level varies substantially between the two species (Fig. 6.24). For Coral Trout, the available biomass relative to unfished levels on the closed reefs was above 0.8, while for Red Throat Emperor it varied between 0.45 and 0.8. As before, the last result can be attributed to the movement dynamics of Red Throat Emperor.

Other objectives expressed by the stakeholders concerned the available biomass on the open reefs. This is the principal objective relating to the harvestable stock and its status. Figure 6.25 shows, not surprisingly, that no management strategy managed to leave the available biomass on the open (fished) reefs above the unfished level. Once again, the reason that such hopeful objectives were formulated was due to the increased expectations in the performance of the recently implemented RAP management arrangements. It is clear that the RAP closures, or any management arrangements, including closing the fishery, would not achieve the objective of attaining greater than unfished biomass 100% of the time. In addition, it is also highly unlikely that the available biomass on the open reefs would exceed unfished levels more than 50% of the time under any of the proposed levels of fishing effort. However, if the objective was to maintain available biomass on open reefs above 30%

of the unfished levels, either 100% or 50% of the time, then these objectives can be achieved under all of the management strategies considered (Fig. 6.26). The ratio of the average available biomass on the open reefs to the unfished available biomass on these reefs was similar for both species, and ranged from between 0.4 to 0.8 (Fig. 6.27).

Stakeholders also identified management objectives in terms of the status of the available biomass relative to that in 2000. Almost all of the management strategies achieved the objective of leaving the available biomass of Coral Trout above the 2000 level (Fig. 6.28), while this objective was achieved for Red Throat Emperor for the management strategies that did not increase effort. The management strategies with a maximum legal size also did poorly in terms of this objective. The ratio relative to the 2000 available biomass across all of the reefs is shown in Fig. 6.29.

The objective that available biomass on closed reefs should be above the 2000 levels 50% or 100% of the time was more likely to be achieved for Coral Trout than for Red Throat Emperor (Fig. 6.30). Higher effort levels meant that it was less likely to achieve this objective for Red Throat Emperor, owing to the effect of adult fish movement. Also, a lower MLS led to slightly lower probability that the available biomass on the closed reefs would be above that in 2000. Not surprisingly, the ratio of available biomass on the closed reefs to available biomass on those reefs in 2000 is higher for Coral Trout than Red Throat Emperor (Fig. 6.31).

The objective that the available biomass should be above the 2000 levels 50% or 100% of the time is less likely to be met on the open reefs if effort is 150% of that in 1996 and area closures were at 50%, or if slot length restrictions are imposed, especially for Red Throat Emperor (Fig. 6.32). The ratio of the available biomass to that in 2000 is somewhat similar for both species, ranging between about 0.8 and 1.7 (Fig. 6.33).

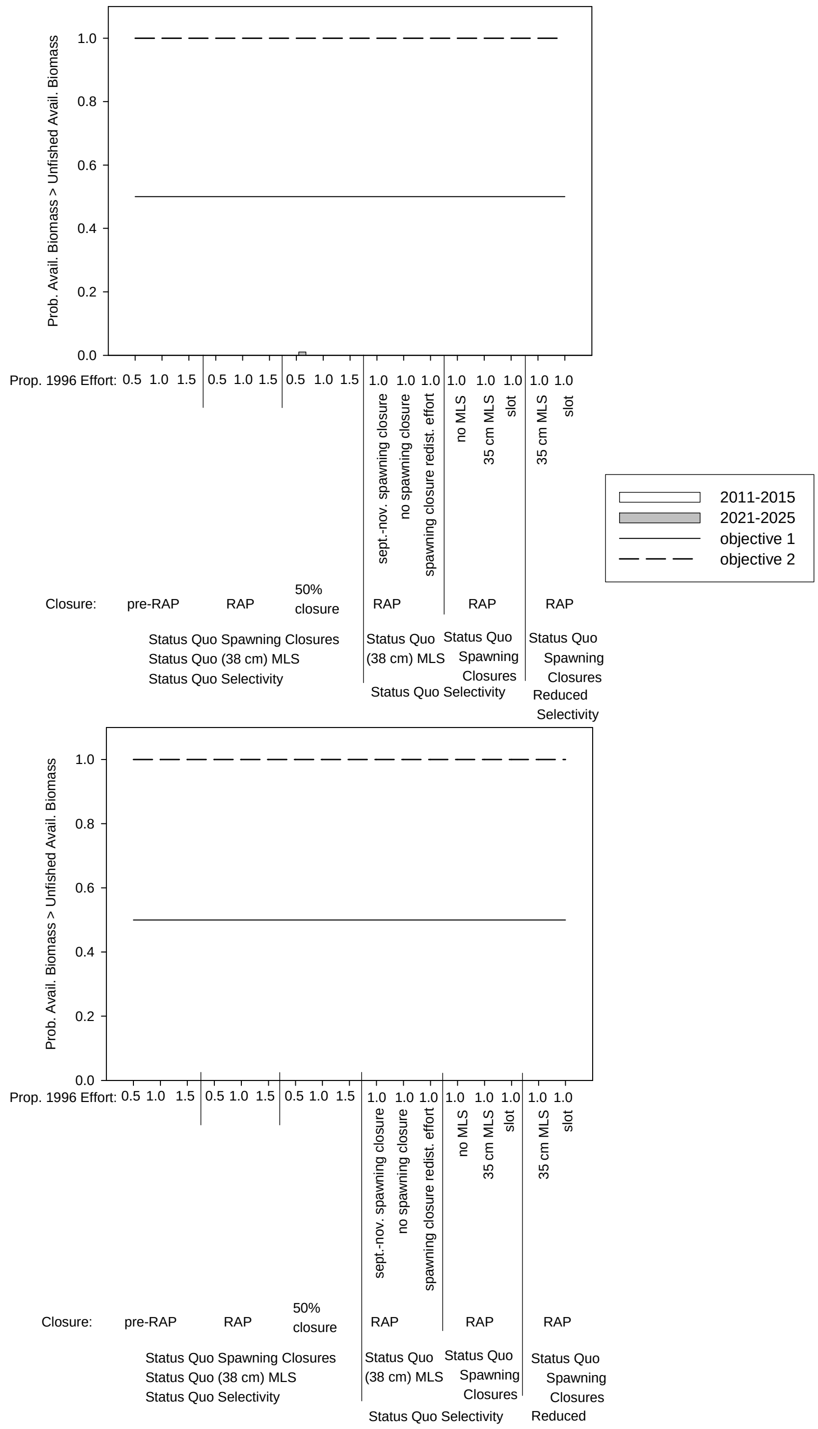


Fig. 6.19. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average available biomass (2011-2015 and 2021-2025) is greater than the unfished available biomass.

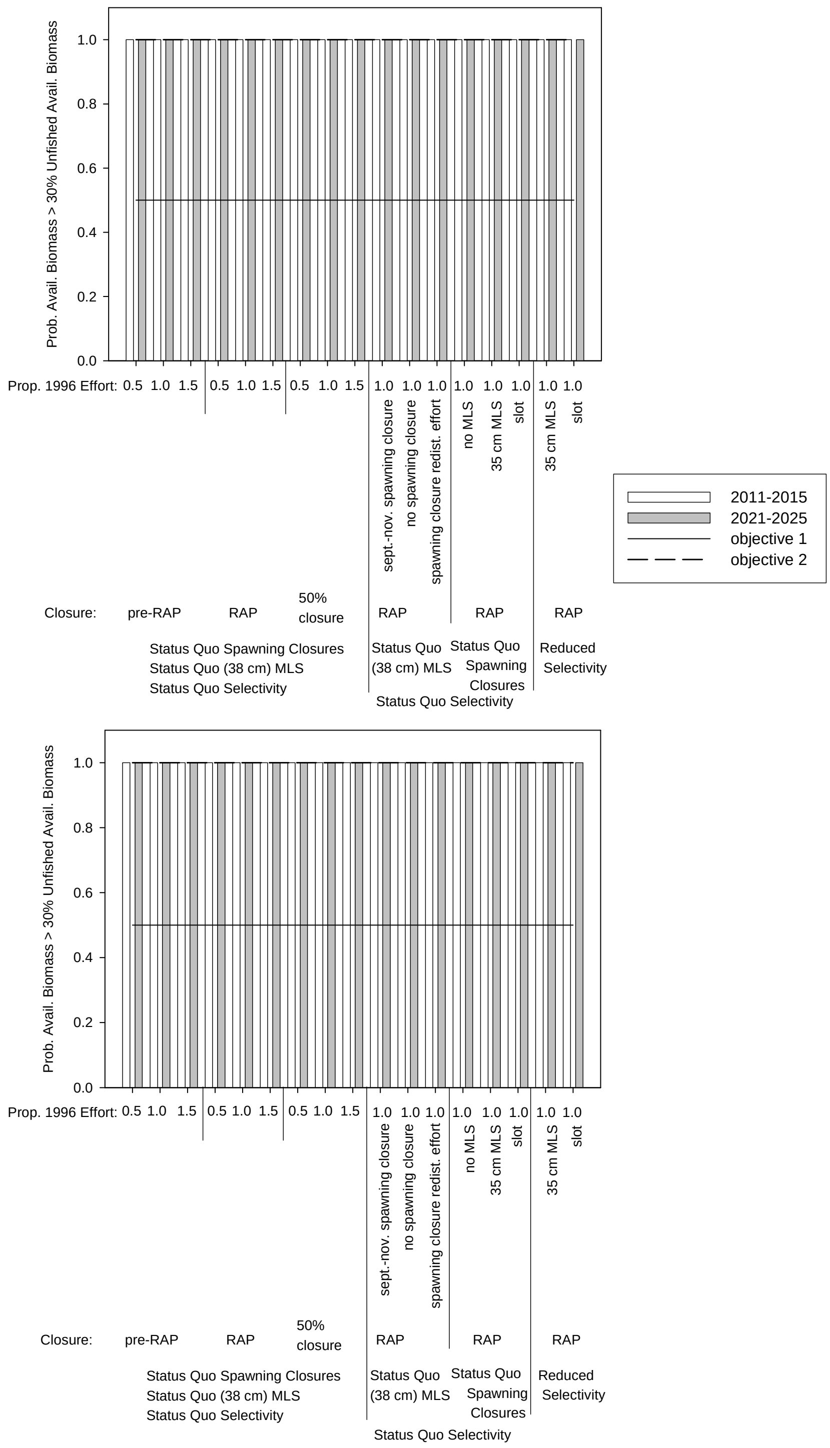


Fig. 6.20. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average available biomass (2011-2015 and 2021-2025) is greater than 30% of the unfished available biomass.

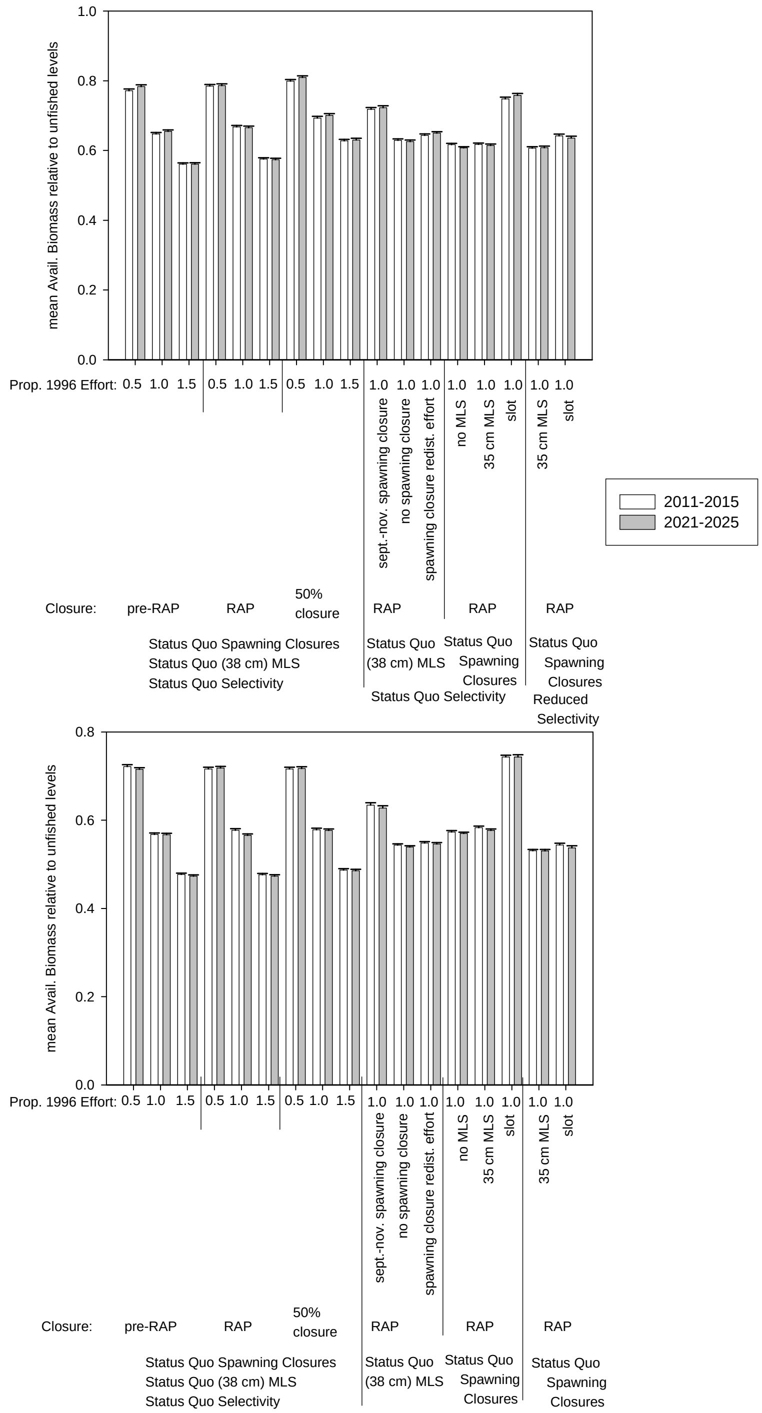


Fig. 6.21. Average (+SE) available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the unfished available biomass, under the vessel dynamics model.

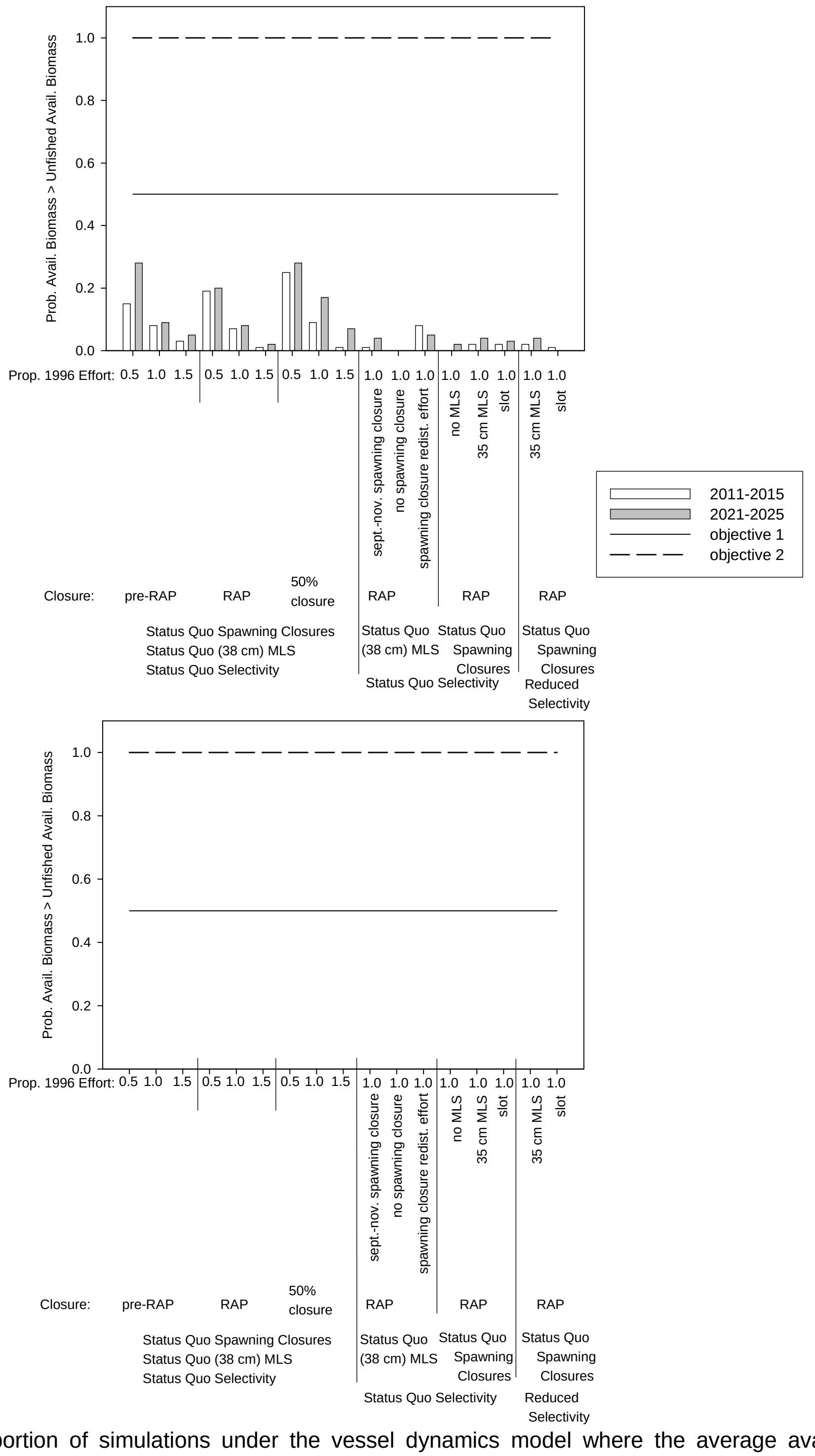


Fig. 6.22. Proportion of simulations under the vessel dynamics model where the average available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the closed reefs is greater than the unfished available biomass on these reefs.

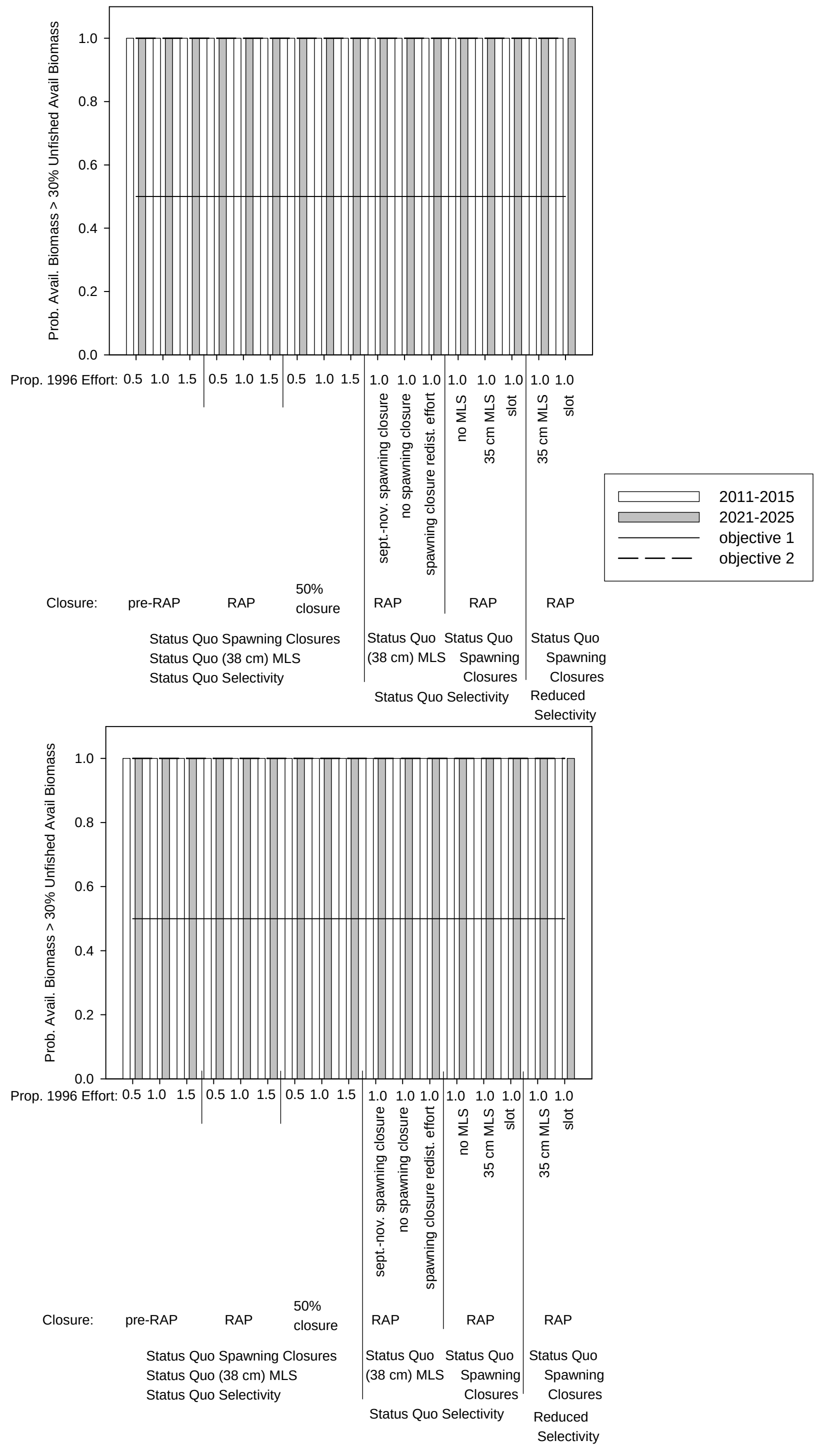


Fig. 6.23. Proportion of simulations under the vessel dynamics model where the average available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on closed reefs is greater than 30% of the unfished available biomass on these reefs.

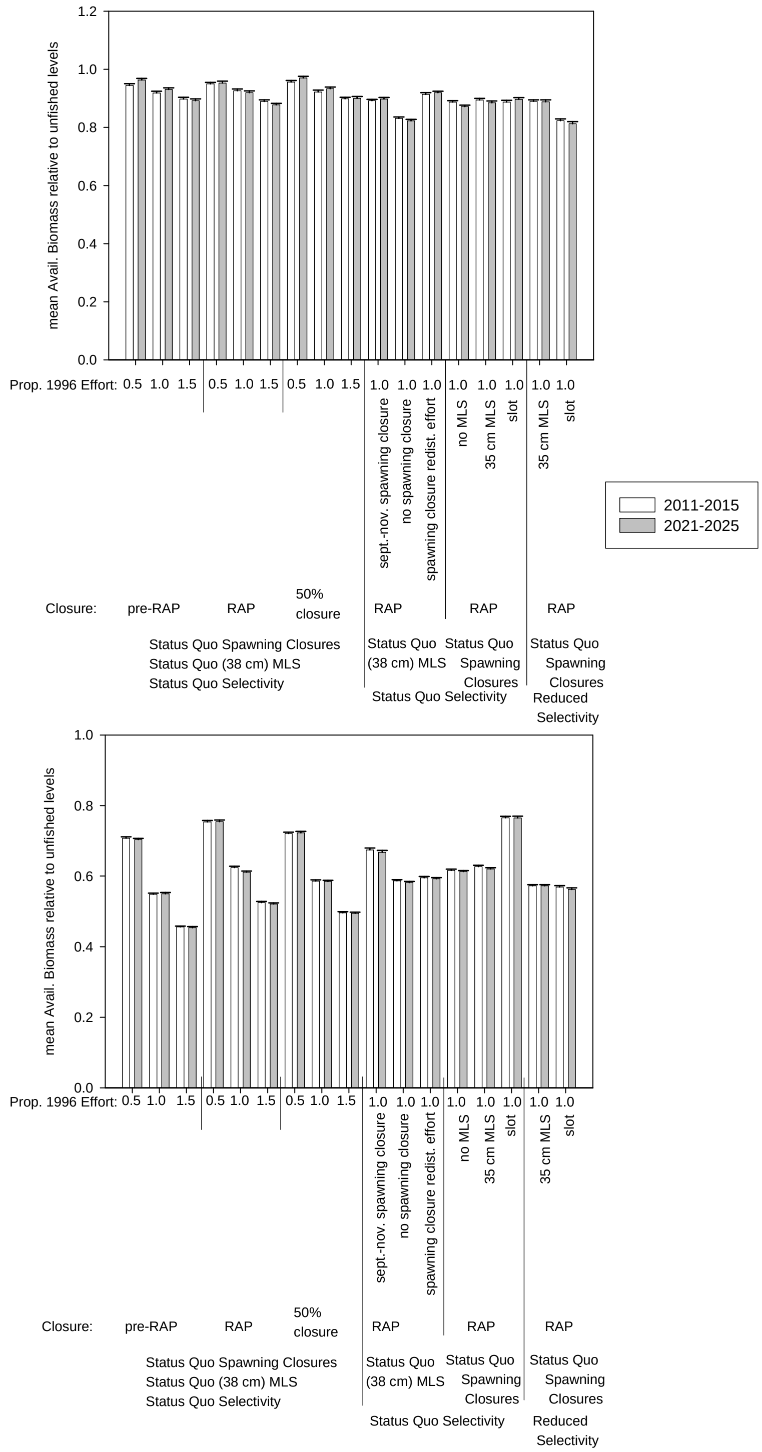


Fig. 6.24. Average (+SE) available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the closed reefs relative to the unfished available biomass on these reefs, under the vessel dynamics model.

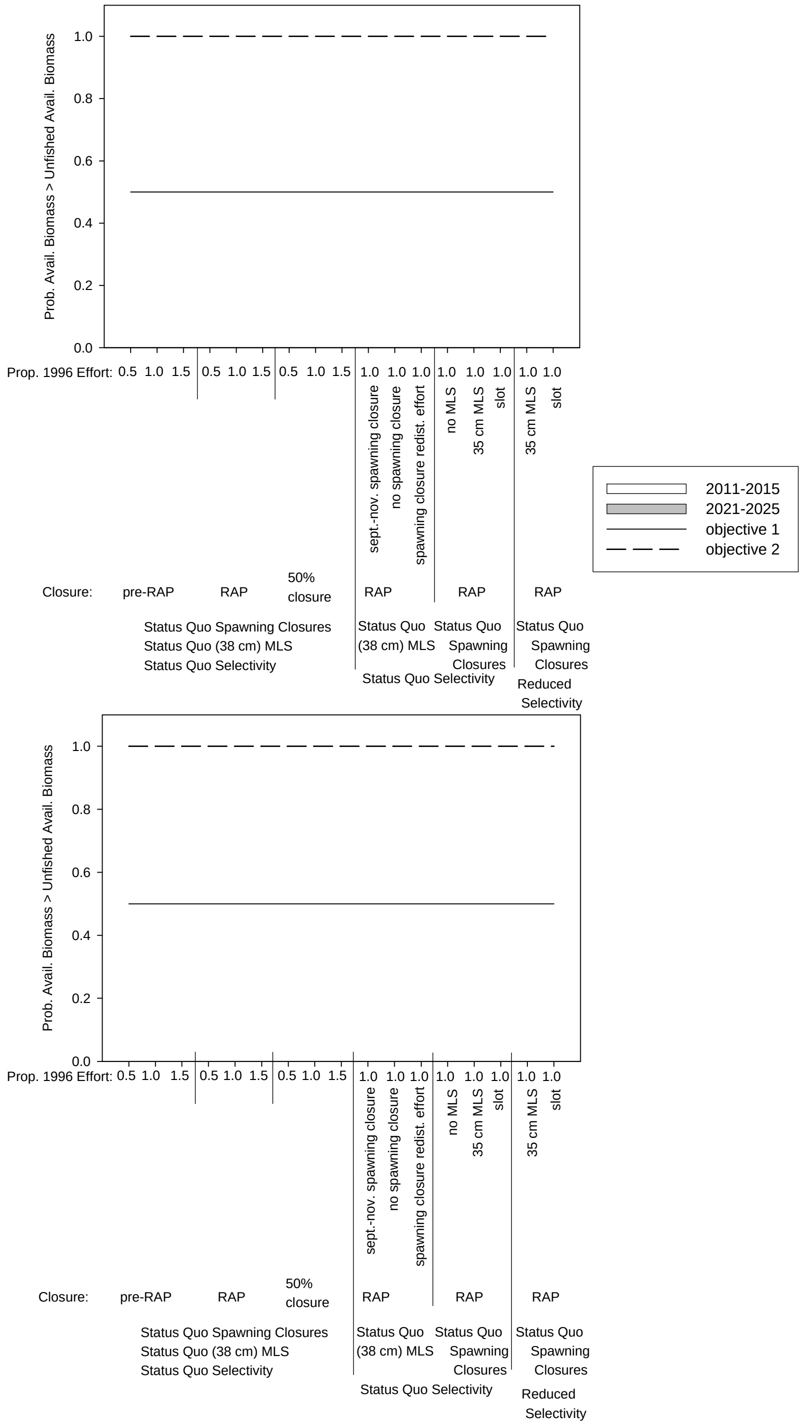


Fig. 6.25. Proportion of simulations under the vessel dynamics model where the average available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the open reefs is greater than the unfished available biomass on these reefs.

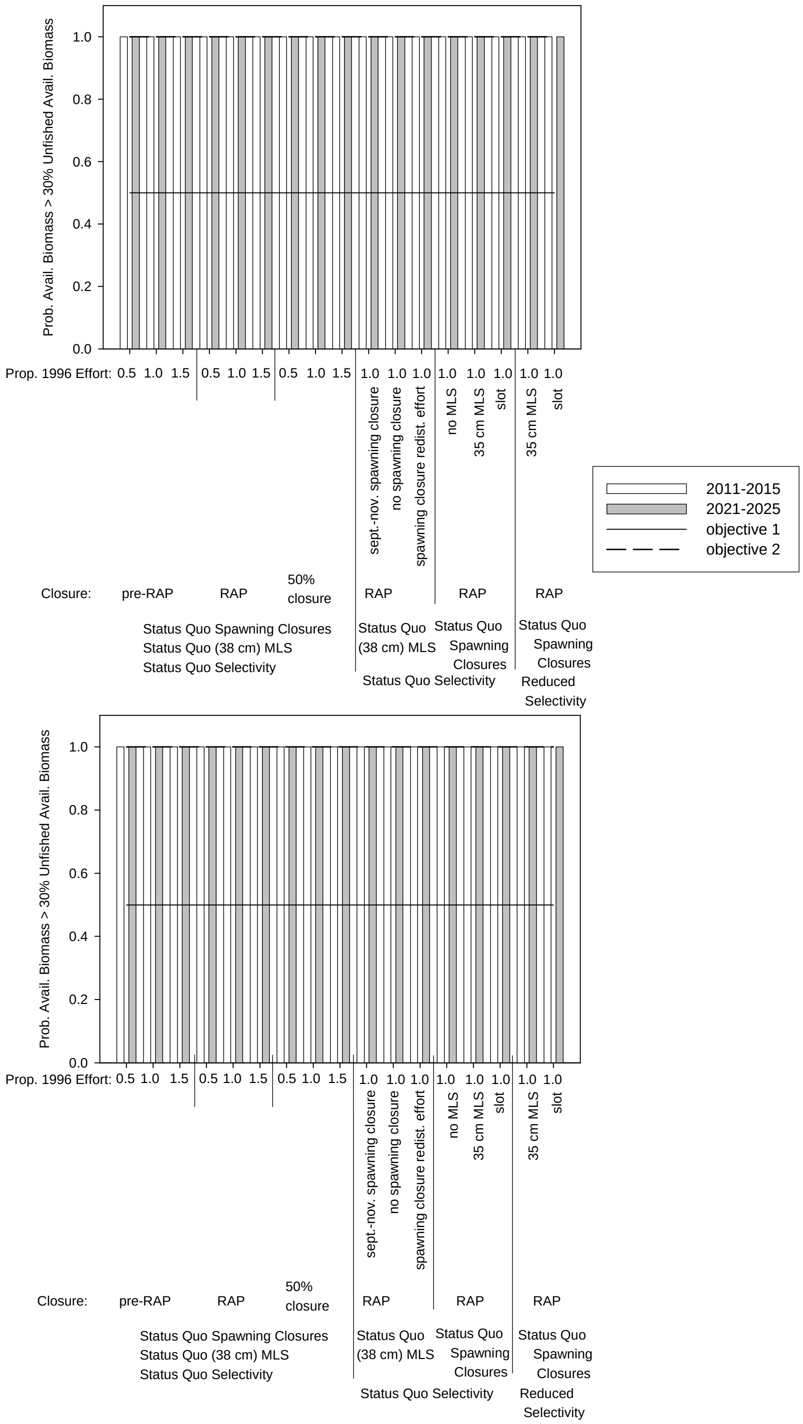


Fig. 6.26. Proportion of simulations under the vessel dynamics model where the average available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom), on the open reefs is greater than 30% of the unfished available biomass on these reefs.

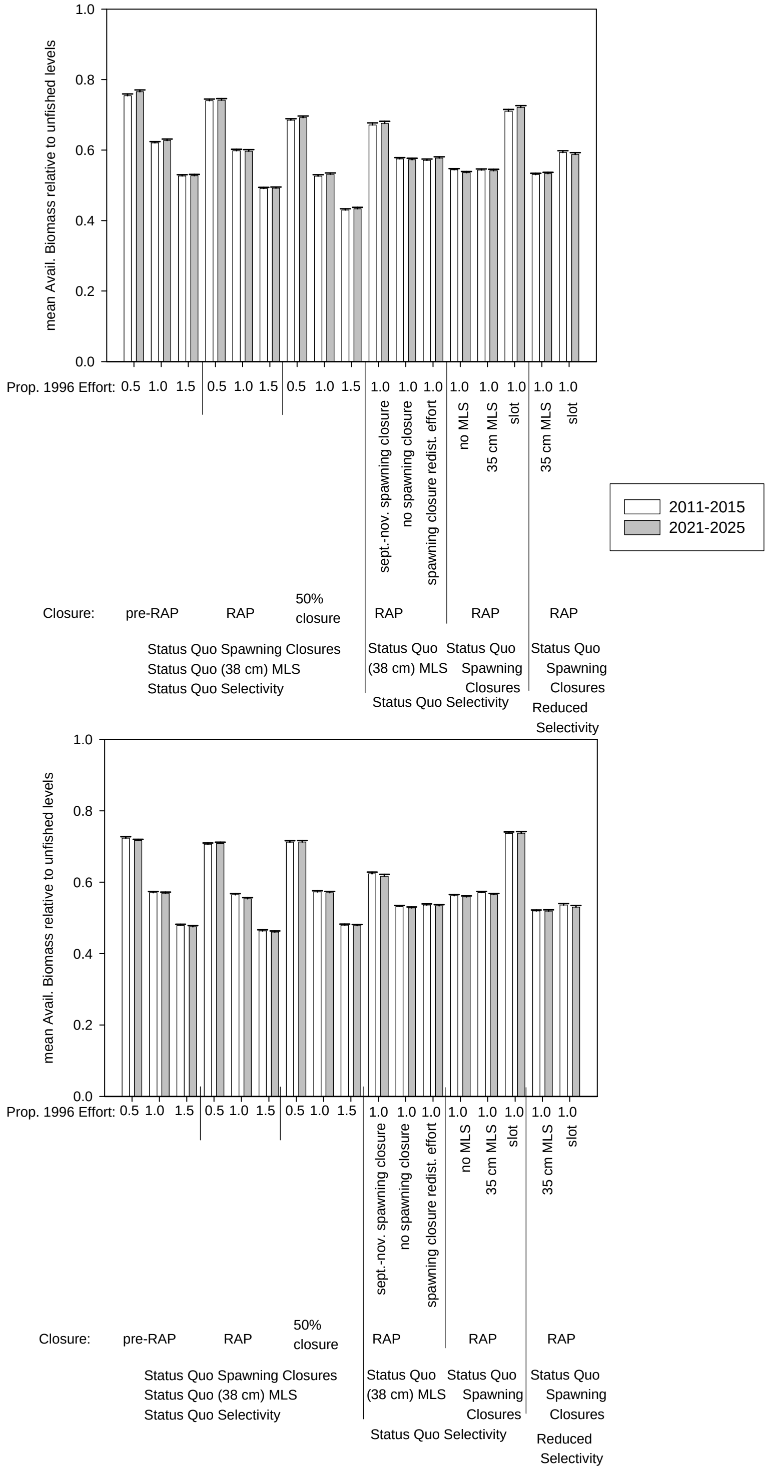


Fig. 6.27. Average (+SE) available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the open reefs relative to the unfished available biomass on these reefs, under the vessel dynamics model.

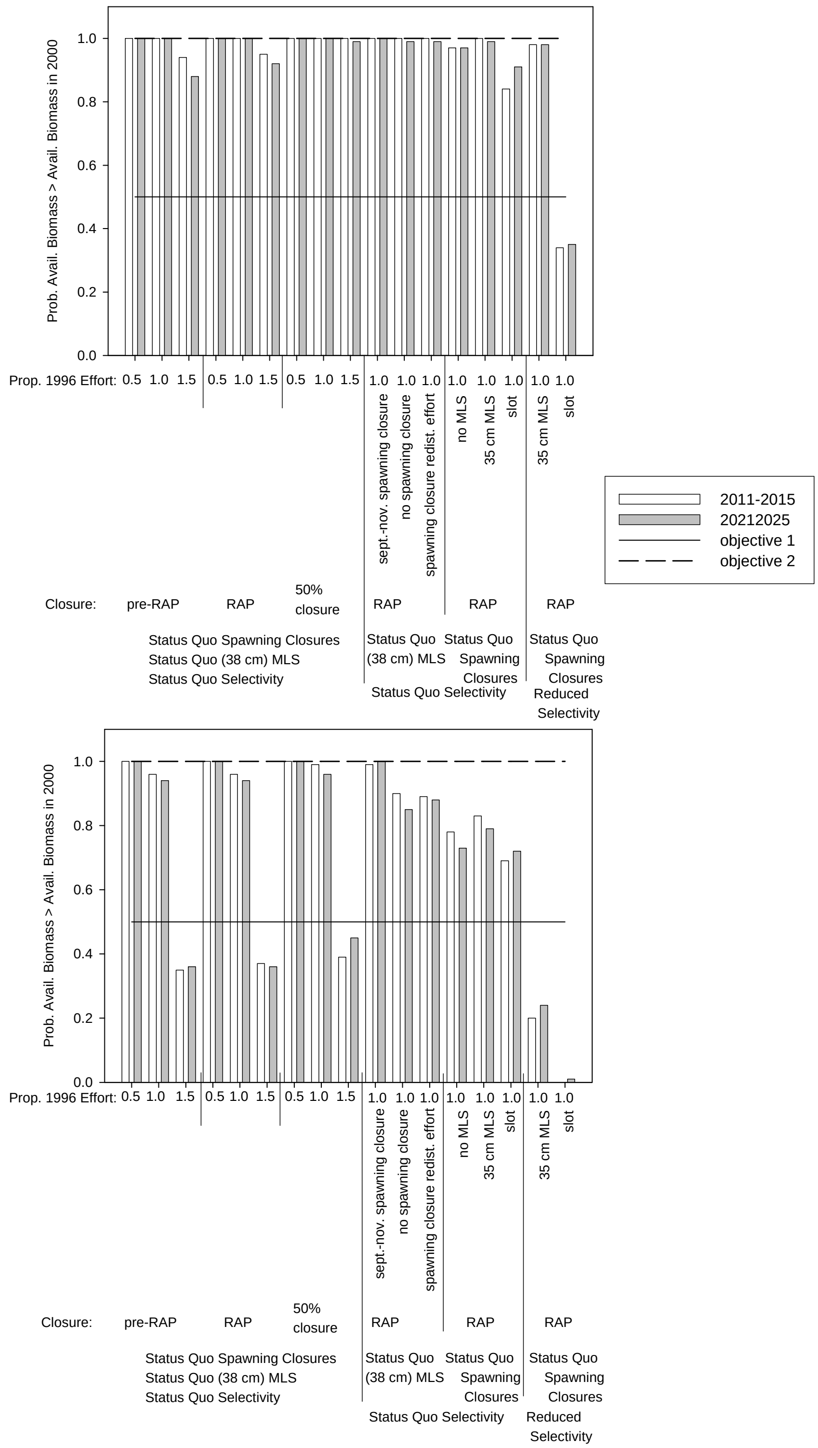


Fig. 6.28. Proportion of simulations under the vessel dynamics model (Coral Trout top, Red Throat Emperor bottom), where the average available biomass (2011-2015 and 2021-2025) is greater than the 2000 available biomass.

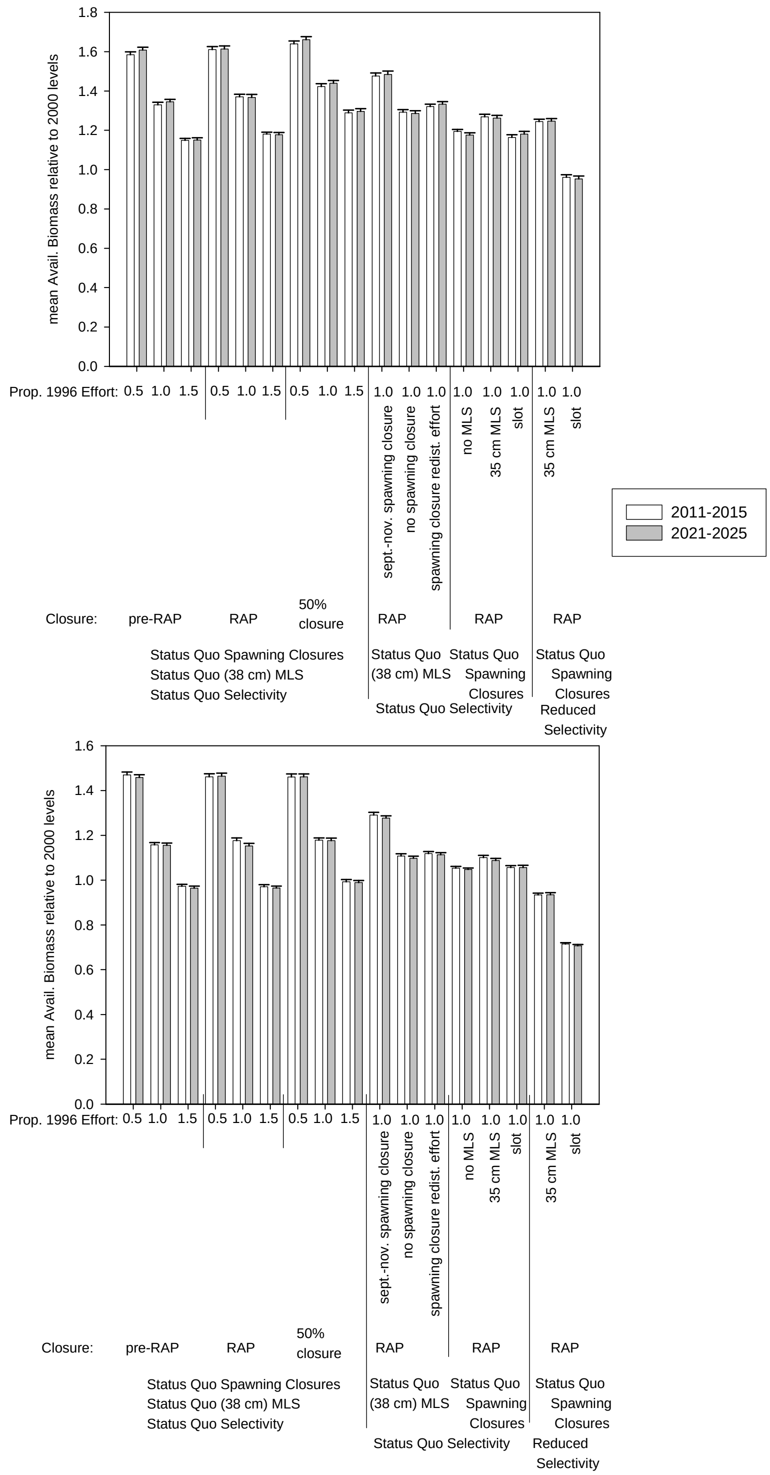


Fig. 6.29. Average (+SE) available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the available biomass on these reefs in 2000, under the vessel dynamics model.

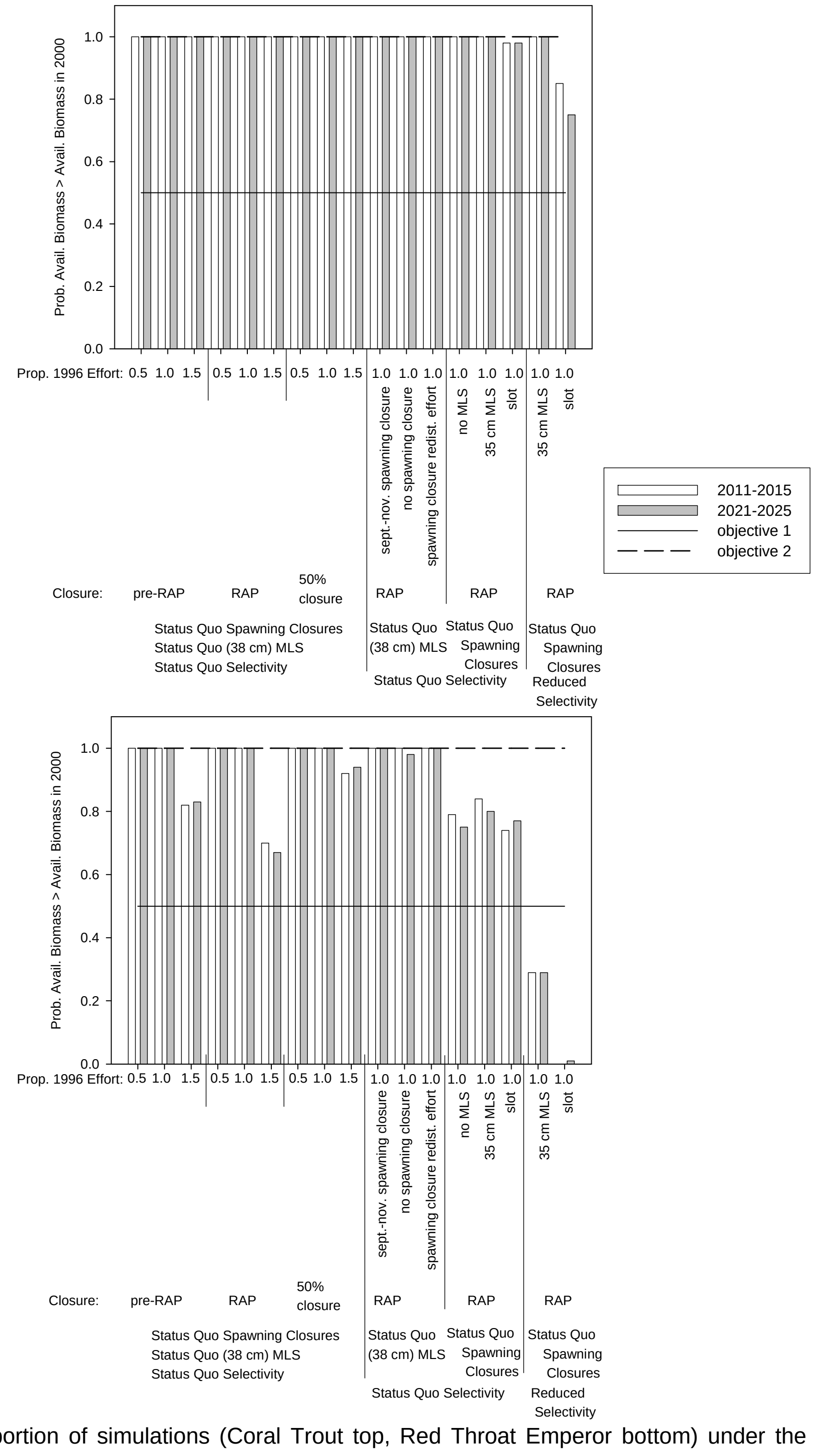
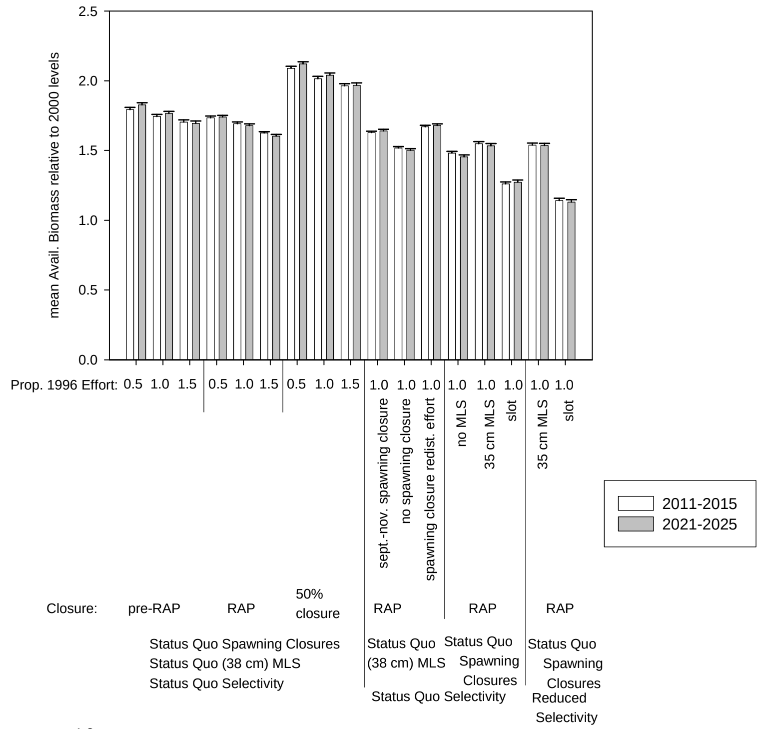


Fig. 6.30. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average available biomass (2011-2015 and 2021-2025) on the closed reefs is greater than the available biomass on these reefs in 2000.



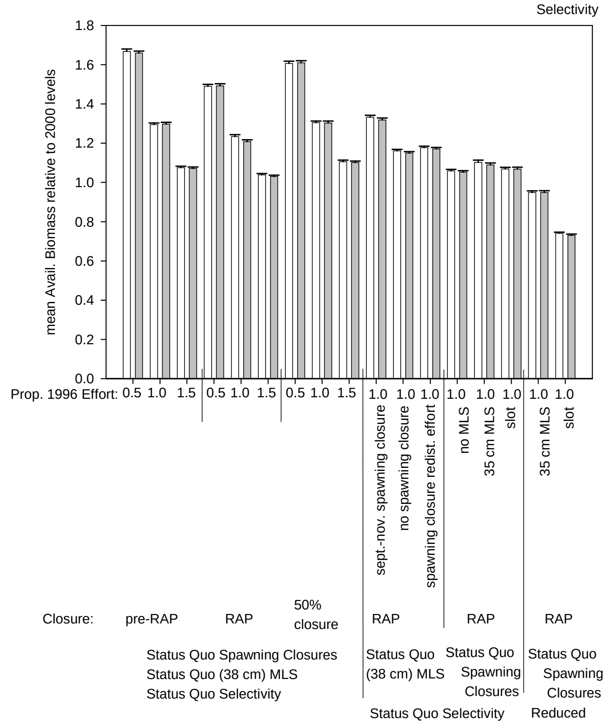


Fig. 6.31. Average (+SE) available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the closed reefs relative to the available biomass on these reefs in 2000, under the vessel dynamics model.

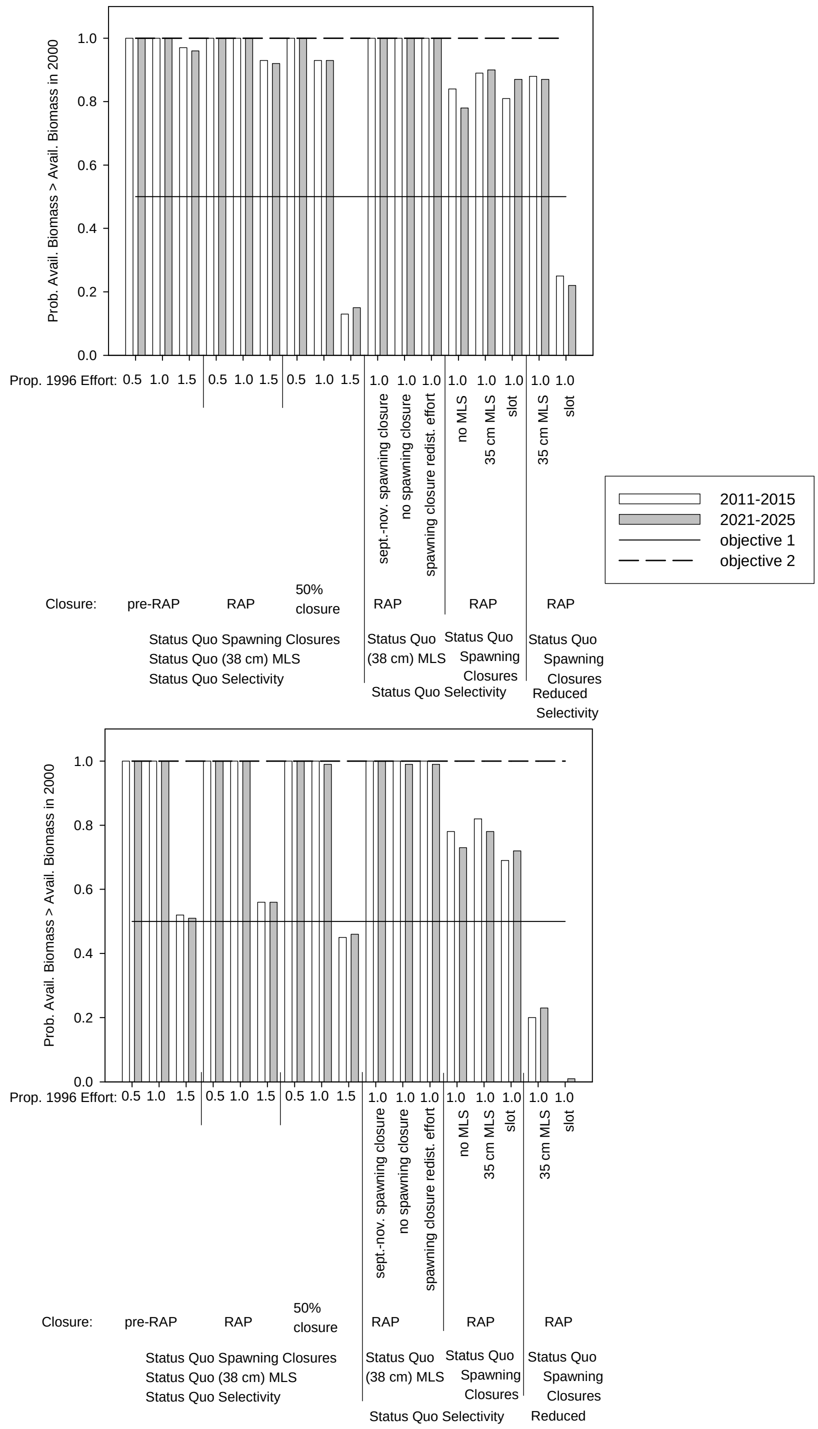


Fig. 6.32. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average available biomass (2011-2015 and 2021-2025) on the open reefs is greater than the available biomass on these reefs in 2000.

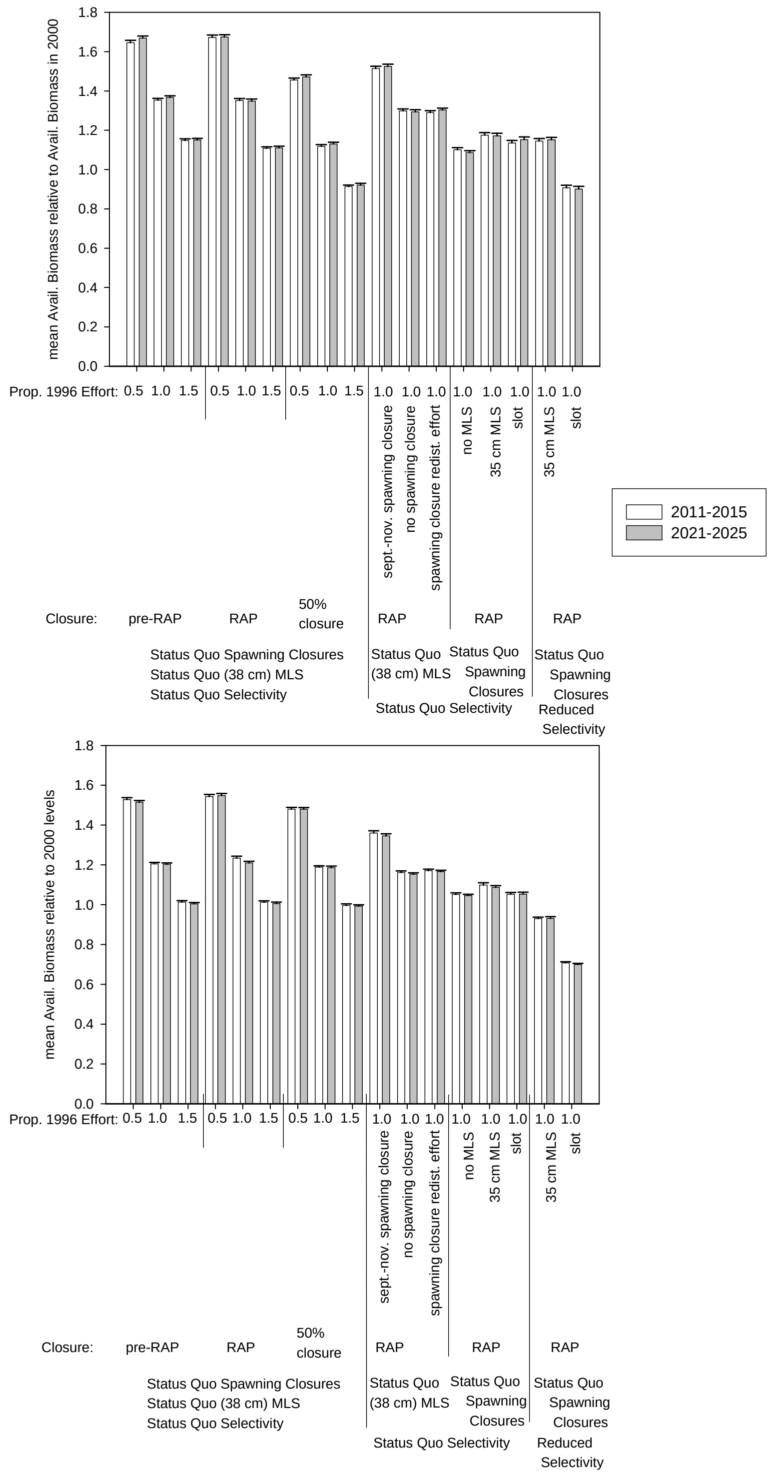


Fig. 6.33. Average (+SE) available biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) on the open reefs relative to the available biomass level on these reefs in 2000, under the vessel dynamics model.

6.1.3. Total biomass

The objectives concerning total biomass (the biomass of all fish that are greater than 20 cm) were similar to those for available and spawning biomass. These objectives stated that, for both Coral Trout and Red Throat Emperor, total biomass should be above unfished, pre-exploitation, levels 100%, or alternatively 50% of the time. Figure 6.34 shows that, as for spawning and available biomass, no management strategy came close to achieving either of these objectives.

Another objective is that total biomass should be above 40% of the unfished level 80% of the time. Figure 6.35 shows that all strategies are able to achieve this objective. The ratio of the total biomass relative to unfished total biomass ranges between 0.6 and 0.8 (Fig. 6.36).

The probability of the total biomass exceeding the total biomass in 2000 is, as expected, highest when effort levels are lowest, including when there is a 3 month spawning closure (Fig. 6.37). The effect of area closures is most evident at high levels of effort. For example, the chance of the total biomass of Coral Trout exceeding the 2000 level at the end of the projection period (2021-2025) increases from 0.8 under pre-RAP closures to about 0.9 under 50% closure at the highest level of effort (1.5 times the 1996 effort level). The ratio of the total biomass relative to total biomass in 2000 ranges between 1.0 and 1.4 for Coral Trout and 0.8 and 1.2 for Red Throat Emperor (Fig. 6.38).

Strategies that reduce effort or increase the amount of area closures lead to higher total biomasses than the current management strategy (Fig. 6.39), and strategies that increase effort or change size limits lead to lower total biomass.

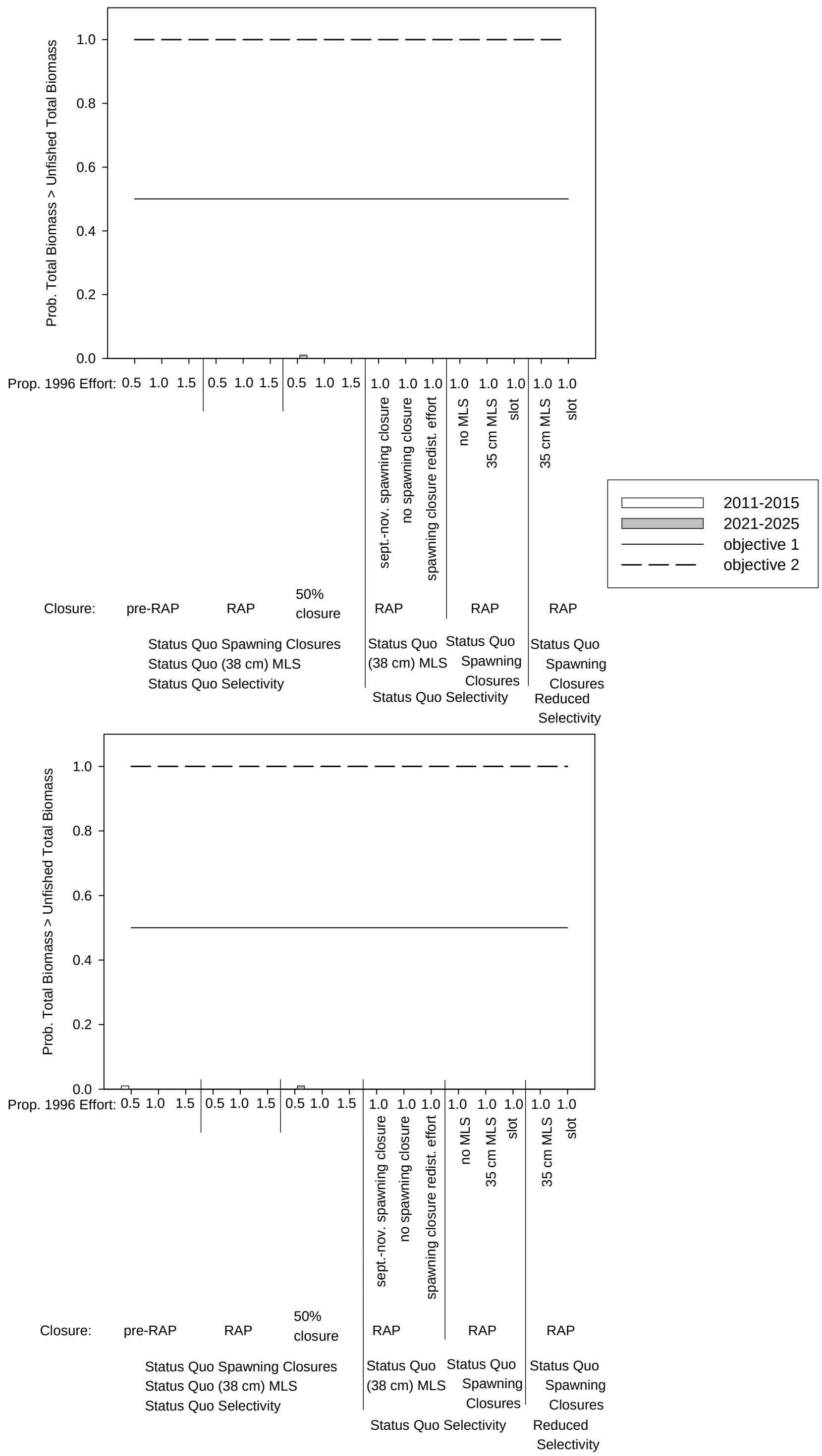


Fig. 6.34. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average total biomass (2011-2015 and 2021-2025) is greater than the unfished total biomass.

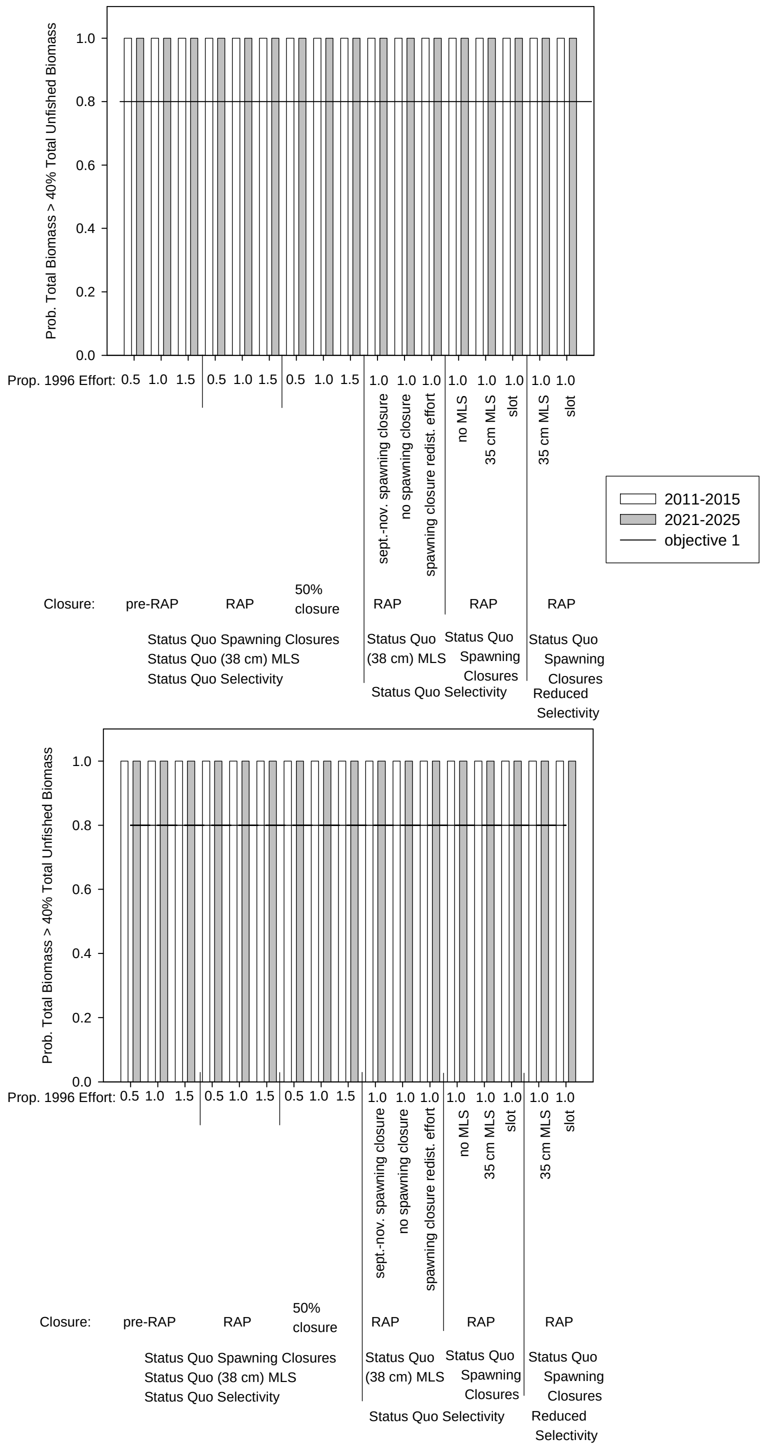


Fig. 6.35. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average total biomass (2011-2015 and 2021-2025) is greater than 40% of the unfished total biomass.

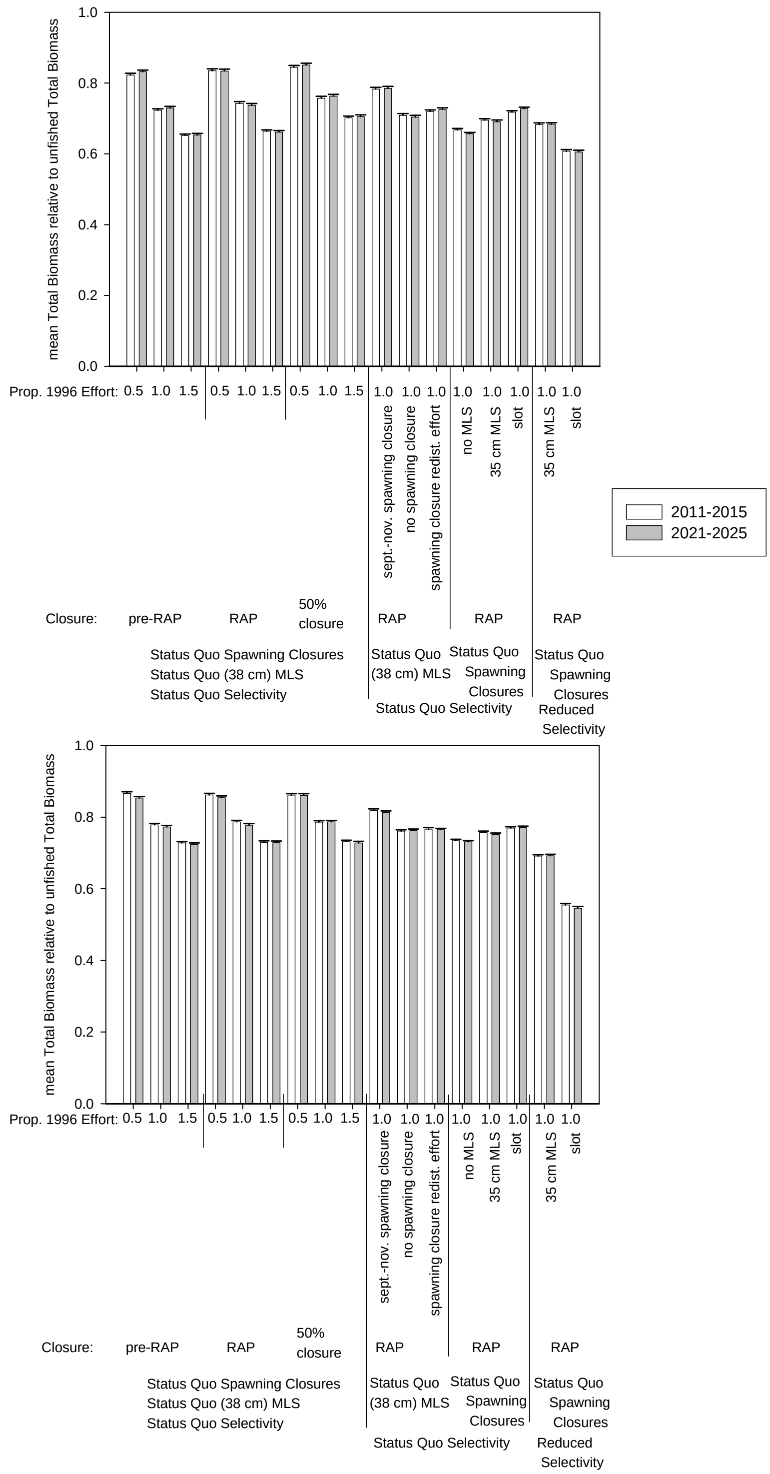


Fig. 6.36. Average (+SE) total biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the unfished total biomass, under the vessel dynamics model.

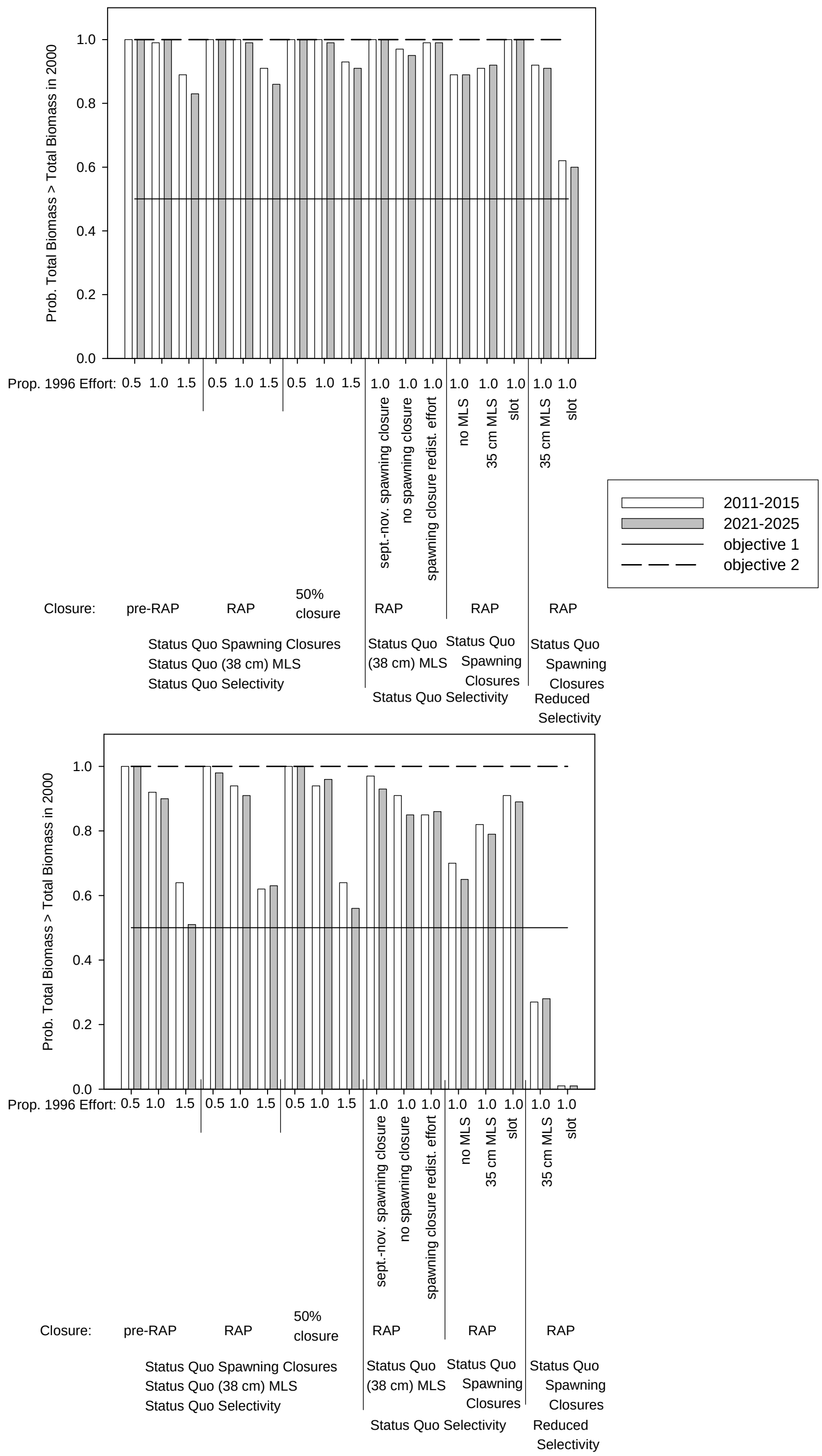
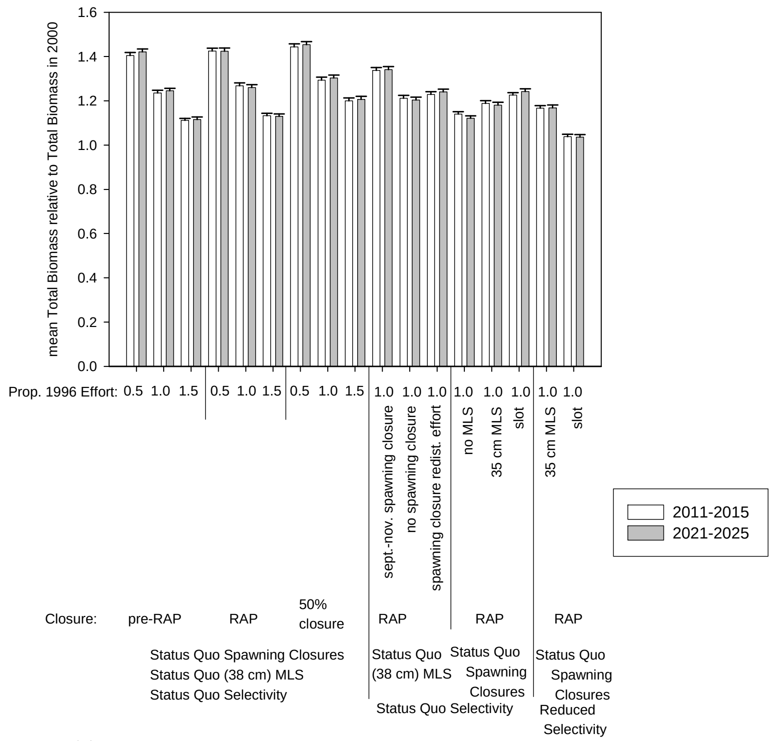


Fig. 6.37. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average total biomass (2011-2015 and 2021-2025) is greater than the 2000 total biomass.



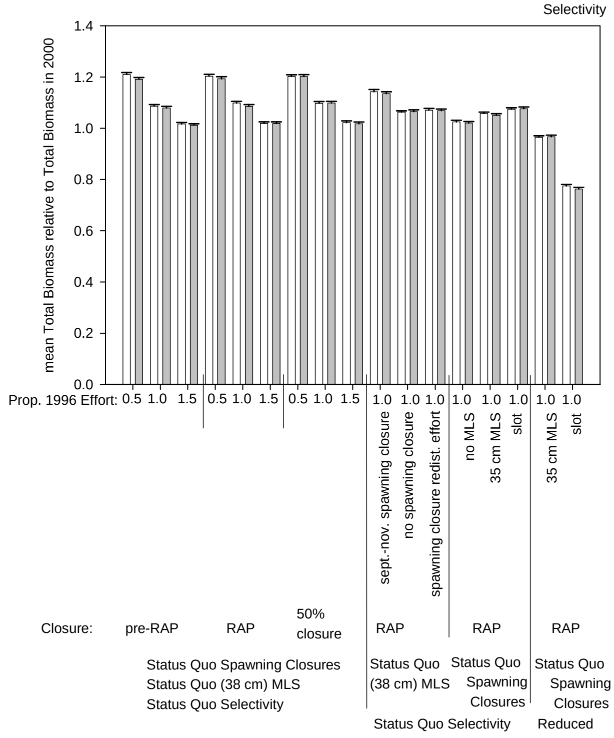


Fig. 6.38. Average (+SE) total biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the 2000 total biomass, under the vessel dynamics model.

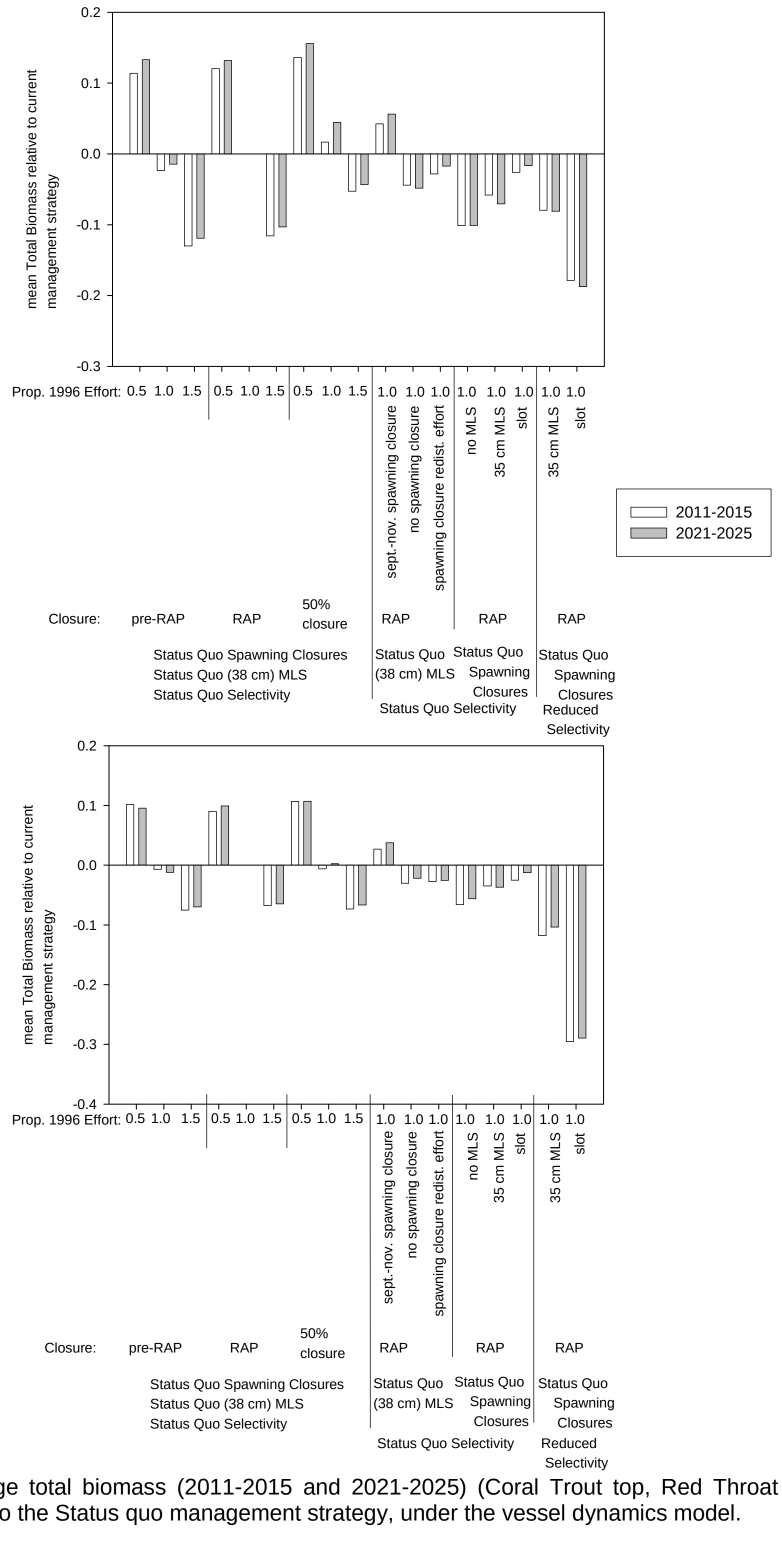


Fig. 6.39. Average total biomass (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the Status quo management strategy, under the vessel dynamics model.

6.1.4. CPUE

Several management objectives related to CPUE (CPUE; catch per unit effort) of the three fishing fleets (commercial, charter and recreational). These objectives include that the CPUE for the three fleets for both species should be no less than 80%, 120% and 150% of the average CPUE from a reference time period 90% of the time. The objectives include 120% and 150% of reference levels because of the feeling that the recently imposed management regulations should improve the stocks enough to benefit the fishery.

The reference time period for the commercial fleet was 1994-1996, and Fig. 6.40 shows that 80% of the CPUE for this reference period was achieved for Coral Trout 90% of the time if effort was reduced (50% of 1996 effort levels or a 3 month, seasonal spawning closure from Sept– Nov) or area closures are reduced or the size limits are reduced, but not if the maximum size limit was considered. Increasing effort strongly reduced any chance of achieving the objective.

The chances of achieving the objective for Red Throat Emperor were smaller than for Coral Trout. The only strategies to achieve the objective were those that both reduced effort and increased the amount of fishable area (pre-RAP area closure) as well as management strategies that reduced gear selectivity.

None of the management strategies were able to increase commercial catch-rates to 120% or 150% of those experienced on average from 1994-1996 (Fig. 6.41, 6.42). As one would expect, the ratio of the commercial CPUE over 2021-2025 relative to that for the reference period shows that lower effort leads to higher CPUE (Fig. 6.43). Also evident for Coral Trout is the effect of area closures. As the amount of area closures increases, and the amount of fishable area decreases, the CPUE declined. This effect is less evident for Red Throat Emperor as this species migrates, and so the effect of area closures is expected to be less.

Comparison of the management strategies relative to the current strategy for commercial CPUE (Fig. 6.44) reiterates many of these effects. Notably, reducing the MLS, while keeping the same gear selectivity, leads to slightly higher CPUE than experienced under the current management strategy. However, reducing the MLS to 28 cm, but adding a maximum legal size leads to lower CPUE for Coral Trout, but higher CPUE for Red Throat Emperor. This was the main difference between the species. The higher CPUE of Red Throat Emperor under reduced selectivity was due to an increased amount of smaller fish available.

Management objectives related to the catch-rates for the other fleets (charter and recreational) were only specified for Coral Trout. These objectives also reflected the optimism of the RAP, with desired objectives of 80%, 120% and 150% of the average CPUE from 1996-2000 for the charter fleet, and from 1998-2000 for the recreational fleet. Figure 6.45 shows that all effort strategies achieved the objective of the CPUE for the charter fleet being 80% of the reference level 90% of the time. As the goal of the objective became more optimistic (120% and 150% of the reference CPUE), the likelihood of the strategies achieving the objective became smaller (Fig. 6.46, 6,47), particularly those strategies with increased effort levels.

The ratio of CPUE for the charter fleet relative to that for the reference period (1996-2000) is shown in Fig. 6.48, where the effect of both changing effort and the amount of area closed to fishing is again evident. The values for this ratio ranged between about 1.0 and 3.0 indicating that the objectives were easily met. The comparison of the strategies relative to the current strategy (Fig. 6.49) also mimics the results from the commercial fleet.

The objective of the recreational fleet attaining 80% of the average CPUE from 1998-2000, was achieved under all management strategies except those with increased effort or a maximum size limit (Fig. 6.50). As the objectives became more optimistic (i.e., achieving 120% and 150% of the average historical CPUE) the likelihood of achieving them decreased (Fig. 6.51, 6.52). The ratio of the CPUE for the recreational fleet to that for the reference period (Fig. 6.53) ranged between 0.8 and 1.4, while Fig. 6.54 shows that the management strategies have roughly the same effect on the recreational CPUE as on the charter (Fig. 6.54).

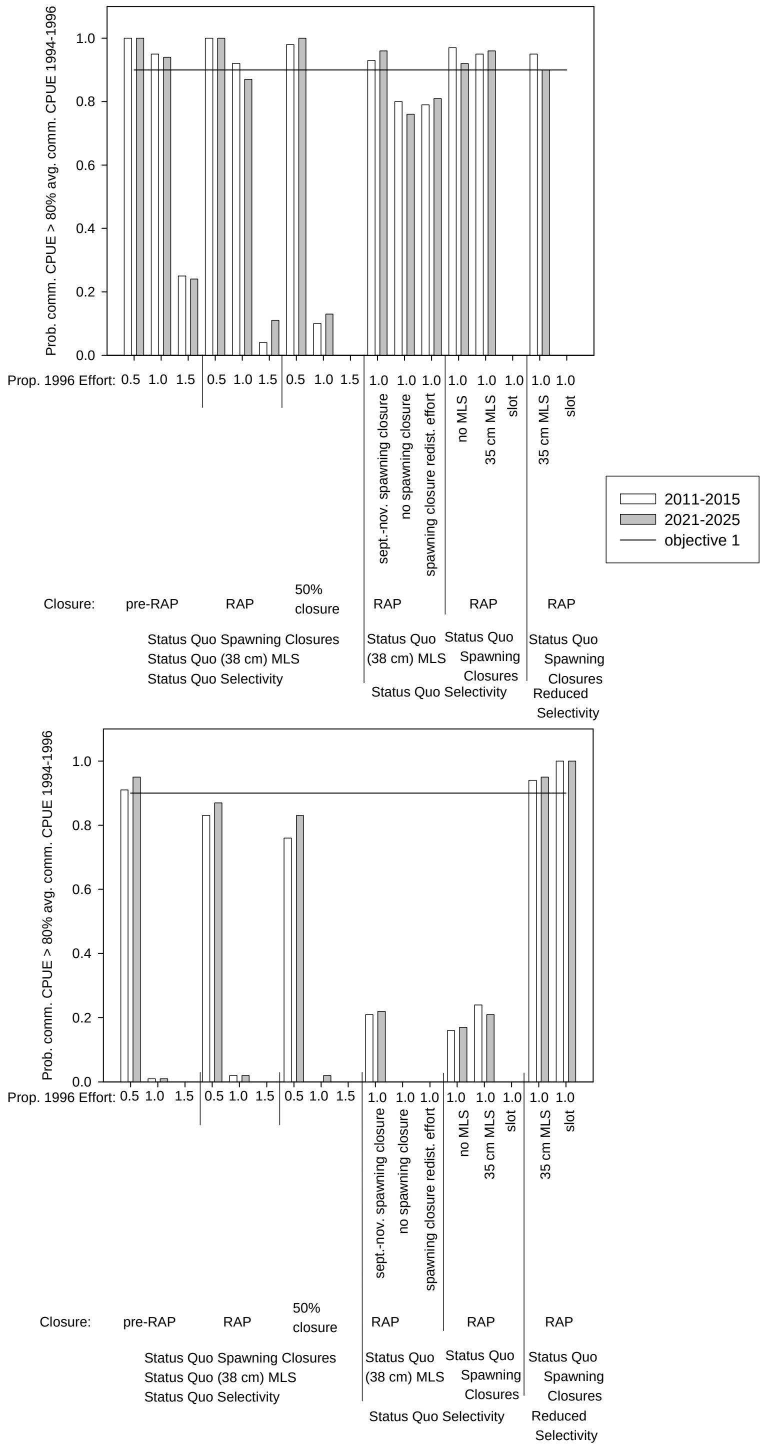


Fig. 6.40. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average commercial CPUE (2011-2015 and 2021-2025) is greater than 80% of the average commercial CPUE (1994-1996).

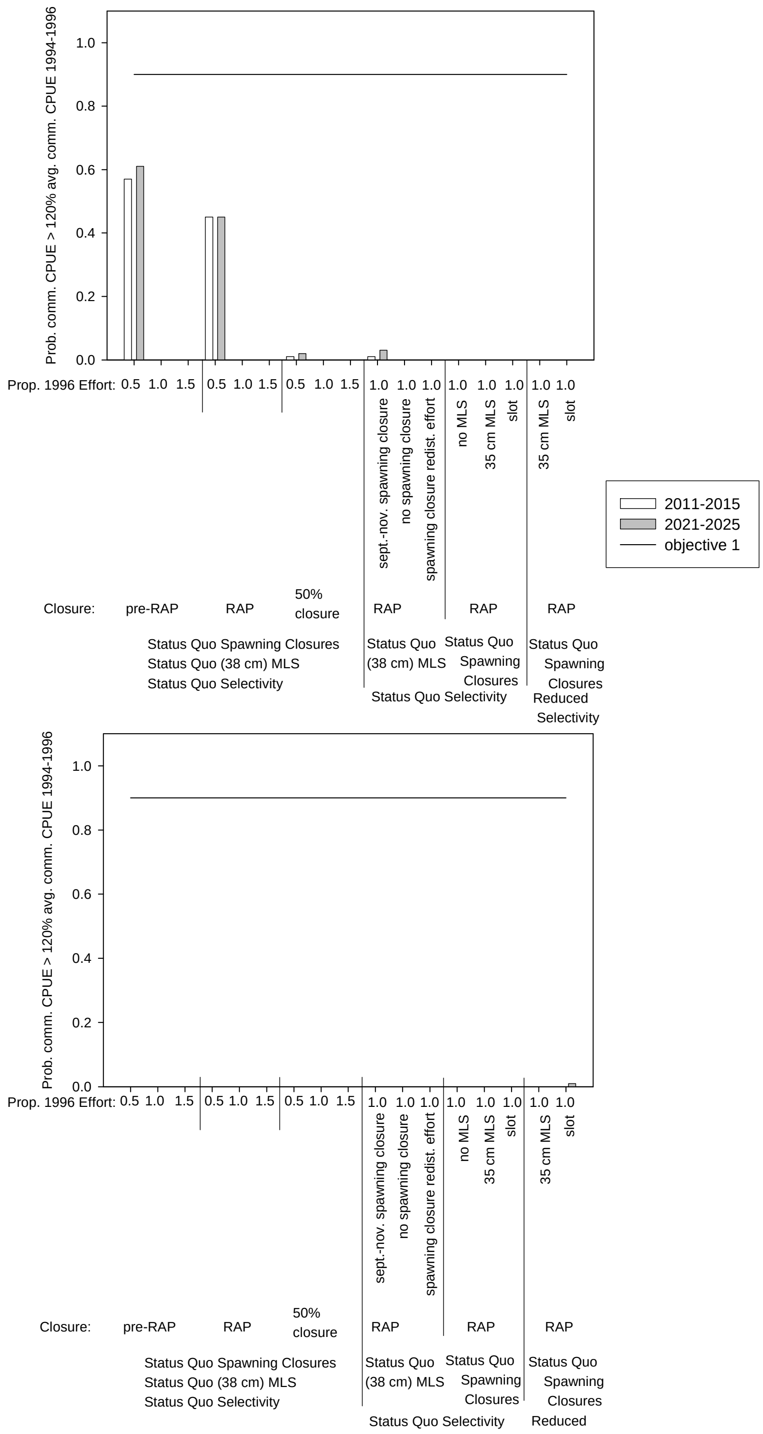


Fig. 6.41. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average commercial CPUE (2011-2015 and 2021-2025) is greater than 120% of the average commercial CPUE (1994-1996).

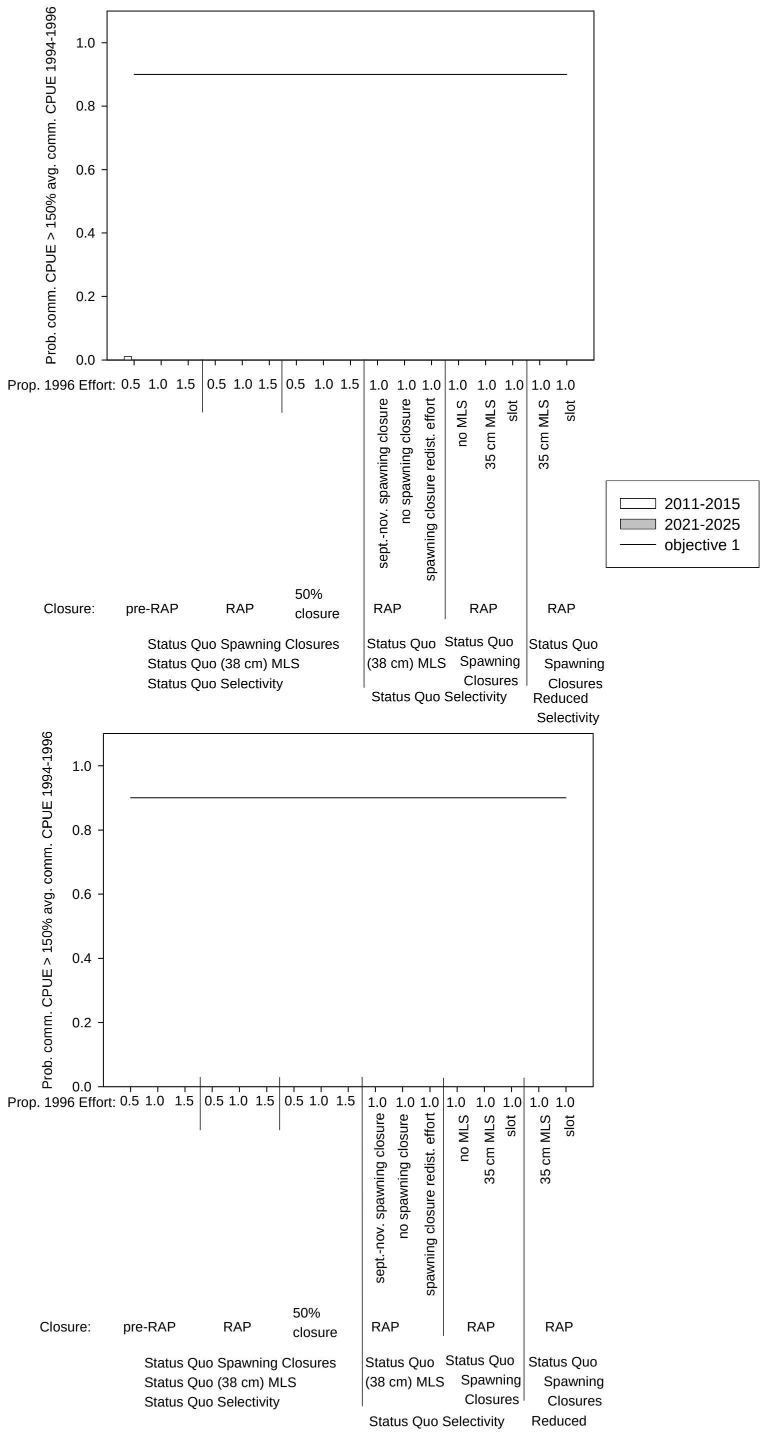


Fig. 6.42. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average commercial CPUE (2011-2015 and 2021-2025) is greater than 150% of the average commercial CPUE (1994-1996).

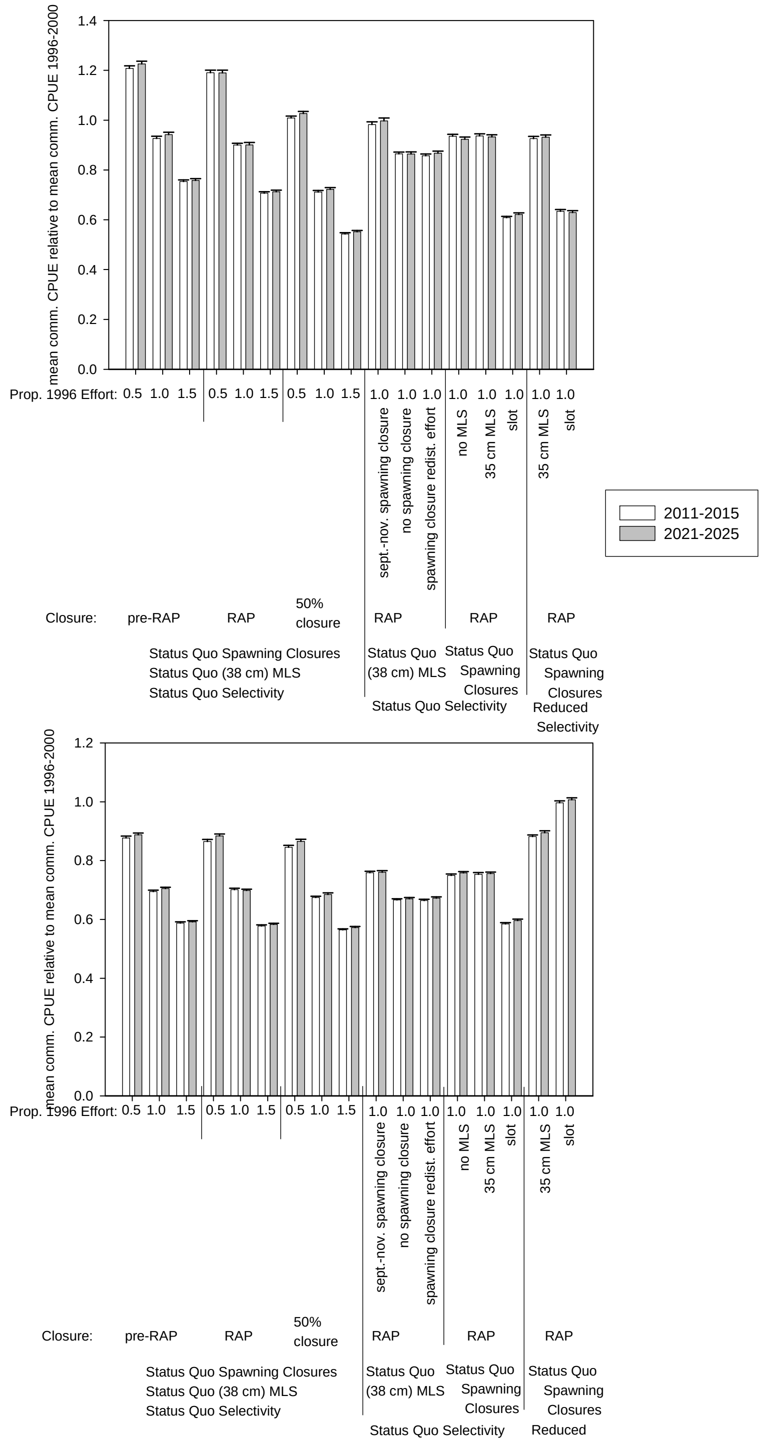


Fig. 6.43. Average (+SE) commercial CPUE (2011-2015 and 2021-2025)) (Coral Trout top, Red Throat Emperor bottom) relative to the average commercial CPUE (1994-1996), under the vessel dynamics model.

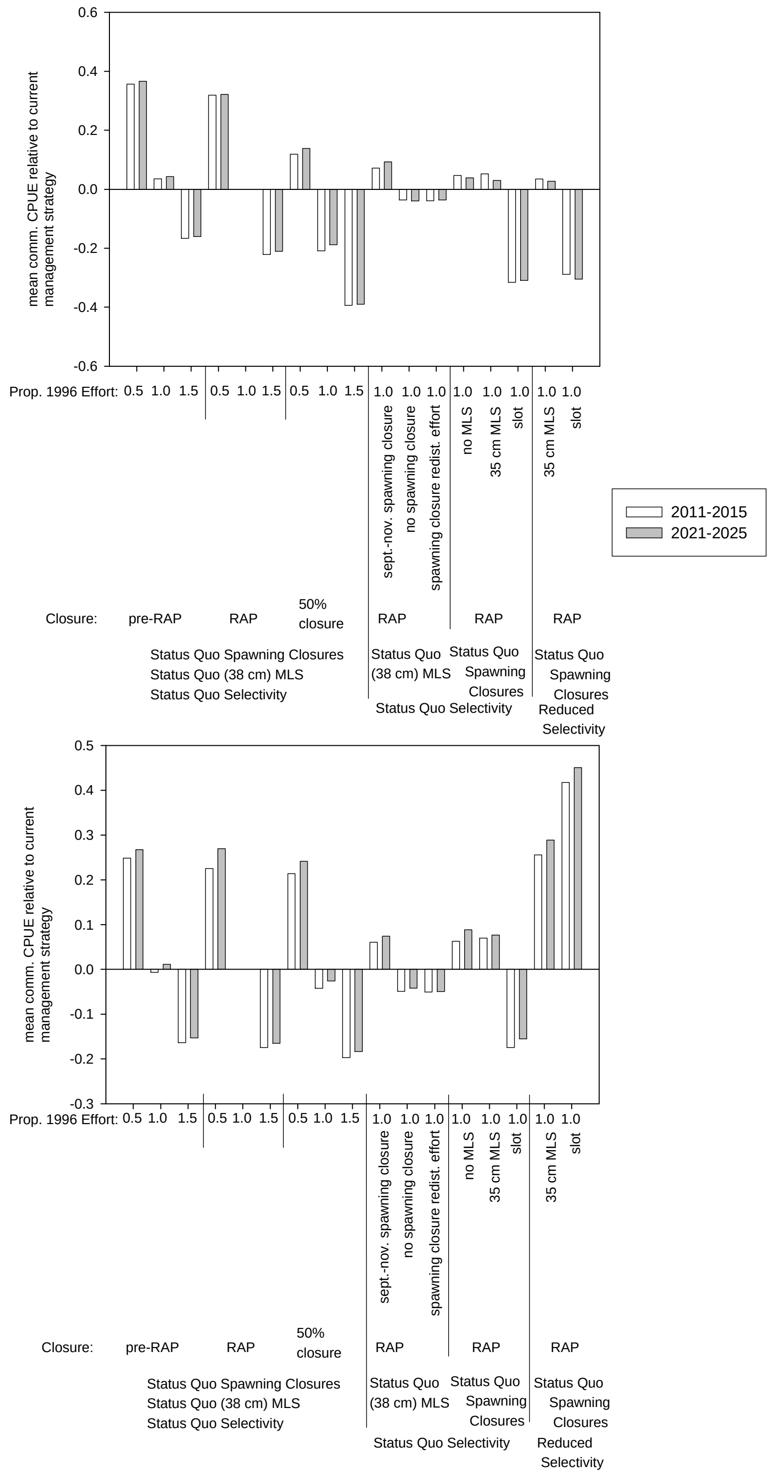


Fig. 6.44. Average commercial CPUE (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to that for the current management strategy, under the vessel dynamics model.

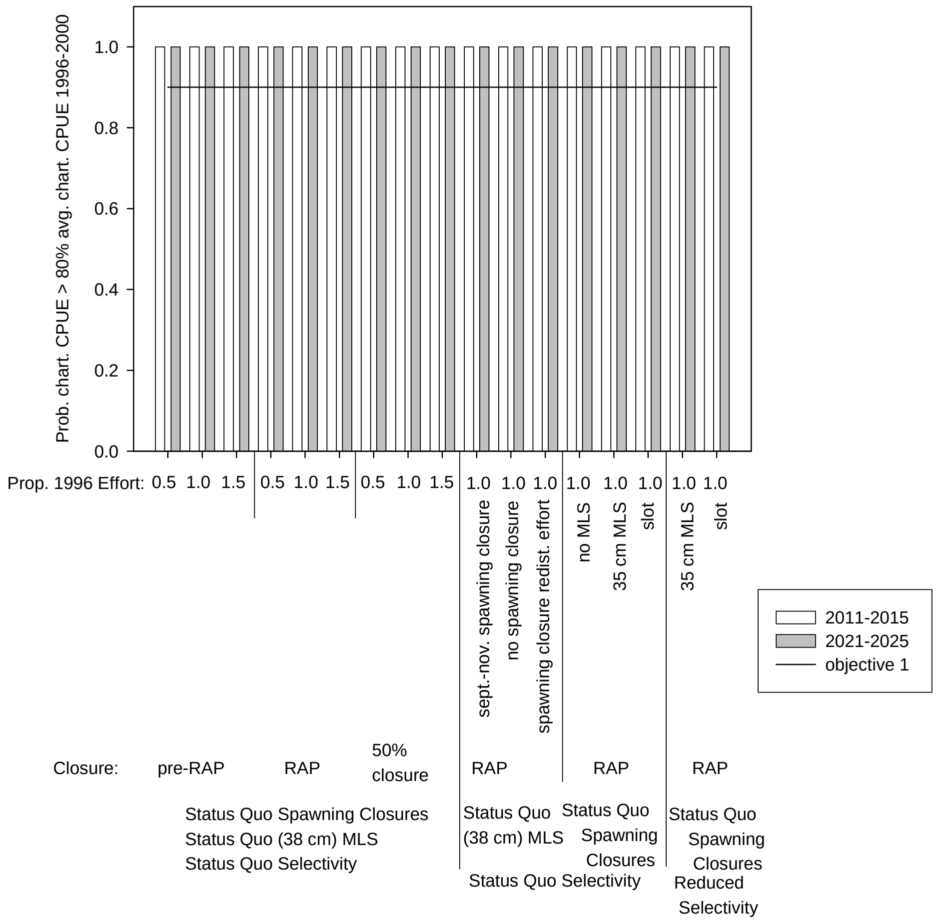


Fig. 6.45. Proportion of simulations where the average charter CPUE for Coral Trout (2011-2015 and 2021-2025) is greater than 80% of the average Coral Trout CPUE for this fleet for 1996-2000, under the vessel dynamics model.

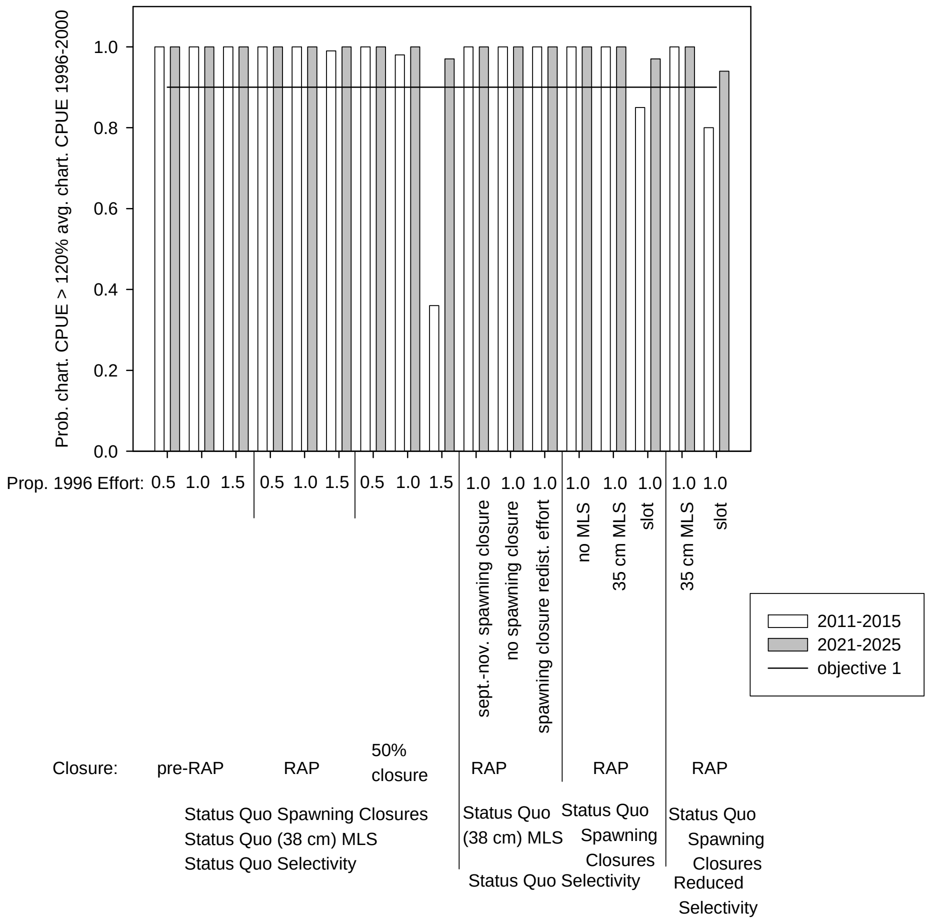


Fig. 6.46. Proportion of simulations where the average charter CPUE for Coral Trout (2011-2015 and 2021-2025) is greater than 120% of the average Coral Trout CPUE for this fleet for 1996-2000, under the vessel dynamics model.

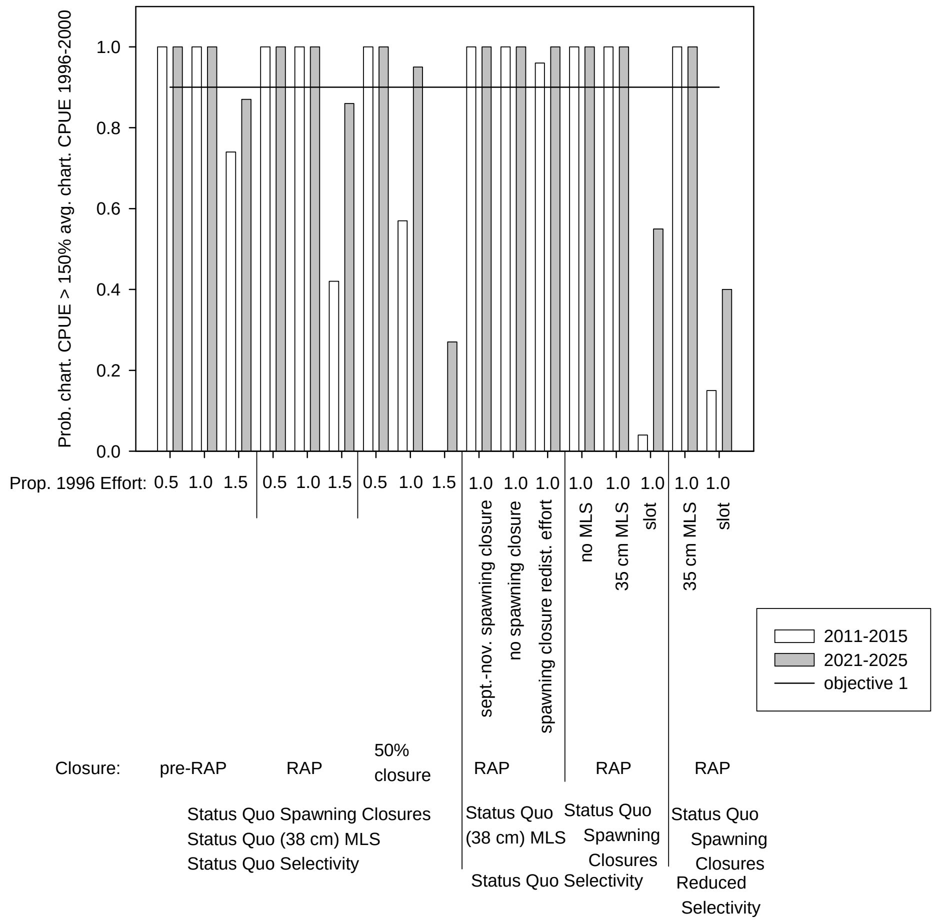


Fig. 6.47. Proportion of simulations where the average charter CPUE for Coral Trout (2011-2015 and 2021-2025) is greater than 150% of the average Coral Trout CPUE for this fleet for 1996-2000, under the vessel dynamics model.

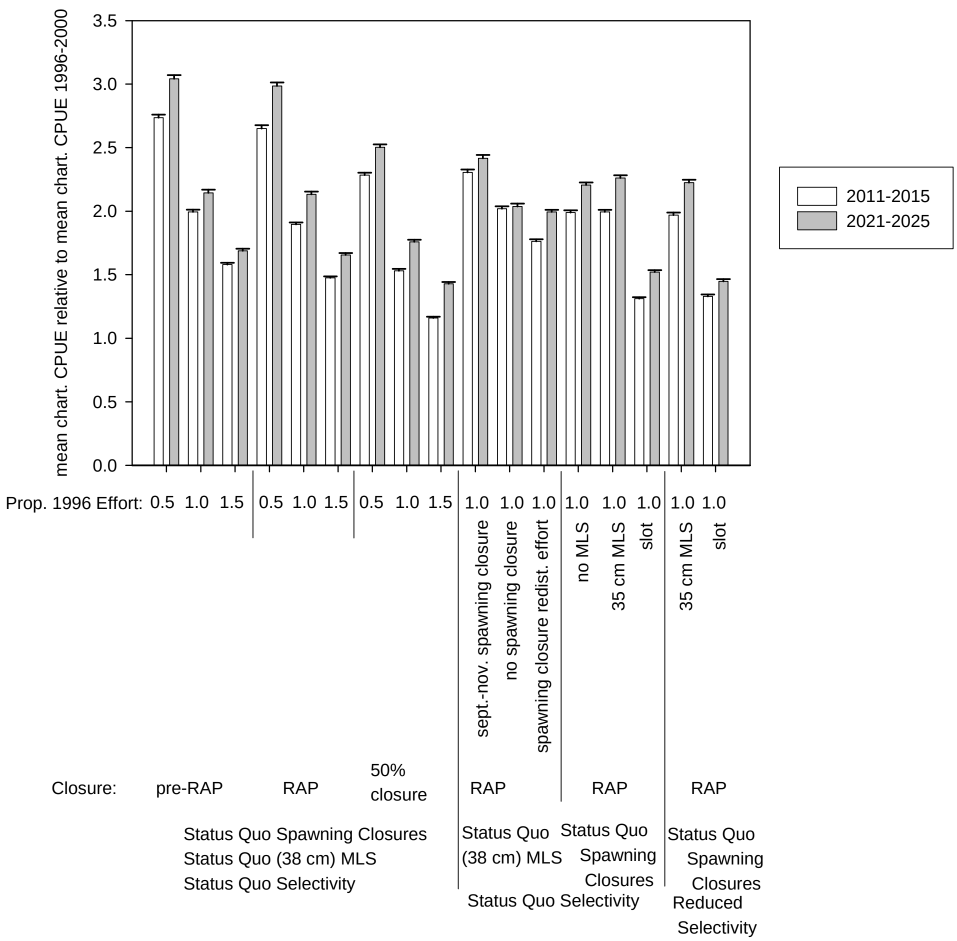


Fig. 6.48. Average (+SE) charter CPUE for Coral Trout (2011-2015 and 2021-2025) relative to that for 1996-2000, under the vessel dynamics model.

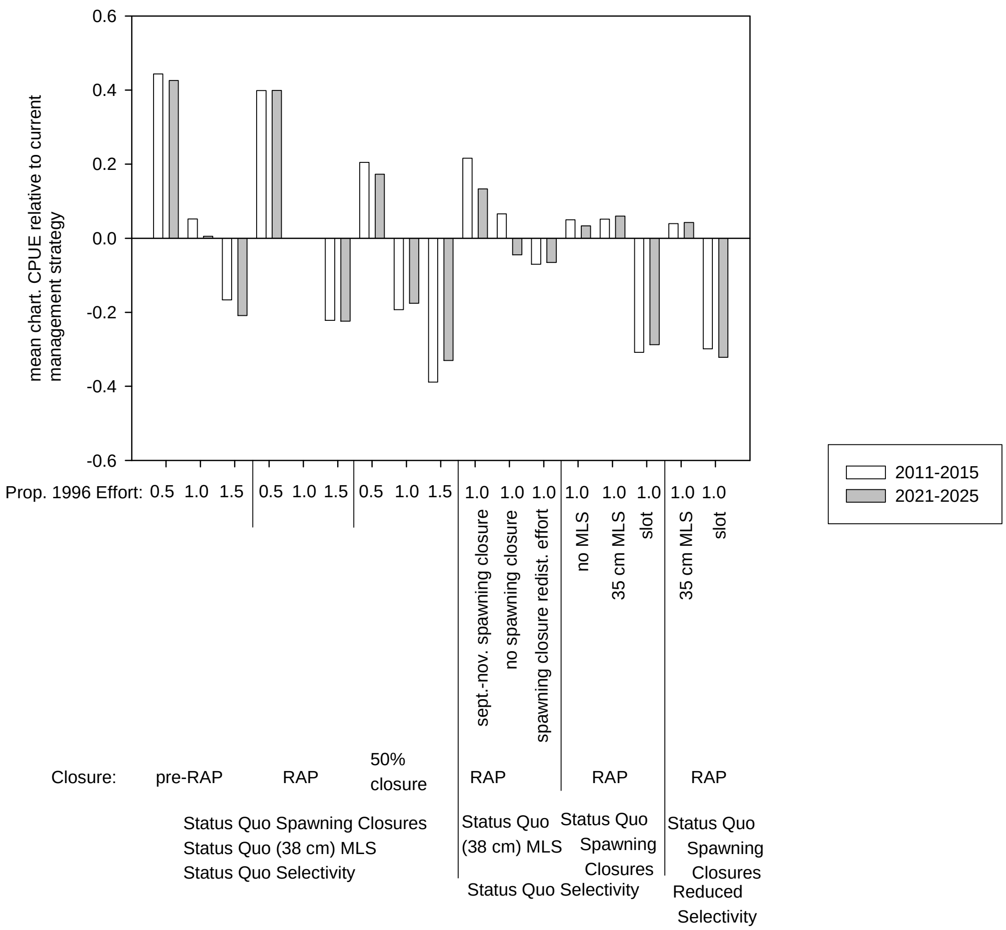


Fig. 6.49. Average charter CPUE for Coral Trout (2011-2015 and 2021-2025) relative to that for the current management strategy, under the vessel dynamics model.

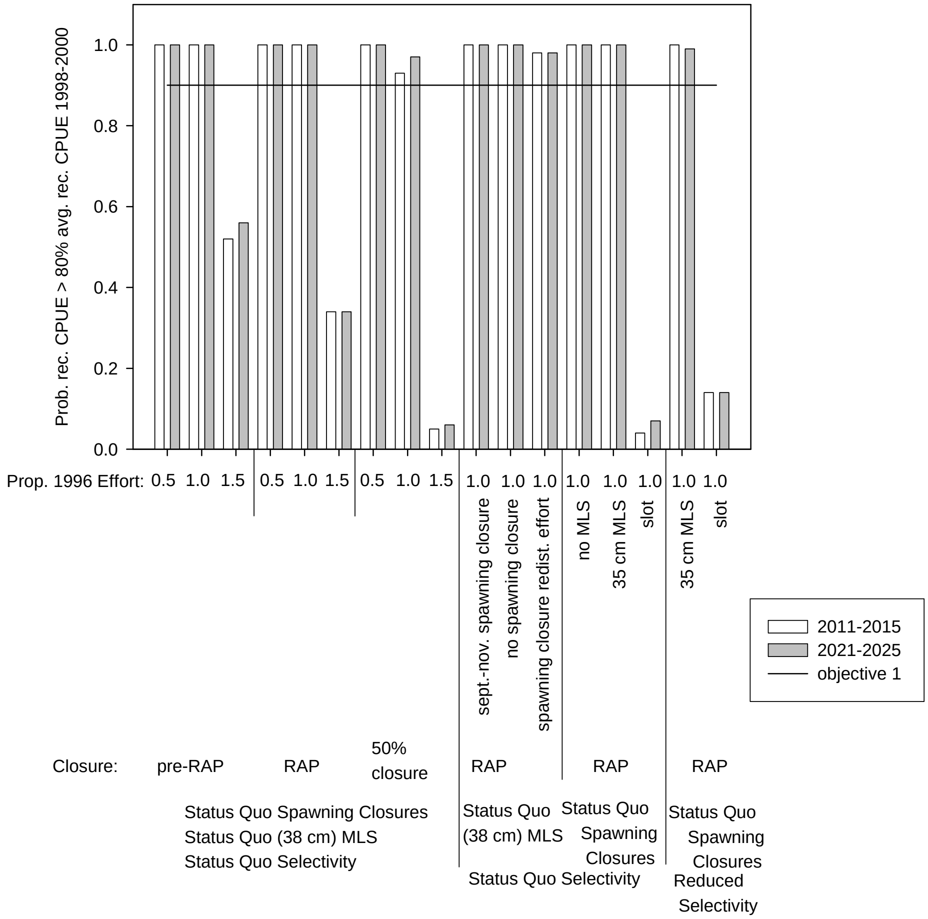


Fig. 6.50. Proportion of simulations where the average recreational CPUE for Coral Trout (2011-2015 and 2021-2025) is greater than 80% of the average Coral Trout CPUE for this fleet for 1998-2000, under the vessel dynamics model.

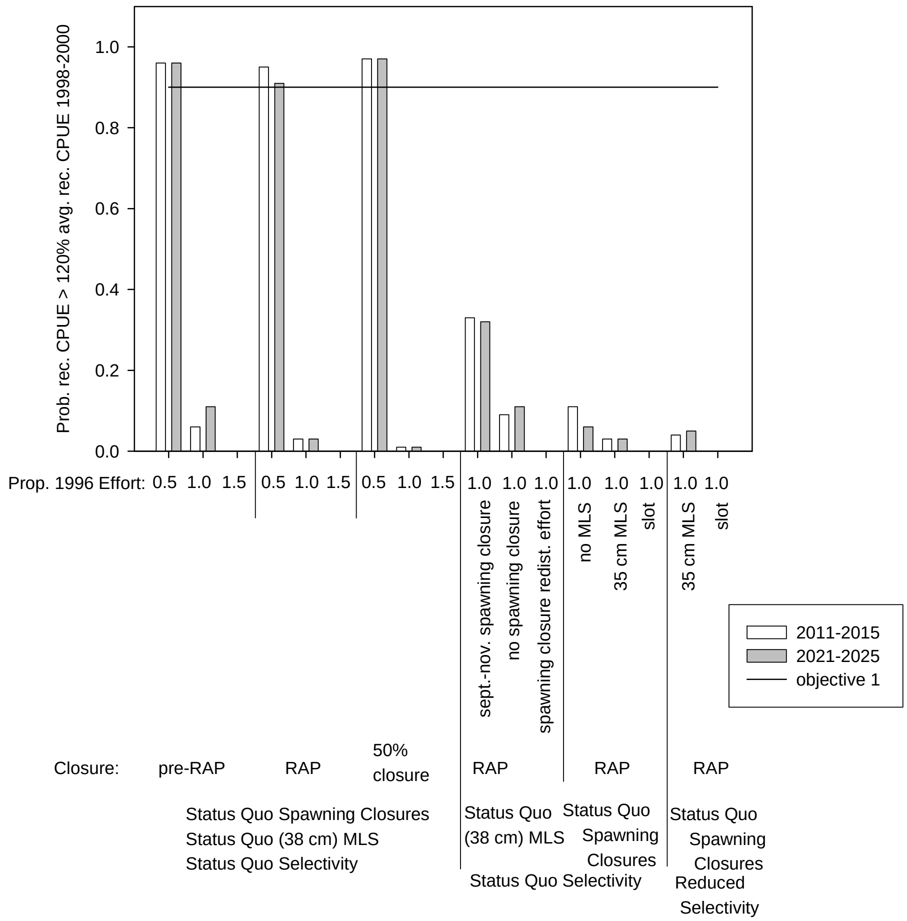


Fig. 6.51. Proportion of simulations where the average recreational CPUE for Coral Trout (2011-2015 and 2021-2025) is greater than 120% of the average Coral Trout CPUE for this fleet for 1998-2000, under the vessel dynamics model.

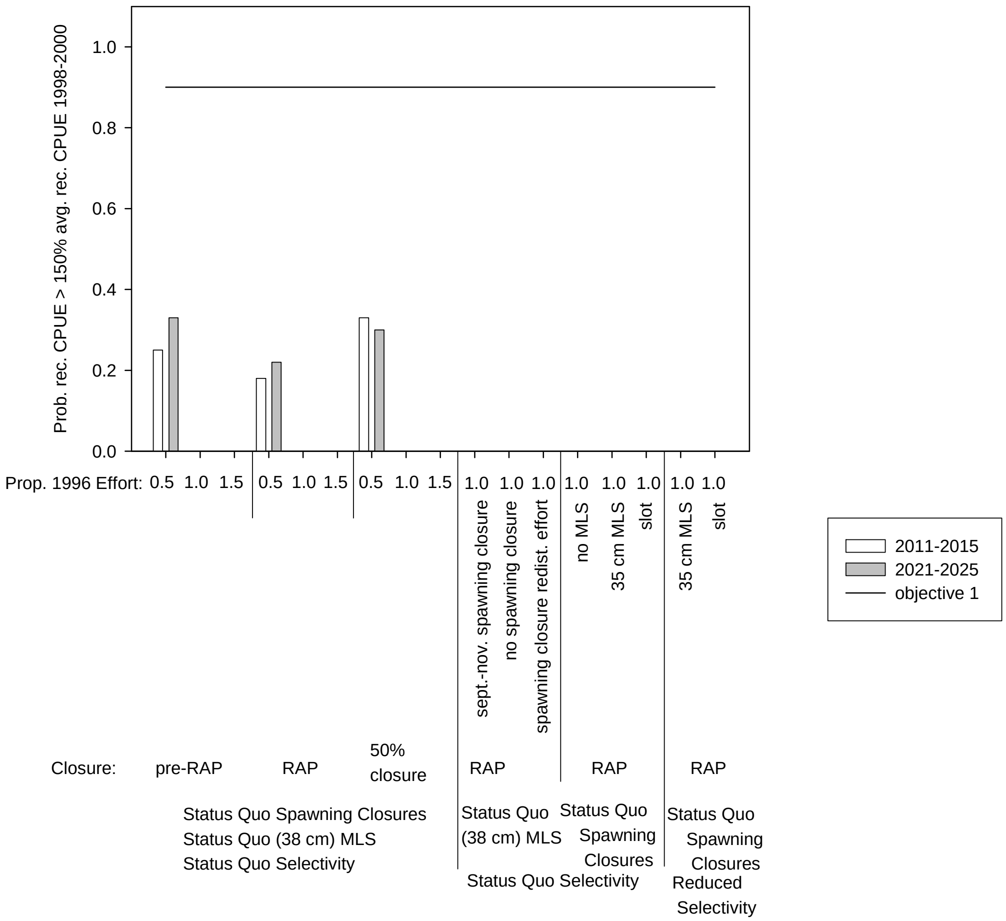


Fig. 6.52. Proportion of simulations where the average recreational CPUE for Coral Trout (2011-2015 and 2021-2025) is greater than 150% of the average Coral Trout CPUE for this fleet for 1998-2000, under the vessel dynamics model.

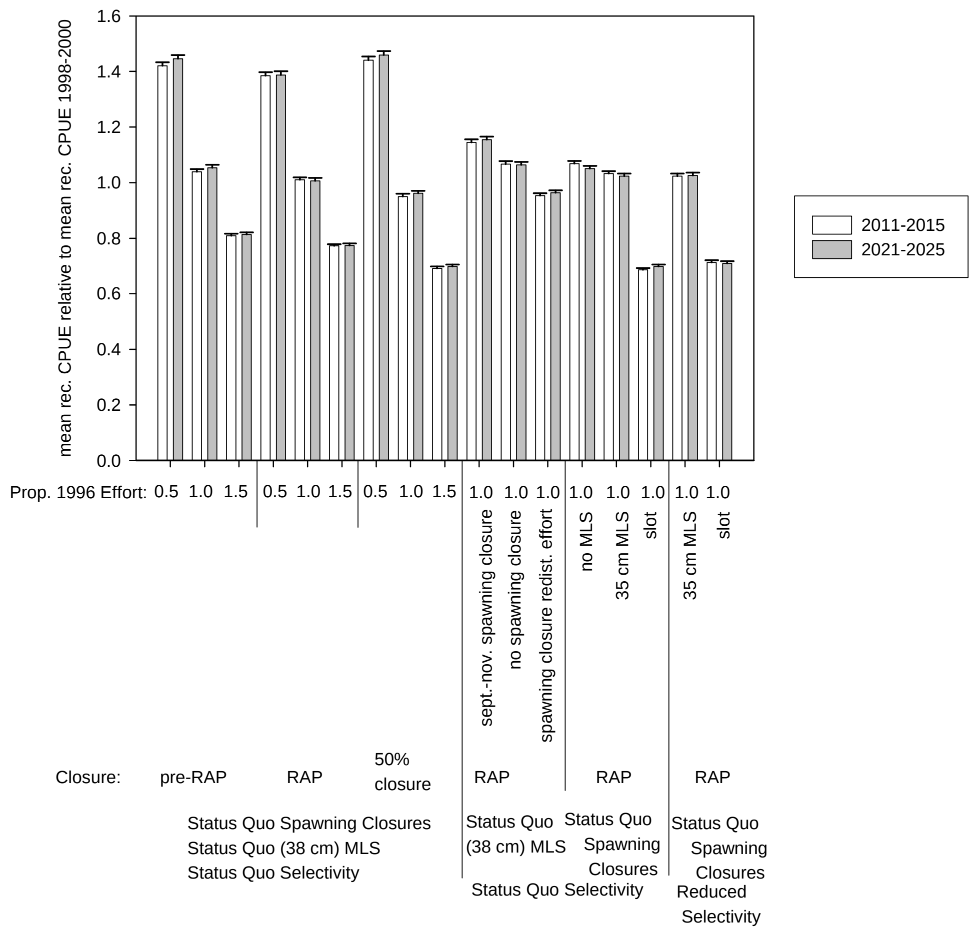


Fig. 6.53. Average (+SE) recreational CPUE for Coral Trout (2021-2025) relative to that for 1998-2000, under the vessel dynamics model.

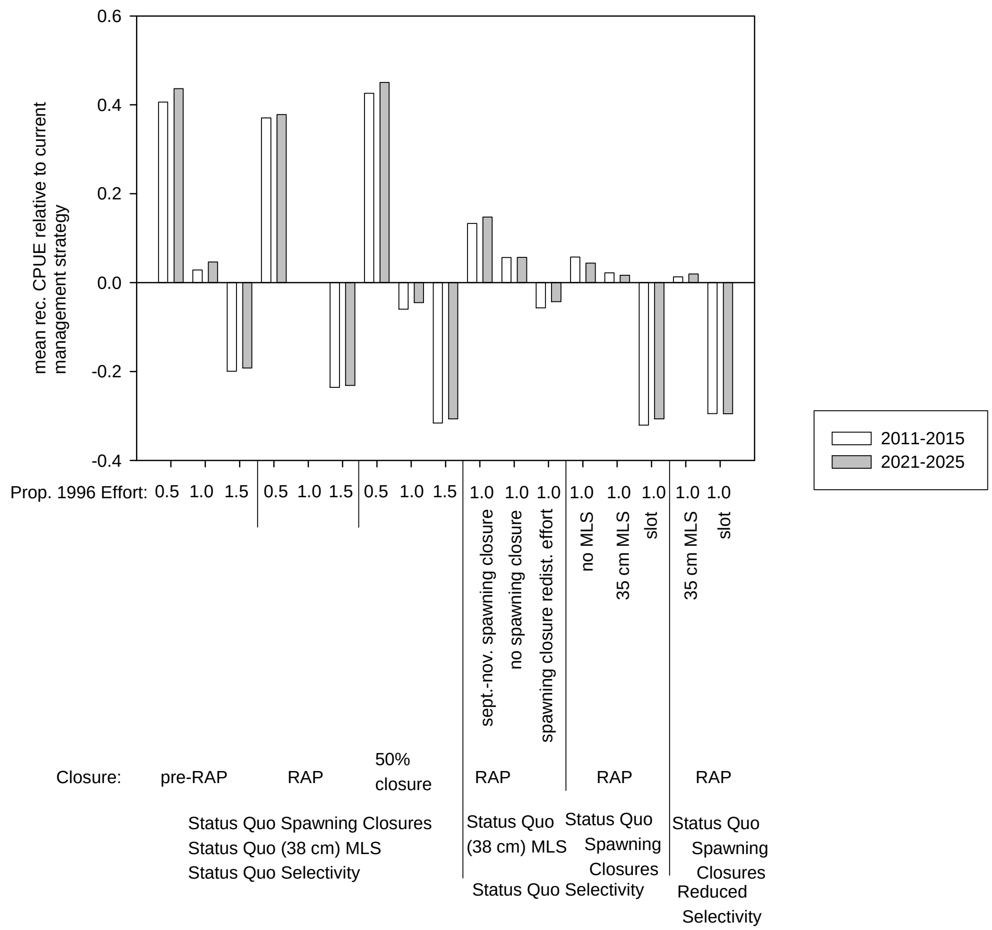


Fig. 6.54. Average recreational CPUE of Coral Trout (2011-2015 and 2021-2025) relative to that for the current management strategy, under the vessel dynamics model.

6.1.5. Regional discards

The objectives for the discards differ between the northern (north of 22°30´) and southern (south of 22°30´) reefs. The objectives for the two species are complementary. The objectives for the north relate to discards of Coral Trout less than 30% of the total catch, and discards of Red Throat Emperor less than 5% of the total catch. In the south, these objectives relate to discards of Coral Trout less than 5% of the total catch, and discards of Red Throat Emperor less than 30% of the total catch. The difference in objectives between the north and south stemmed in part from concern by those fishers in the southern part of the GBR that a large portion of the catch of Red Throat Emperor is small fish. This is consistent with the population dynamics and movement of Red Throat Emperor we have modelled, and advanced by Williams (2003), which depicts spawning in the southern portion of the GBR, with gradual northward migration of adults. Discards of Coral Trout were less of a concern, but regionally opposite to Red Throat Emperor, generally because there was an expectation that there are fewer fish in the north. As a result the threshold for Coral Trout discards in the north was higher (30%) than in the south (5%).

The chance of achieving the management objective of a discard rate lower than 30% for Coral Trout in the northern reefs was met by all management strategies (Fig. 6.55). It was only slightly more difficult to achieve the more restrictive objective of a 5% discard rate in the southern reefs (Fig. 6.55); the only management strategies that did not achieve this objective involved the slot size restriction. The average discard rates (Fig 6.56) showed that the reason most of the management strategies achieved the objectives was because discard rates ranged between 1% and 6% of the total catch. The strategies with slot limit restrictions led to the most discards relative to the current management strategy (Fig. 6.57) because fish above the maximum legal size were released. Most other strategies led to more discards compared to the current management strategy, with lower effort levels and reduced selectivity leading to roughly double the discard rate, presumably as a result of increasing numbers of juvenile fish as the stock demographics change in response to lower fishing mortality. Not surprisingly, the strategy with no MLS had a 100% reduction in discards compared to the current management strategy.

All of the management strategies achieved both objectives for both northern and southern reefs for Red Throat Emperor (Fig. 6.58). The discard rates for Red Throat Emperor differ somewhat between the northern and southern reefs (Fig. 6.59). For example, under reduced effort (0.5x 1996 levels) and pre-RAP closures, the discard rate of Red Throat Emperor in the north is about 2%, while in the south it is closer to 3%. The reason for this is that younger, smaller, fish tend to be found in the southern reefs, whereas older, larger Red Throat Emperor tend to move northward according to the model. The discard rate for management strategies with slot size restrictions is higher in the north because most of these fish are above the maximum legal size. In comparing the strategies with the current management strategy (Fig. 6.60) the results differed slightly from those for Coral Trout. Specifically, there are fewer discards in the south from the slot management strategies because there were fewer large Red Throat Emperor in the southern reefs to be caught and subsequently released.

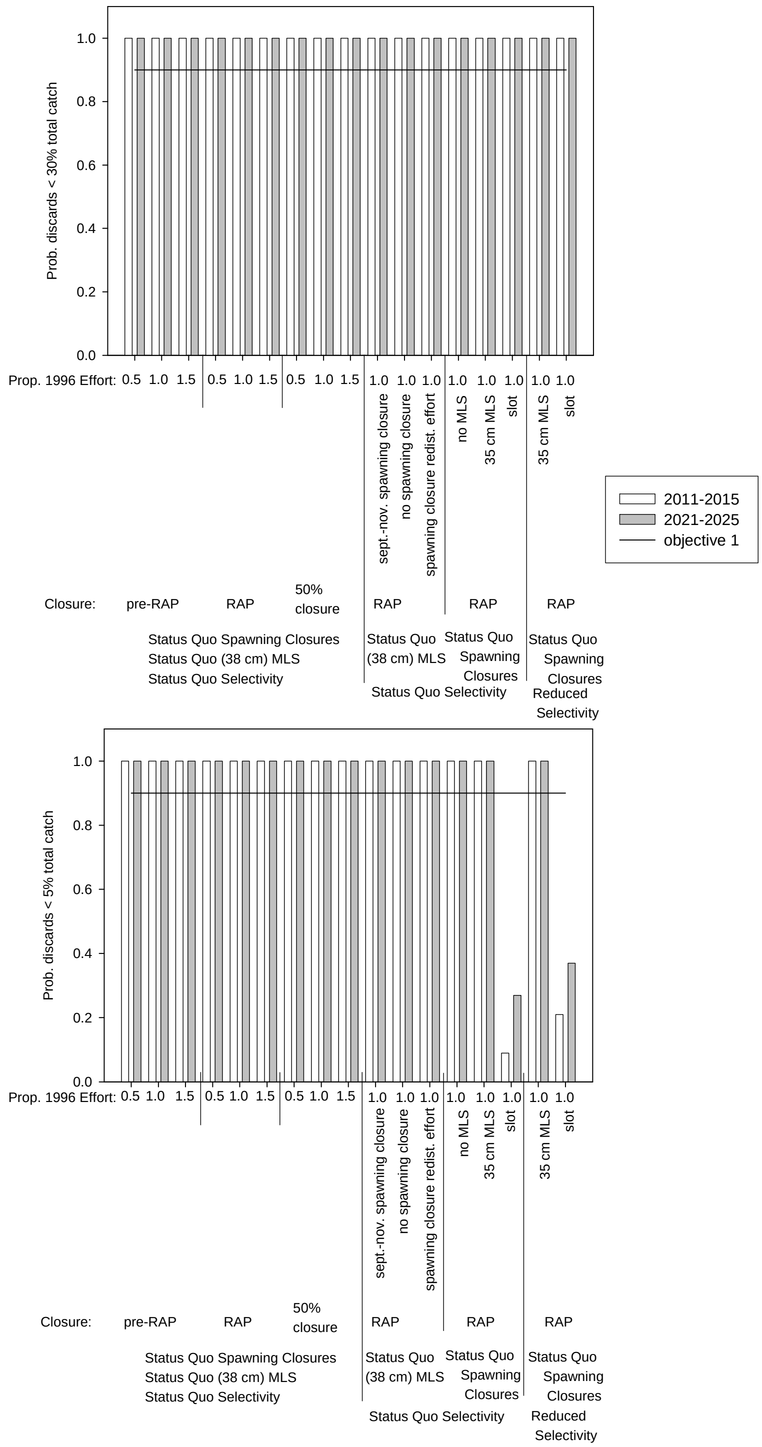


Fig. 6.55. Proportion of simulations where the average Coral Trout discards (2011-2015 and 2021-2025) in the northern (top) GBR is less than 30%, and in the southern (bottom) GBR is less than 5% of the total catch, under the vessel dynamics model.

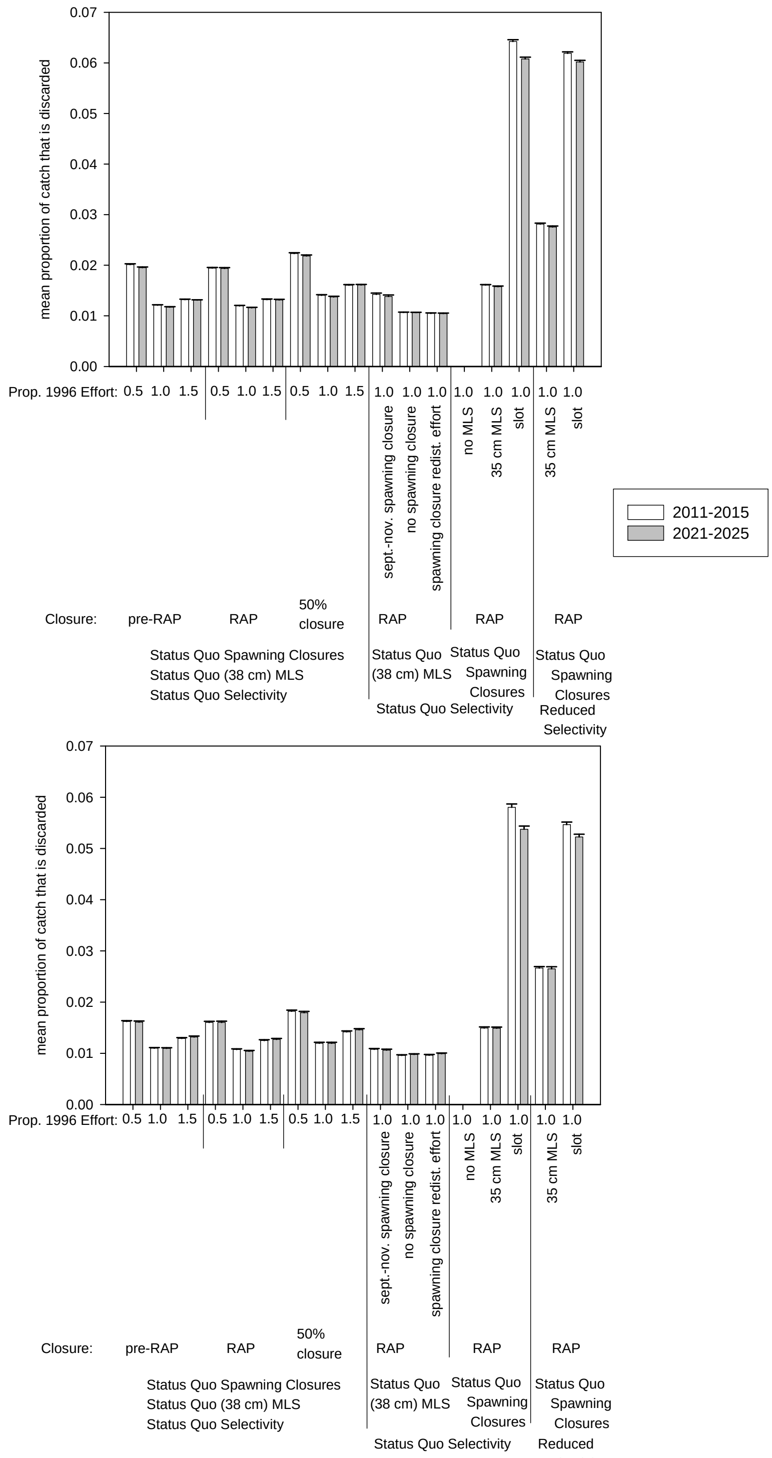


Fig. 6.56. Average (+SE) proportion of the total Coral Trout catch that is discarded in the northern (top) and southern (bottom) GBR, under the vessel dynamics model.

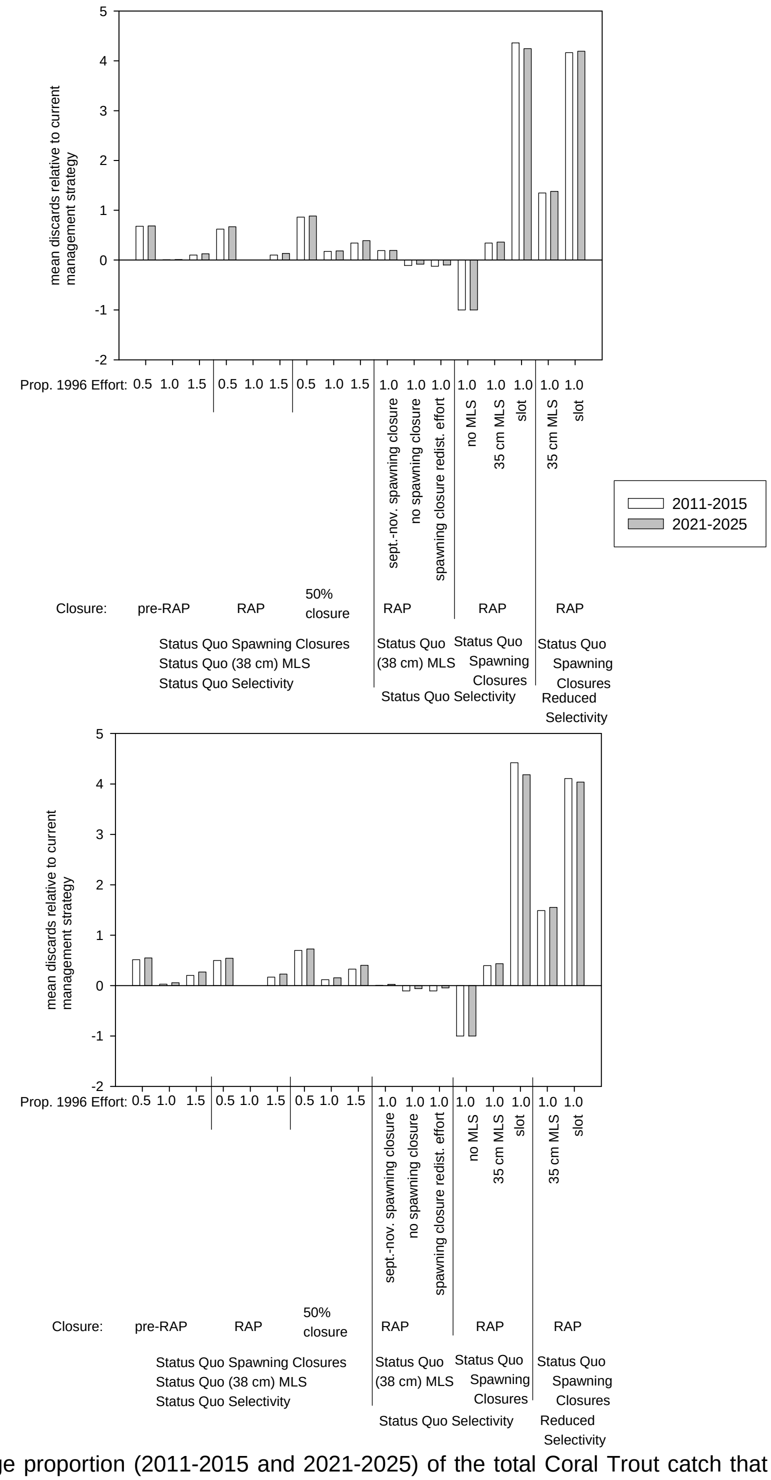
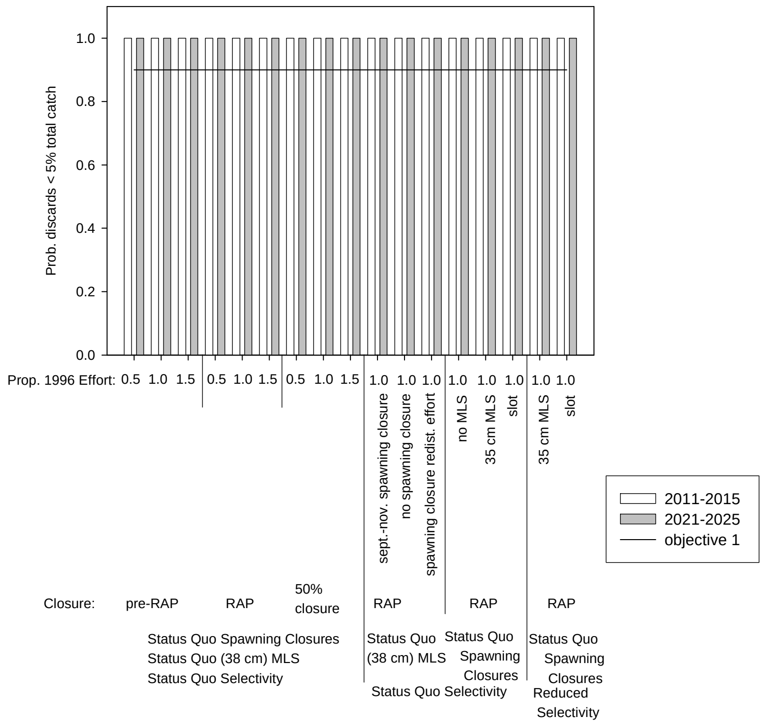


Fig. 6.57. Average proportion (2011-2015 and 2021-2025) of the total Coral Trout catch that is discarded in the northern (top) and southern (bottom) GBR, relative to the discard rates under the current management strategy, under the vessel dynamics model.



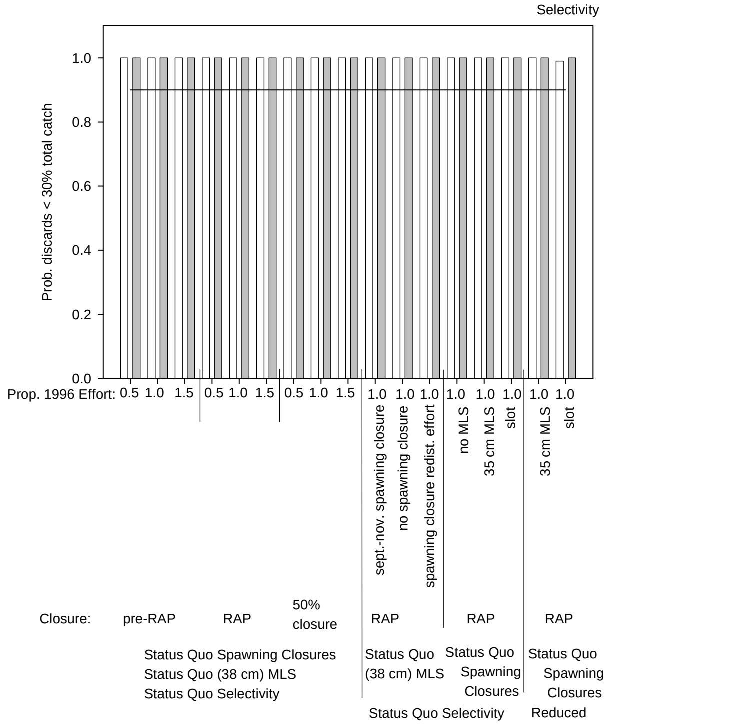


Fig. 6.58. Proportion of simulations where the average Red Throat Emperor discards (2011-2015 and 2021-2025) in the northern (top) GBR is less than 5%, and in the southern (bottom) GBR is less than 30% of the total catch, under the vessel dynamics model.

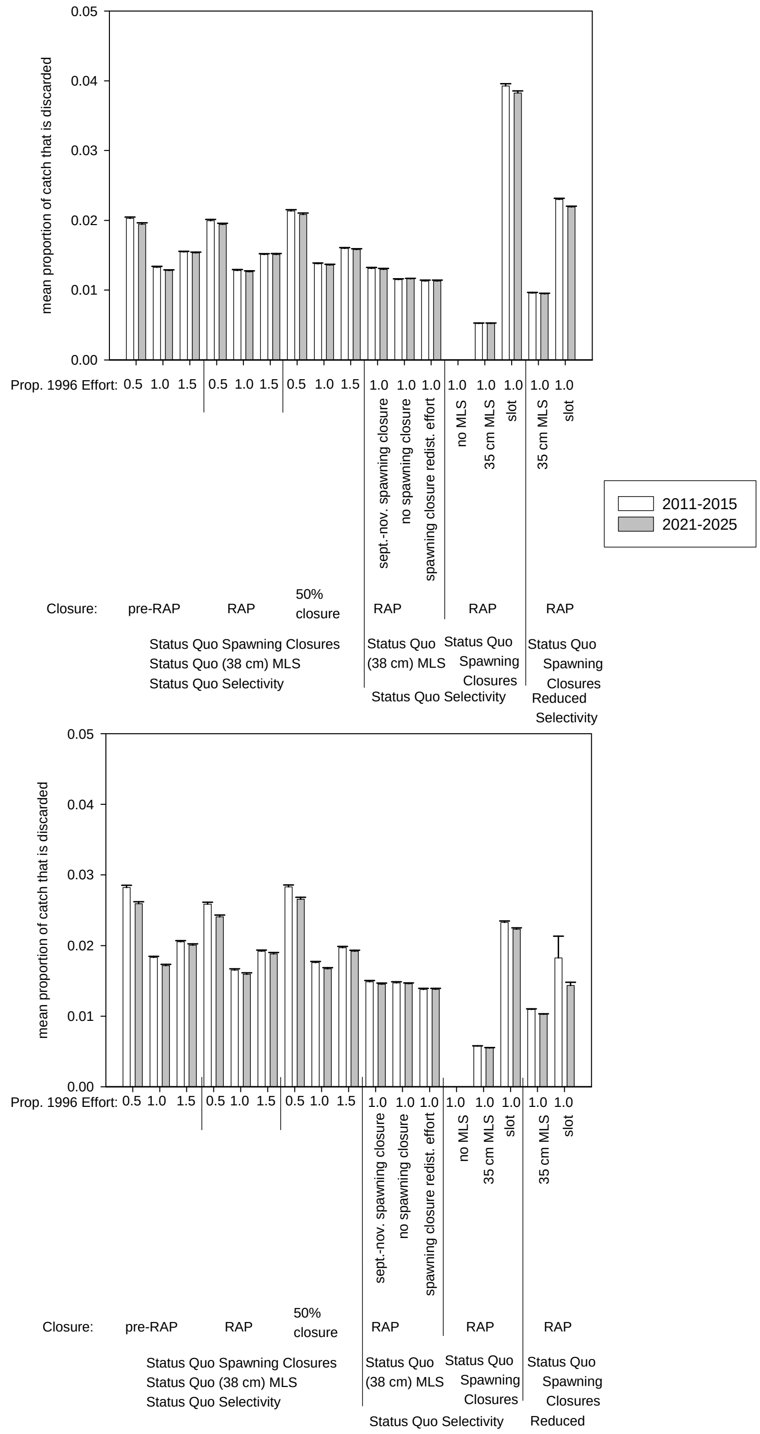


Fig. 6.59. Average (+SE) proportion (2011-2015 and 2021-2025) of the total Red Throat Emperor catch that is discarded in the northern (top) and southern (bottom) GBR, under the vessel dynamics model.

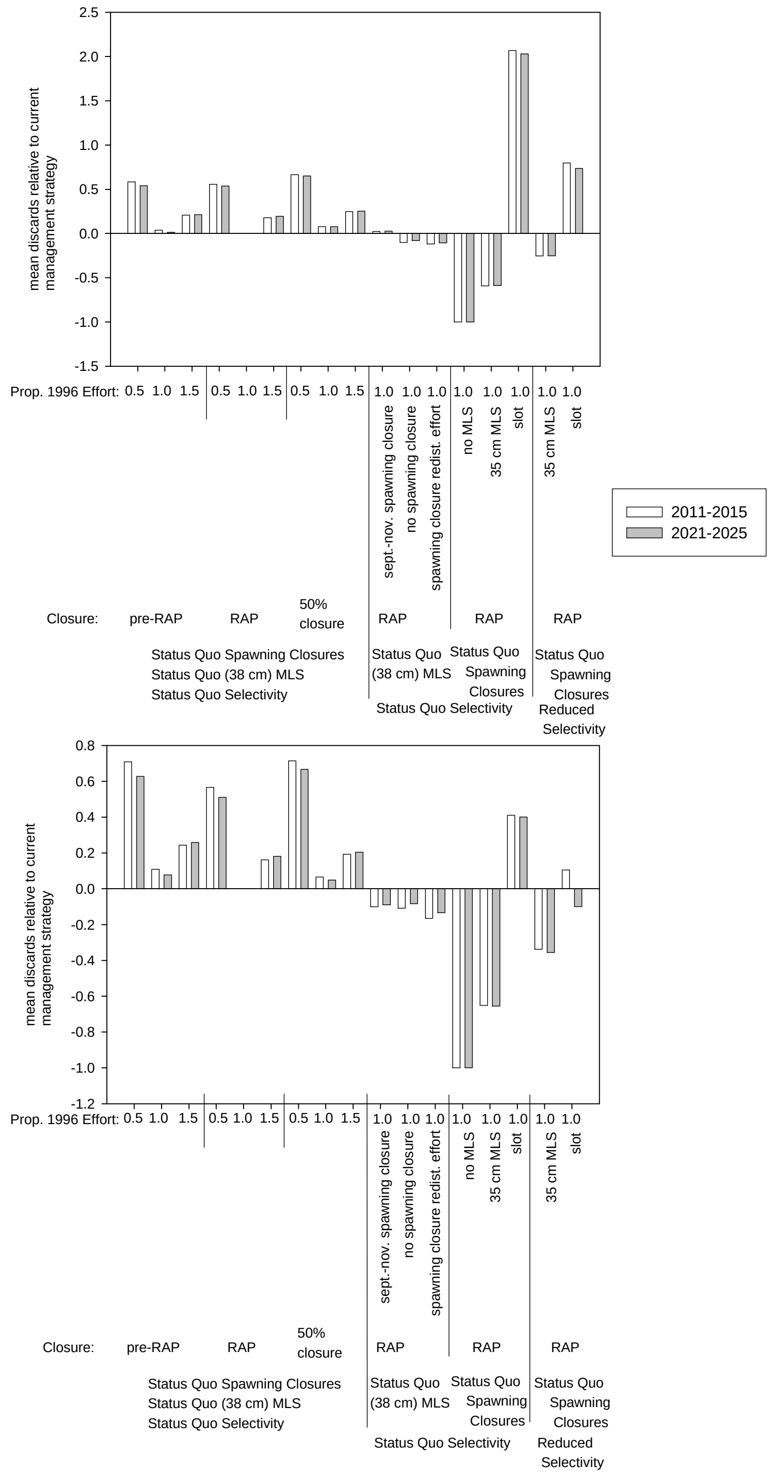


Fig. 6.60. Average proportion (2011-2015 and 2021-2025) of the total Red Throat Emperor catch that is discarded in the northern (top) and southern (bottom) GBR relative to the discard rates under the current management strategy, under the vessel dynamics model.

6.1.6. Harvest

Two harvest (i.e. retained catch) objectives were specified for each species. The first of these relates to the ratio of the retained catch to the total catch of the charter fleet, where all of the management strategies achieve the objective that over 90% of the catch is retained (Fig. 6.61). The proportion of total catch that is retained by the charter fleet indicates that almost all of the catch is retained (Fig 6.62).

The second objective related to harvest pertains to the catch by the commercial fleet relative to the current quotas by species, the idea being that the quota is a desired catch. The effectiveness of the management strategies at achieving this objective, for both species, is shown in Fig. 6.63. In general, the objective is most likely to be met for Coral Trout at the current effort levels (1996 effort) or increased effort, given the current RAP closures. Increasing the amount of area closed to fishing reduces the chances of achieving this objective, as does decreasing the amount of effort to 0.5x 1996 levels. Reducing the MLS will also satisfy the objective although the slot size restriction, with the maximum legal size, does not. The results are somewhat different for Red Throat Emperor. Only the increased effort or strategies that involve reduced gear selectivity lead to catches that are the same or larger than the current quotas for Coral Trout and Red Throat Emperor. Decreasing the MLS increases the likelihood of achieving the objective.

The ratio of the harvest relative to the quota by species is shown in Fig. 6.64. Management strategies under the lower 0.5x 1996 effort caught as low as 60% of the Coral Trout quota and about 50% of the Red Throat Emperor quota. The harvests under each of the management strategies are compared to those under the current management strategy in Fig. 6.65. As expected higher effort levels lead to more catch, as does reducing the MLS.

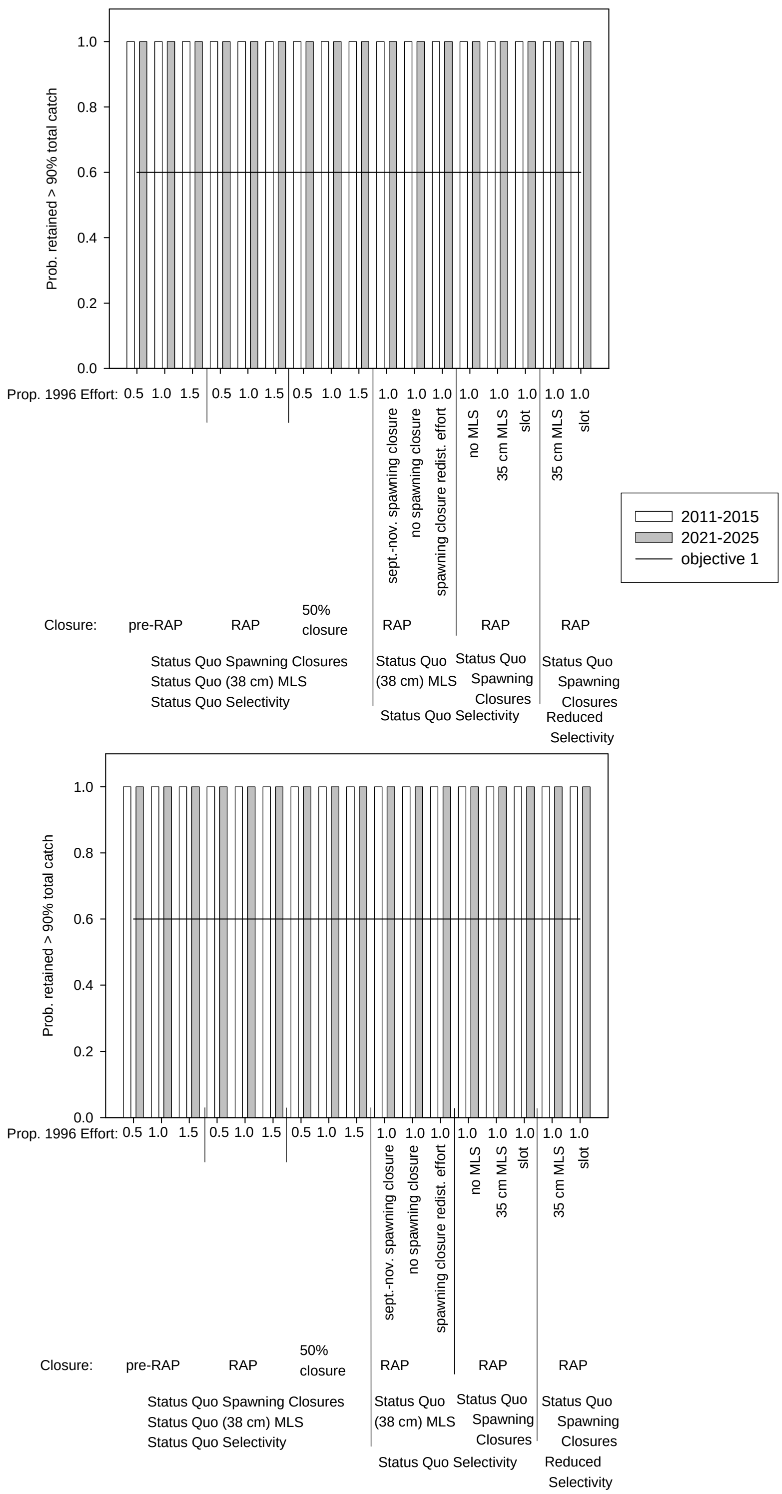


Fig. 6.61. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where over 90% of the total catch by the charter fleet is retained.

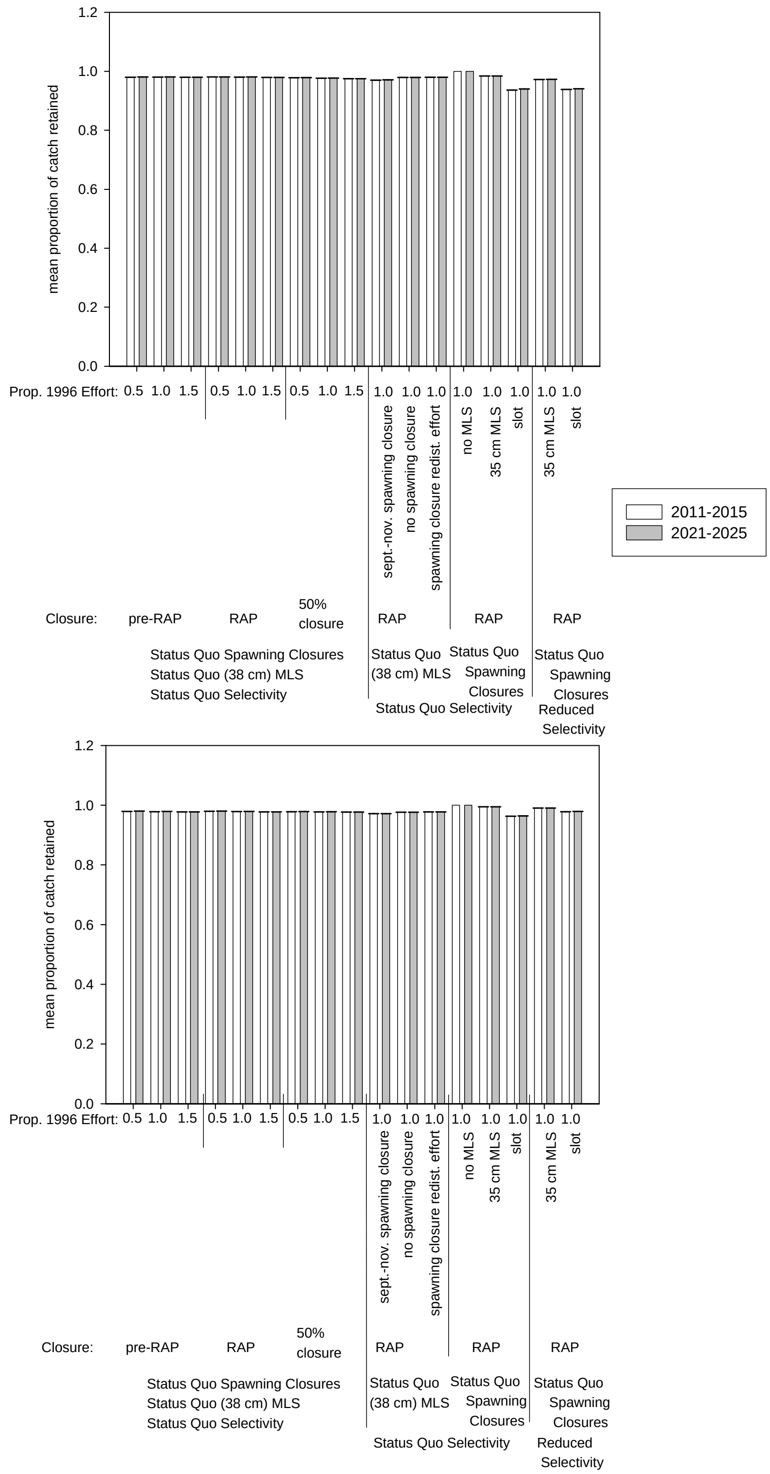


Fig. 6.62. Ratio of the retained catch (Coral Trout top, Red Throat Emperor bottom) to the total catch (2011-2015 and 2021-2025), under the vessel dynamics model.

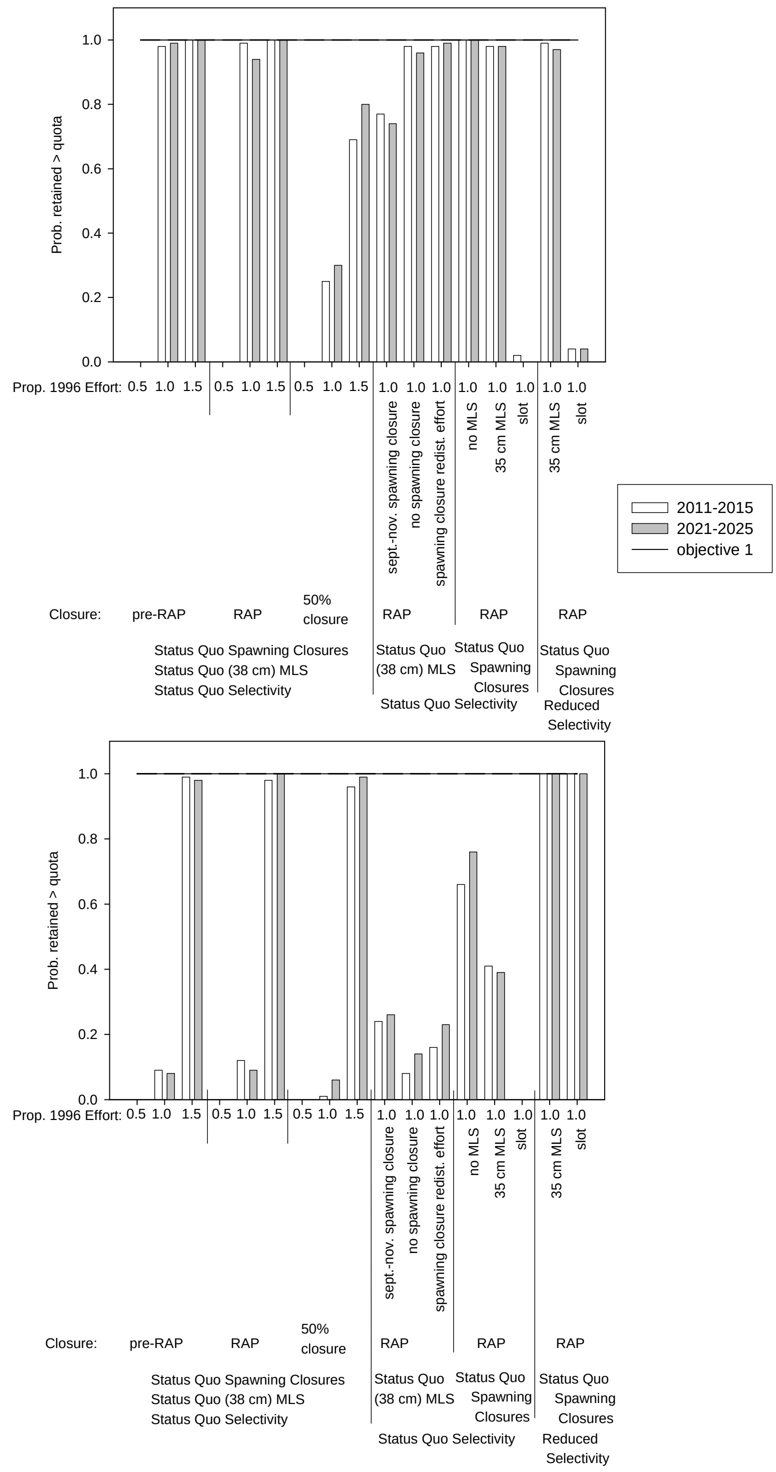


Fig. 6.63. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where the average harvest (2011-2015 and 2021-2025) is greater than the current quota (1300 t Coral Trout, 700 t Red Throat Emperor).

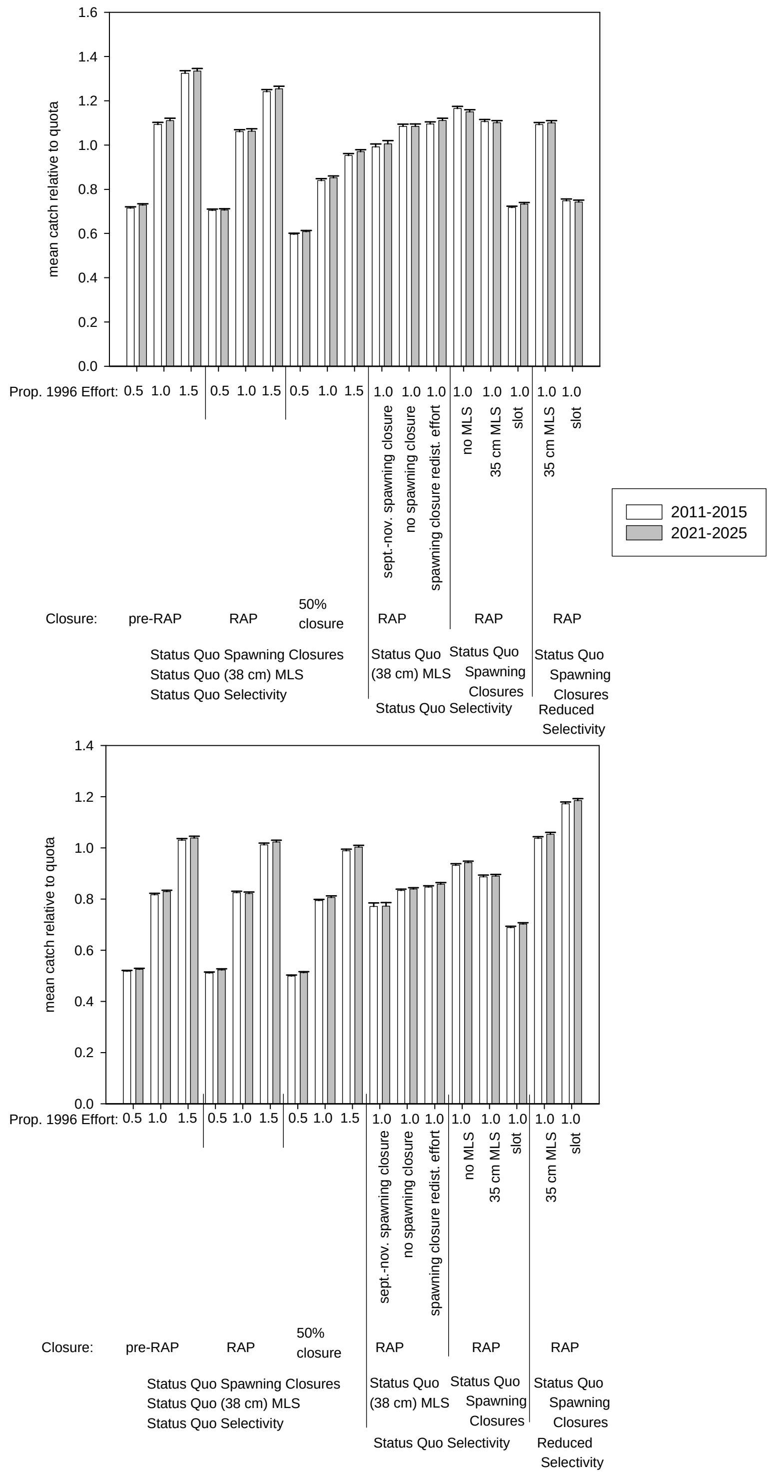


Fig. 6.64. Average harvest (2011-2015 and 2021-2025) (Coral Trout top, Red Throat Emperor bottom) relative to the current quota, under the vessel dynamics model.

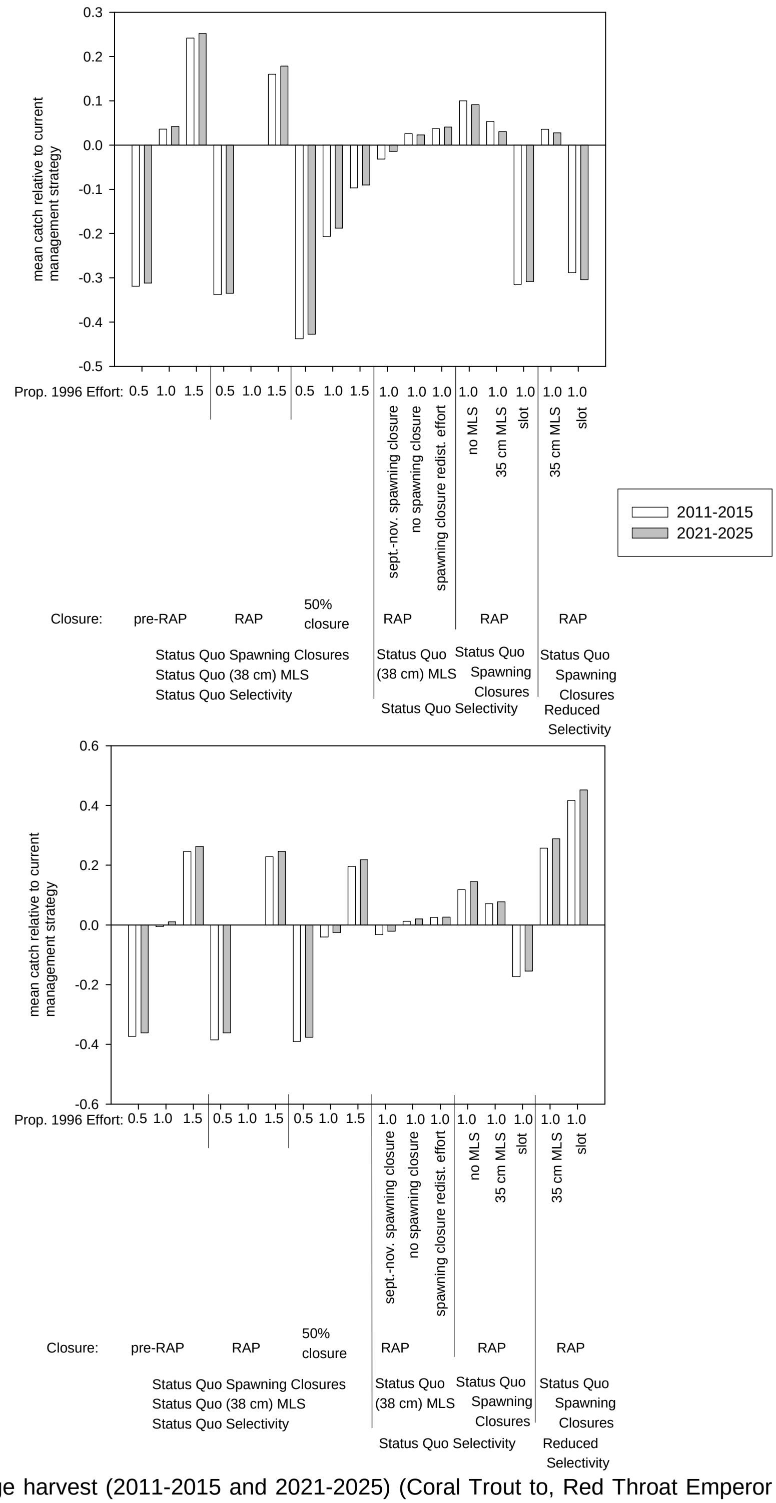


Fig. 6.65. Average harvest (2011-2015 and 2021-2025) (Coral Trout to, Red Throat Emperor bottom) relative to that under the current management strategy, under the vessel dynamics model.

6.1.7. Big fish

Fishing satisfaction among recreational fishers is often related to the chance of catching a 'big fish', which, for the purposes of this project, is a fish larger than 50 cm. The objective defined a 'good chance of catching a big fish' as when more than 50% of the catch consisted of “big” fish. This objective was not achieved by any management strategy (Fig. 6.66). An alternative objective, roughly equivalent to catching one big fish in a 'bag', was that more than 20% of the catch consisted of big fish. This objective was achieved by many of the management strategies for Coral Trout, but it was never achieved for Red Throat Emperor mainly because this species grows more slowly, and to smaller sizes than Coral Trout. The probability of achieving this objective for Coral Trout was greater if effort remains at the 1996 level or below, regardless of the amount of area closed; reducing the MLS dropped the probability of achieving this objective to virtually zero (Fig. 6.67).

The proportion of big fish in the catch, for each of the management strategies is shown in Fig. 6.68. This proportion is much higher for Coral Trout, ranging as high as about 0.25, whereas for Red Throat Emperor it did not exceed 0.04. This proportion drops substantially (particularly for Red Throat Emperor) if the MLS is reduced. Figure 6.69 compares the proportion of the recreational catch that is 'big fish' to that under the current management strategy. For Coral Trout, effort reductions, which include 0.5x 1996 effort as well as the 3 month spawning seasonal closure, result in more big fish in the catch compared to the current management strategy. Any increases in the amount of 'big' Red Throat Emperor, fish in the recreational catch is marginal, but it remains the case that reducing the MLS will lead to fewer large fish in the catch.

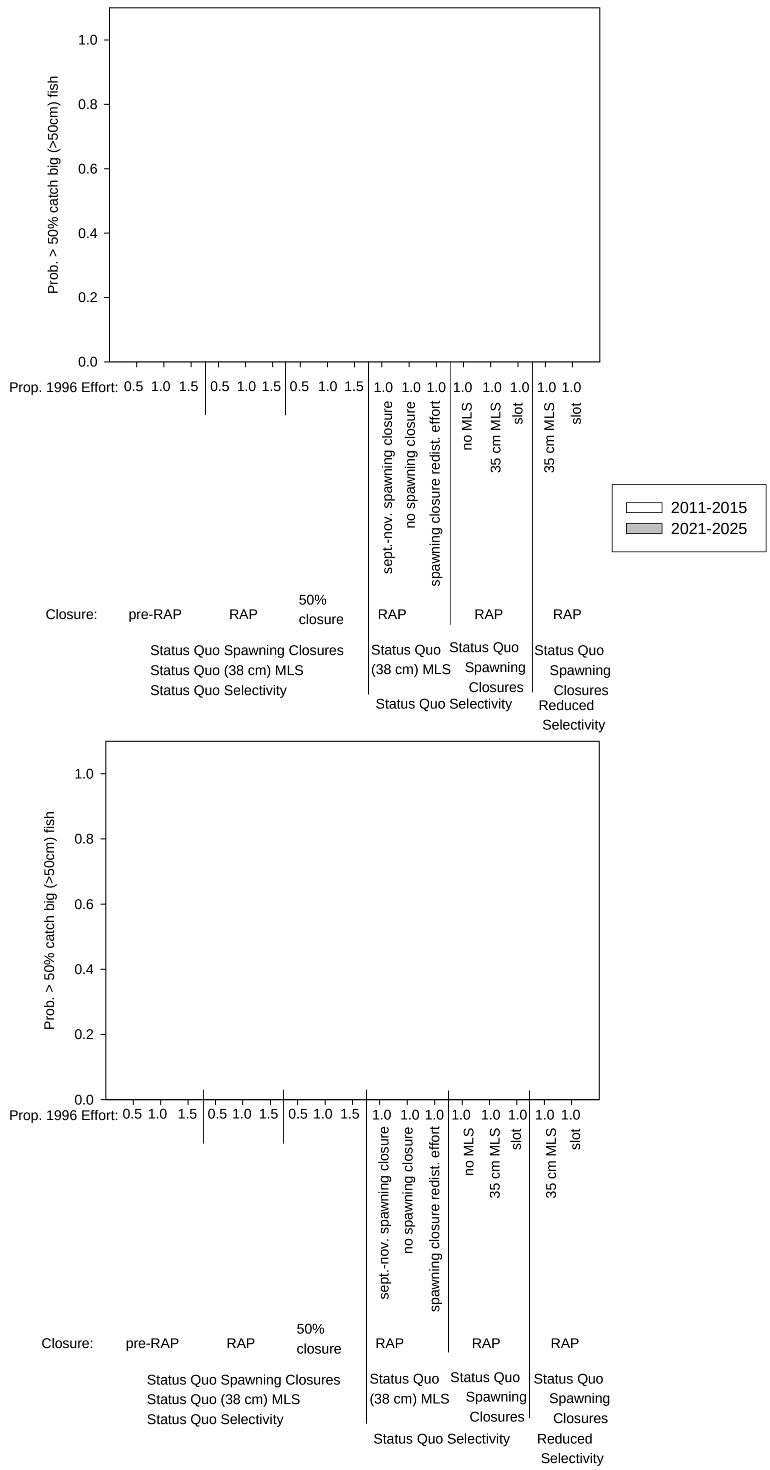


Fig. 6.66. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where greater than 50% of the harvest by the recreational sector (2011-2015 and 2021-2025) are fish >50 cm.

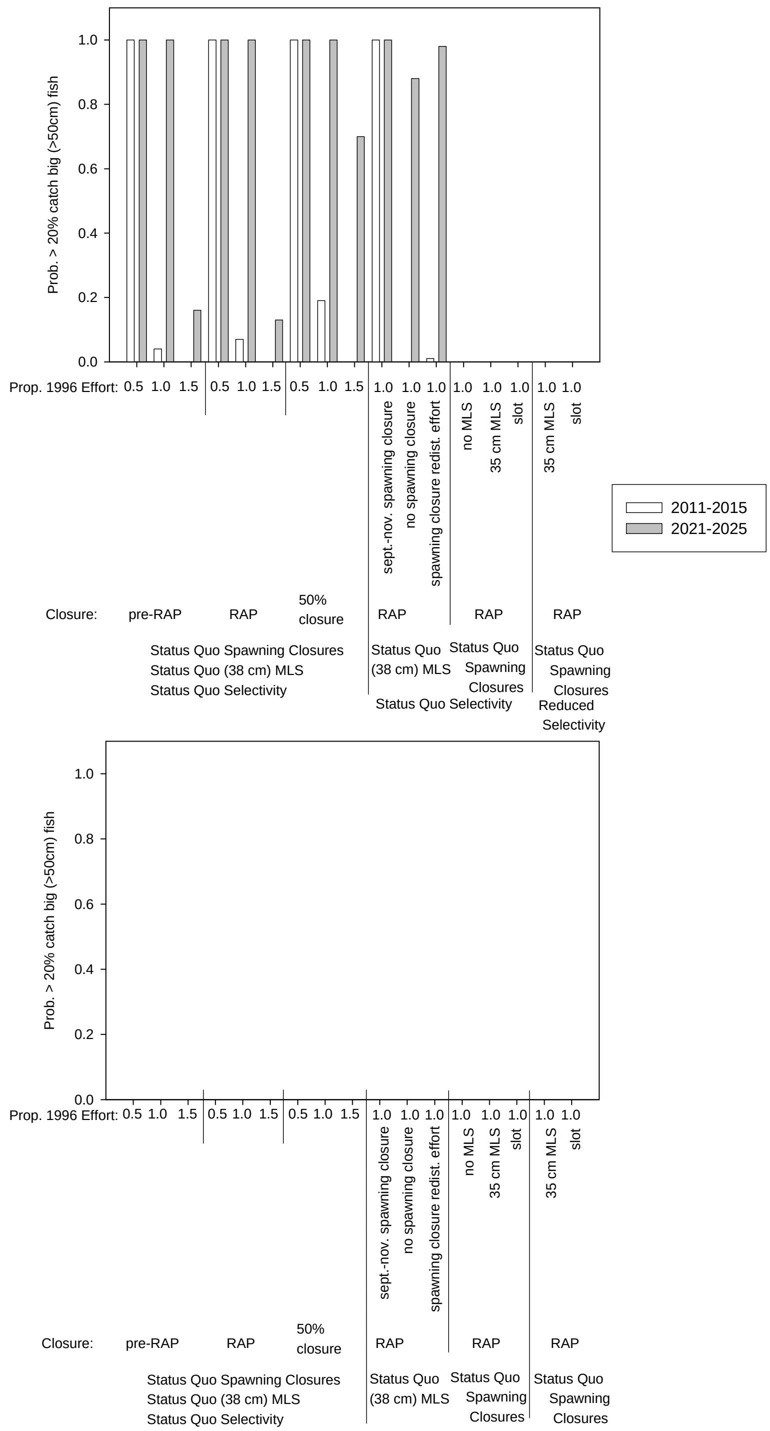


Fig. 6.67. Proportion of simulations (Coral Trout top, Red Throat Emperor bottom) under the vessel dynamics model, where greater than 20% of the harvest by the recreational sector (2011-2015 and 2021-2025) are fish >50 cm .

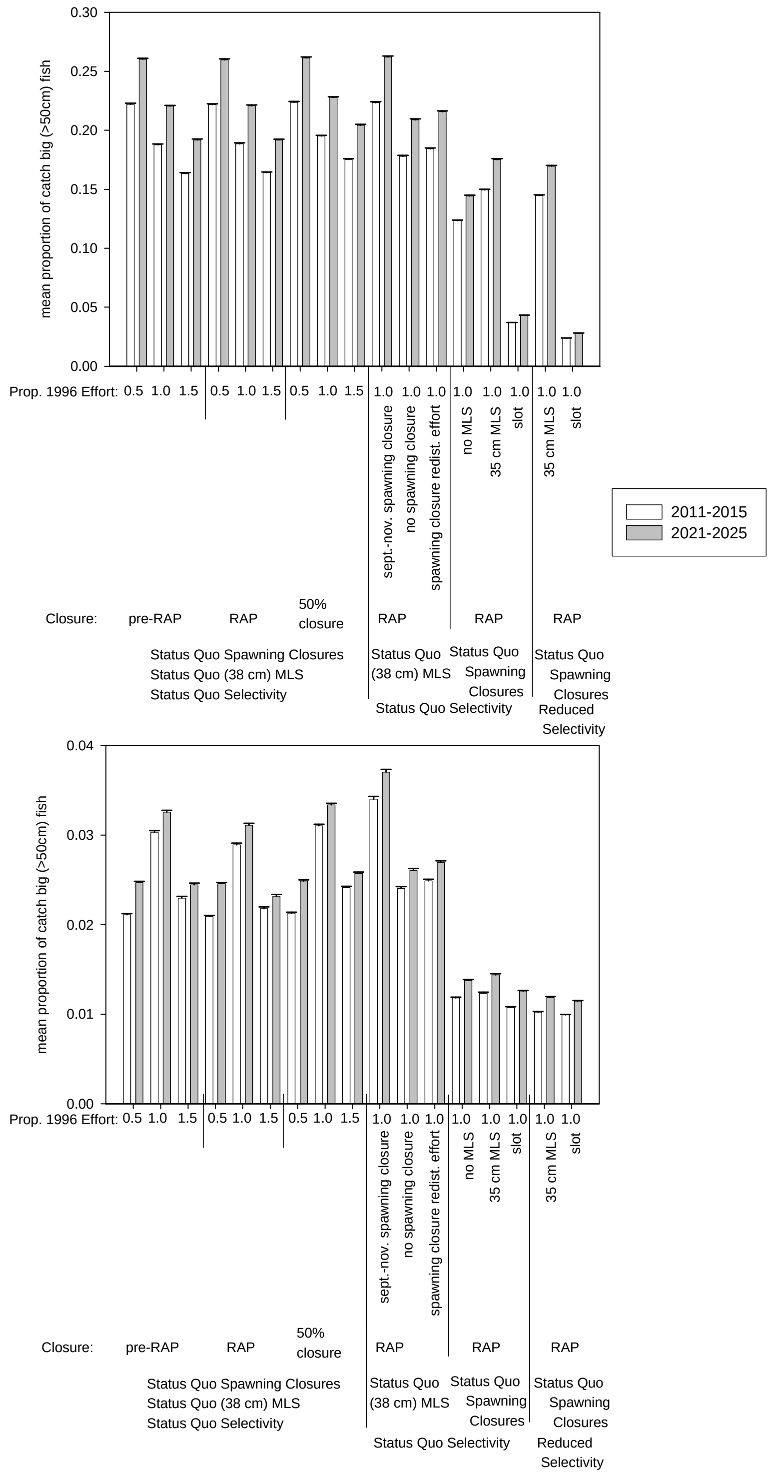


Fig. 6.68. Average (+SE) proportion of the harvest by the recreational fleet (2011-2015 and 2021-2025) that are fish >50 cm (Coral Trout top, Red Throat Emperor bottom), under the vessel dynamics model.

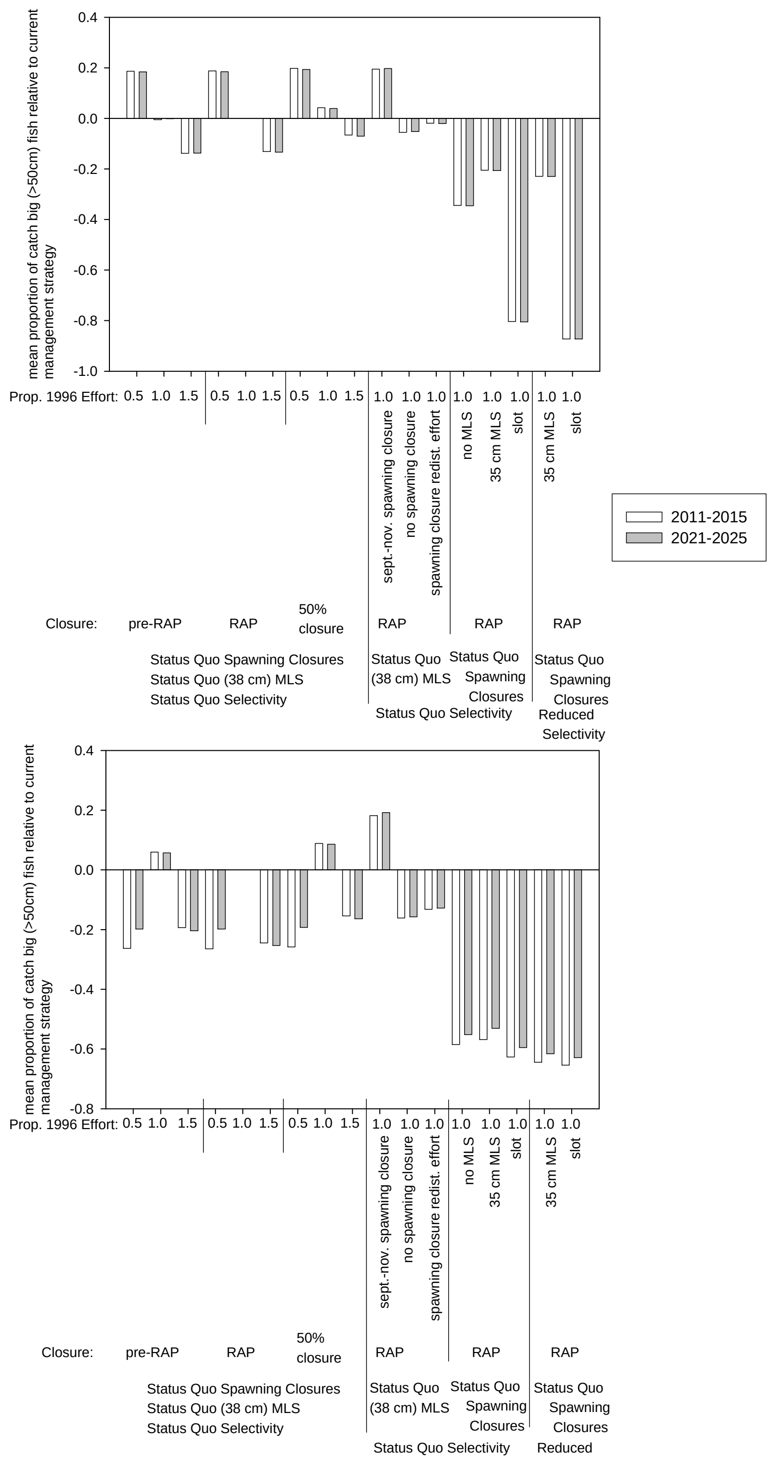


Fig. 6.69. Average (+SE) proportion of the harvest by the recreational fleet (2011-2015 and 2021-2025) that are fish >50 cm (Coral Trout top, Red Throat Emperor bottom) relative to current management strategy, under the vessel dynamics model.

6.1.8 Performance summary

The results for the major management objectives are aggregated and synthesised in Table 6.1 which shows the mean value of the performance indicators from each management strategy in the last five years of projection relative to the reference value across all simulations under the vessel dynamics model. The performance indicators relate to the five categories of management objective: conservation, stock, harvest, economic and satisfaction.

The model results show that reducing effort is the most effective way of maximizing the conservation and stock objectives for both species. The management strategy that is best at maximizing the harvest objective depends on the species. Specifically, increasing effort and the amount of area open to fishing (decreasing area closures to pre-RAP) and removing the MLS achieves the highest harvest of Coral Trout and reducing the selectivity of the gear, combined with changing the MLS leads to the largest harvests of Red Throat Emperor. Reducing effort would lead to higher CPUE of Coral Trout, and reducing the selectivity of the gear combined with changing MLS would lead to the best CPUE of Red Throat Emperor. However, the economic and harvest benefits for Red Throat Emperor of reducing gear selectivity and the MLS, should be balanced against the poor performance of strategies that involve these factors on the conservation and stock objectives. The best strategies for the satisfaction objective, which involved having a good chance of catching a fish >50 cm, involved reducing effort.

Care must be taken in interpreting the absolute values of the quantities in Table 6.1. This is because the purpose of evaluating management strategies using an MSE is to make comparisons among strategies, and not to make claims that a particular management strategy will lead to a particular outcome.

Table 6.1. Summary of performance indicators for different objectives from the last five years of the projection period (2021-2025) under different management strategies and the vessel dynamics model. Colours blue: the highest (best) value for a column, green the second highest value, red the lowest (worst) value and orange the second lowest value (CT : Coral Trout, RTE Red Throat Emperor, SB spawning biomass, AB available biomass, TB total biomass).

Strategy					Objective											
					Conservation		Stock				Harvest		Economic		Satisfaction	
Effort	Spatial Closure	Seasonal Closure	MLS	Indicator (reference):	SB on closed reefs (unfished)		AB on open reefs (2000)		TB on open reefs (2000)		Retained (quota)		Comm. CPUE mean (94-96)		Rec. Big fish (>50cm)	
					CT	RTE	CT	RTE	CT	RTE	CT	RTE	CT	RTE	CT	RTE
0.5	Pre-RAP	3 X 9	38cm		**0.96**	0.87	**1.67**	**1.51**	**1.41**	**1.19**	0.73	0.53	**1.23**	0.89	**0.26**	**0.02**
0.5	RAP	3 X 9	38cm		**0.96**	**0.90**	**1.67**	**1.55**	**1.41**	**1.20**	**0.71**	**0.52**	**1.19**	0.88	**0.26**	**0.02**
0.5	50%	3 X 9	38cm		**0.97**	**0.89**	1.47	1.48	1.30	1.18	**0.61**	**0.51**	1.03	0.87	**0.26**	**0.02**
1.0	Pre-RAP	3 X 9	38cm		0.93	0.80	1.37	1.20	1.22	1.08	1.11	0.83	0.94	0.71	0.22	**0.03**
1.0	RAP	3 X 9	38cm		0.92	0.83	1.35	1.21	1.21	1.09	1.06	0.82	0.90	0.70	0.22	**0.03**
1.0	50%	3 X 9	38cm		0.93	0.83	1.13	1.19	1.08	1.08	0.85	0.81	0.72	0.69	**0.23**	**0.03**
1.5	Pre-RAP	3 X 9	38cm		0.90	0.75	1.15	1.00	1.08	1.01	**1.33**	1.04	0.76	0.59	0.19	**0.02**
1.5	RAP	3 X 9	38cm		0.89	0.79	1.11	1.01	1.06	1.02	1.25	1.02	0.71	**0.58**	0.19	**0.02**
1.5	50%	3 X 9	38cm		0.91	0.77	**0.92**	0.99	**0.95**	1.00	0.97	1.00	**0.55**	**0.57**	0.20	**0.03**
<1.0	RAP	Sept-Nov	38cm		0.94	0.86	**1.52**	1.35	**1.33**	1.14	1.01	0.77	1.00	0.76	**0.26**	**0.04**
1.0	RAP	None	38cm		0.88	0.82	1.29	1.15	1.18	1.06	1.08	0.84	0.86	0.67	0.21	**0.03**
1.0	RAP	Re-dist	38cm		0.93	0.82	1.30	1.17	1.19	1.07	1.11	0.86	0.87	0.67	0.22	**0.03**
1.0	RAP	3 X 9	None		**0.87**	0.78	1.09	1.05	1.06	1.02	1.15	0.94	0.92	0.76	0.14	**0.01**
1.0	RAP	3 X 9	35cm		0.89	0.80	1.17	1.09	1.13	1.05	1.10	0.89	0.93	0.76	0.18	**0.01**
1.0	RAP	3 X 9	Slot		0.90	0.80	1.15	1.05	1.21	1.08	0.73	0.70	**0.62**	0.60	**0.04**	**0.01**
	RAP	3 X 9	35cm	redu. Sel.	0.89	**0.74**	1.15	**0.93**	1.11	**0.96**	1.10	**1.05**	0.93	**0.90**	0.17	**0.01**
	RAP	3 X 9	Slot	redu. Sel.	**0.81**	**0.56**	**0.90**	**0.70**	**0.97**	**0.76**	0.74	**1.18**	0.63	**1.01**	**0.03**	**0.01**

6.2. Effort allocation model

Many of results for the effort allocation model are qualitatively identical to those for the vessel dynamics model. These results were not repeated in detail except as noted below but are summarised.

6.2.1. Regional discards

The management objective that the discard rate of Coral Trout in the northern reefs is less than <30% was met by all of the management strategies, while on the southern reefs most of the management strategies failed to achieve the management objective that the discard rate be <5% (Fig. 6.70). The failure to achieve the latter management objective is due to high discard rates over 2021-2024 for some of the management strategies, particularly those with low effort (Fig. 6.71). The results in Fig. 6.71 differ markedly from those for the vessel dynamics model (Fig. 6.56) for which discard rates of Coral Trout in the southern reefs are < 6%. In addition, the discard rates for the interim, or transitional, period (2010-2015), under the effort allocation model are more similar to, but nevertheless higher than, those under the vessel dynamics model.

The difference in results between the two effort models arises because of the regional fidelity in effort alloction between the two models. The boundary between the northern and southern regions, specified by stakeholders, occurs at 22°30', which demarcates the reefs of the Capricorn-Bunkers from the rest of the Marine Park. In the vessel dynamics model, effort is constrained to this region because fishing vessels were allocated to ports and are restricted in where they can fish in relation to their home port. In the effort allocation model, however, although effort can be regionally constrained (Mapstone et al. 2004), we did not impose such restrictions in the current simulations. As a result, effort from the southern Capricorn-Bunkers region gradually moved north so that less than 10% of the effort that was there at the start remained there by the end of the projection. The increased discards in the southern reefs under the effort allocation model from 2021-2025, compared to both the vessel dynamics model and the prior period from 2011-2015, is therefore most likely due to increased numbers of smaller fish resulting from the recovery of biomass in this region due to reduced fishing pressure. The comparison of the management strategies relative to the current management strategy shows the differences between the northern and the southern reefs (Fig. 6.72), which also demonstrates that reduced effort leads to changes in demographics, especially by the 2021-2025 period.

The management objective that the discard rate of Red Throat Emperor in the northern reefs is less than <5% and that in the southern reefs is less than <30% was satisfied by all of the management strategies (Fig. 6.73). As for Coral Trout, the discard rates for Red Throat Emperor were higher in the south than in the north (Fig. 6.74). Fig. 6.75 shows discard rates in the southern reefs are higher than the current management strategy for the low effort strategies, and in the latter part of the simulation (2021-2025).

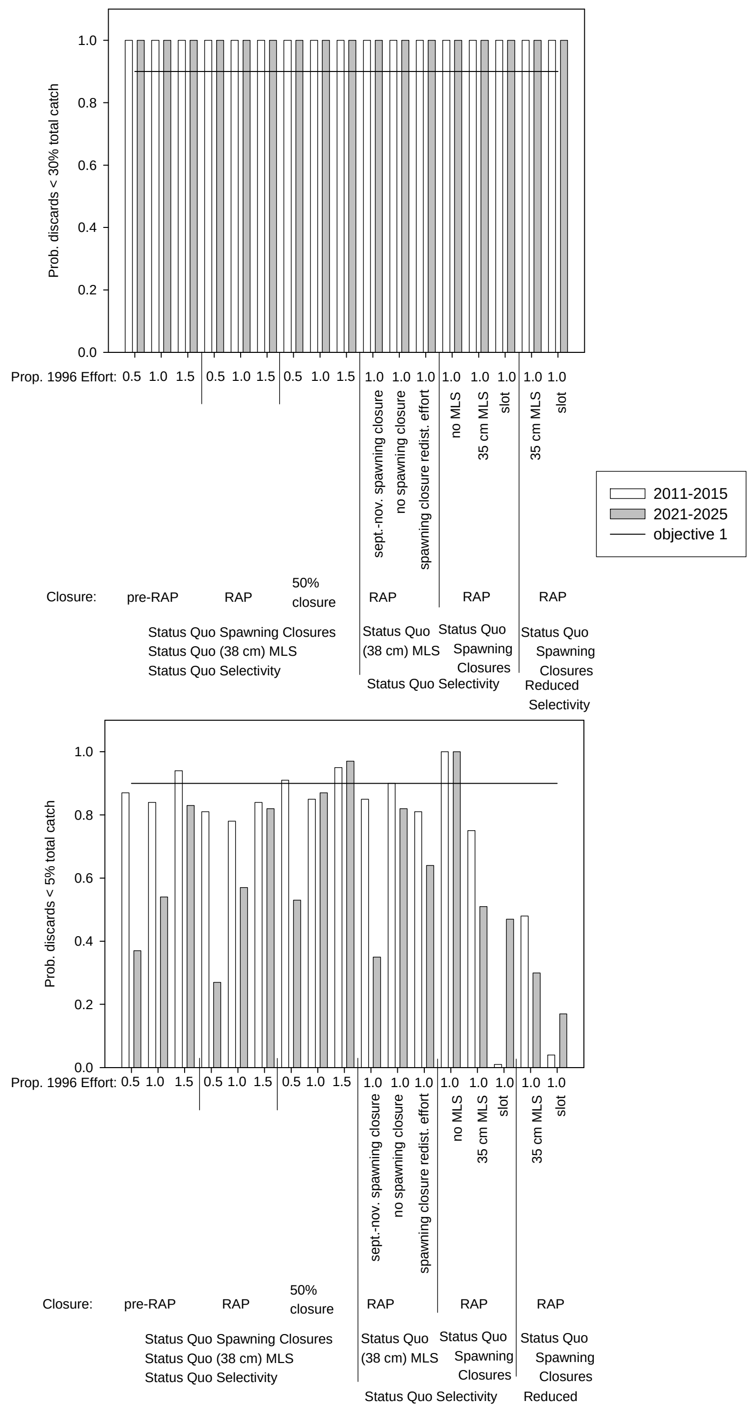


Fig. 6.70. Proportion of simulations where the average Coral Trout discards (2011-2015 and 2021-2025) in the northern (top) GBR is less than 30%, and in the southern (bottom) GBR is less than 5% of the total catch, under the effort allocation model.

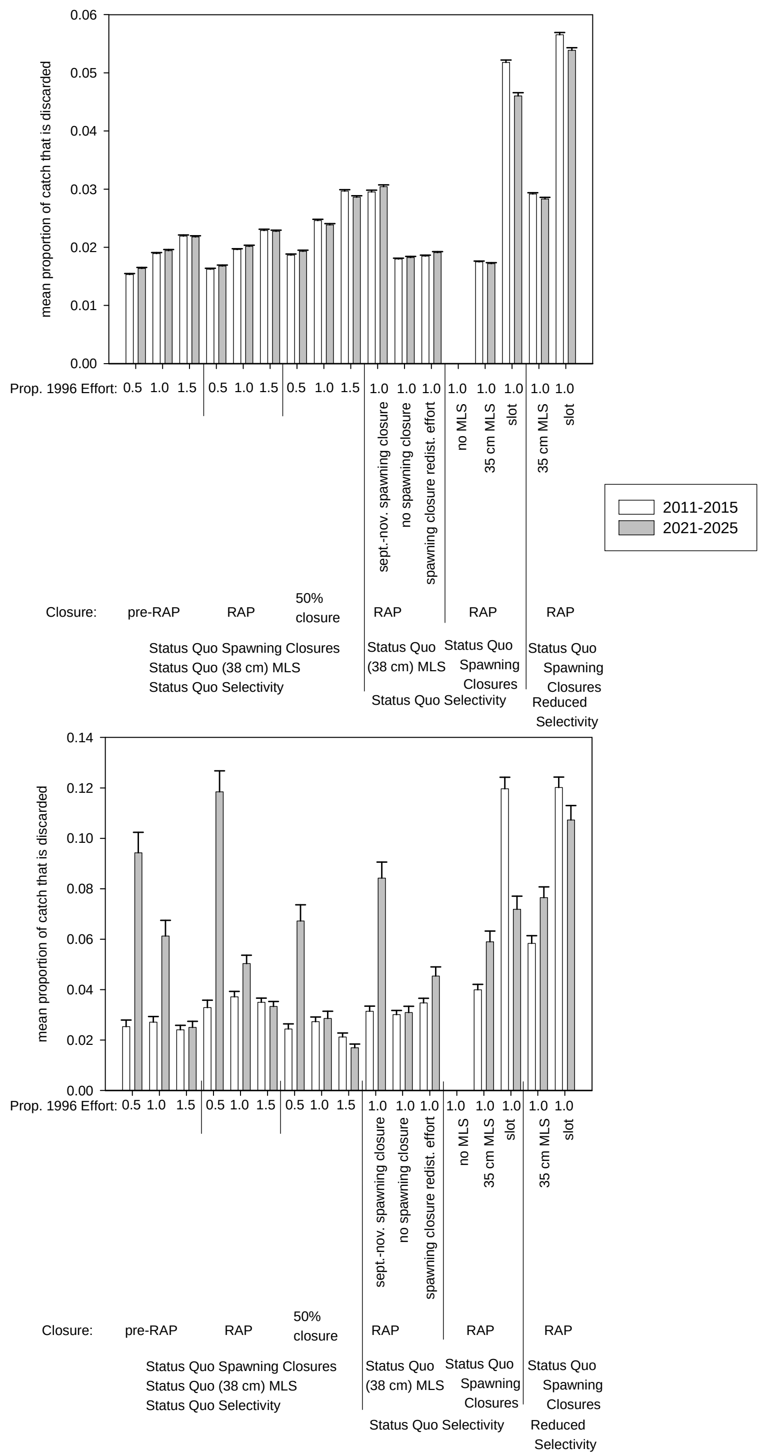


Fig. 6.71. Average (+SE) proportion of the total Coral Trout catch that is discarded in the northern (top) and southern (bottom) GBR, under the effort allocation model.

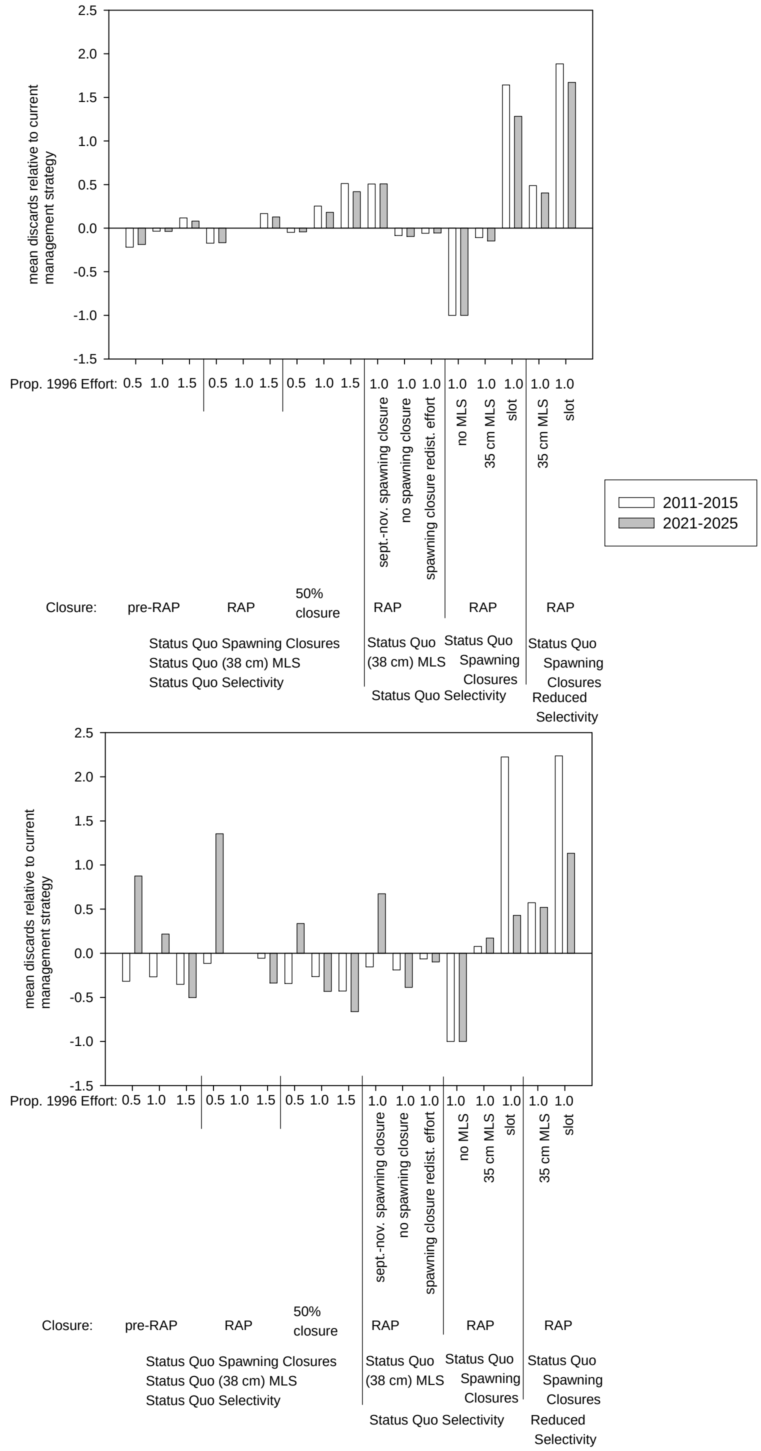


Fig. 6.72. Average proportion (2011-2015 and 2021-2025) of the total Coral Trout catch that is discarded in the northern (top) and southern (bottom) GBR relative to the discard rates under the current management strategy, under the effort allocation model.

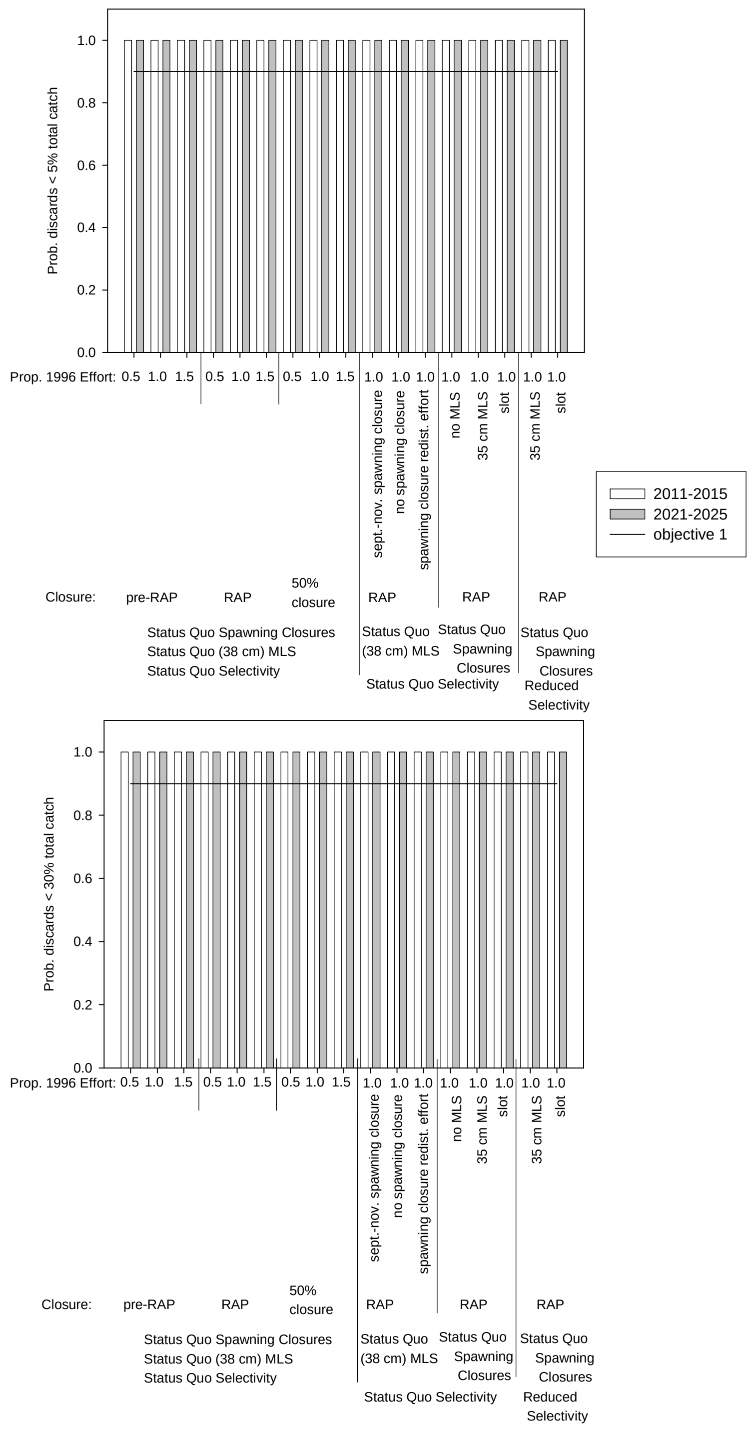


Fig. 6.73. Proportion of simulations where the average Red Throat Emperor discards (2011-2015 and 2021-2025) in the northern (top) GBR is less than 5%, and in the southern (bottom) GBR is less than 30% of the total catch, under the effort allocation model.

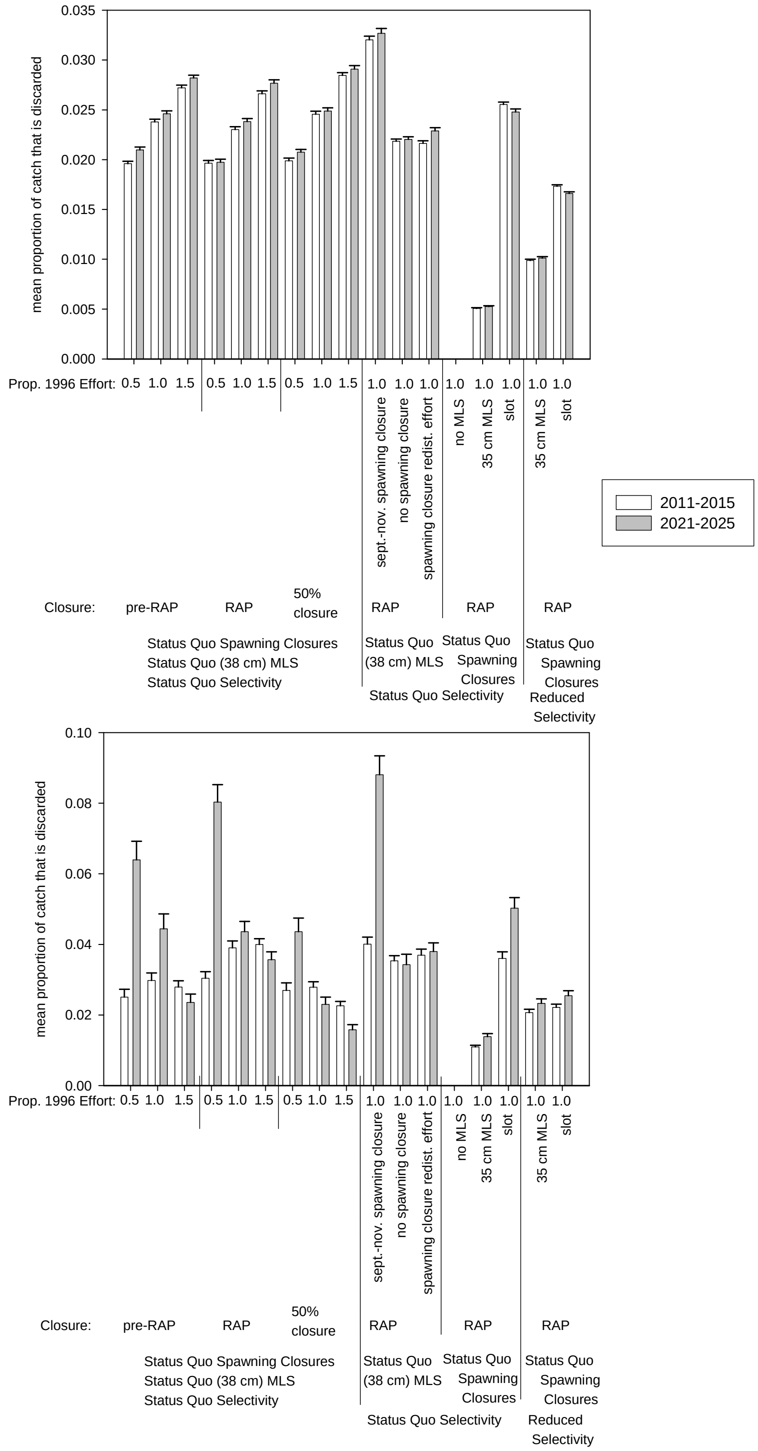


Fig. 6.74. Average (+SE) proportion (2011-2015 and 2021-2025) of the total Red Throat Emperor catch that is discarded in the northern (top) and southern (bottom) GBR, under the effort allocation model.

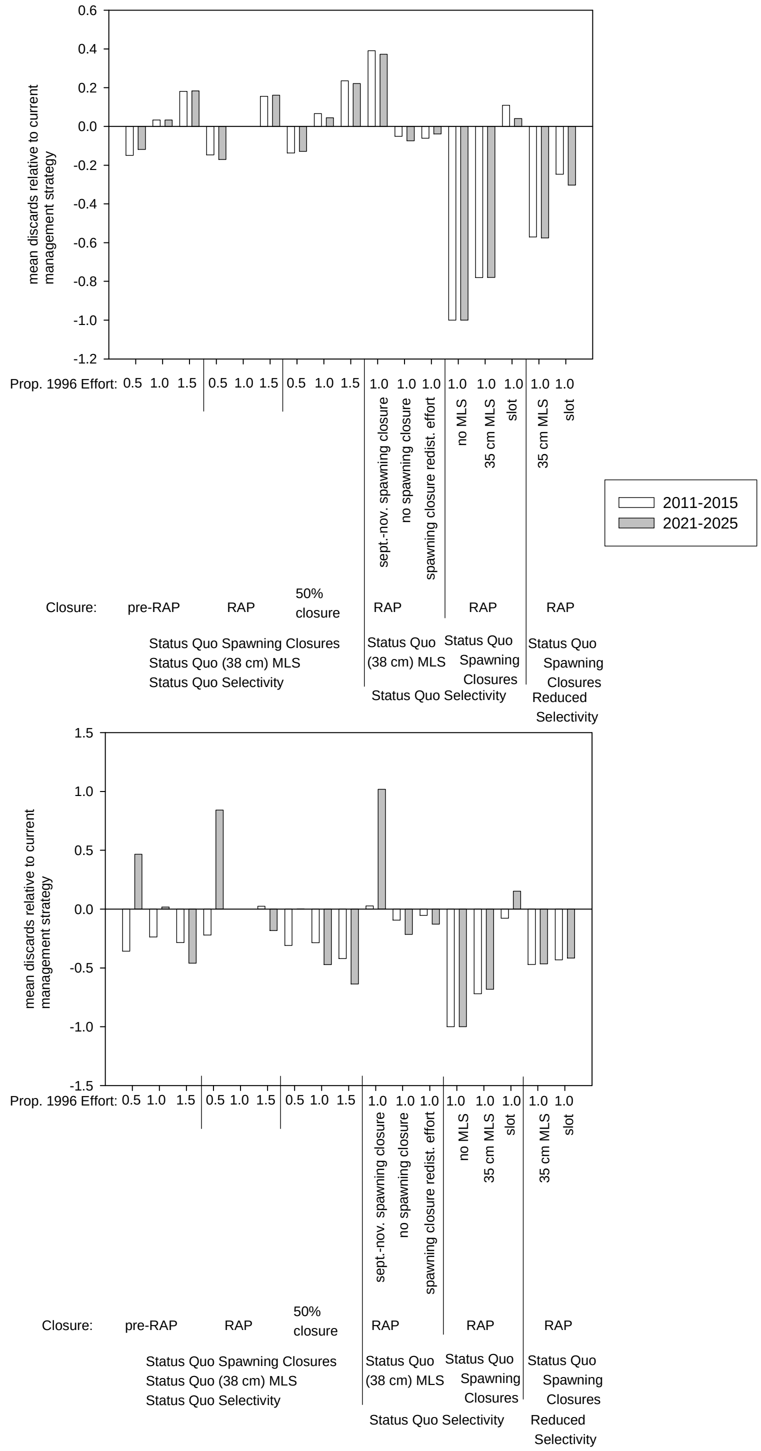


Fig. 6.75. Average proportion (2011-2015 and 2021-2025) of the total Red Throat Emperor catch that is discarded in the northern (top) and southern (bottom) GBR relative to the discard rates under the current management strategy, under the effort allocation model.

6.2.2. Performance summary

The summary of average performance indicator values for the major management objectives for each management strategy under the effort allocation model (Table 6.2) shows results similar to those obtained under the vessel dynamics model.

As anticipated from the results for the vessel dynamics model, reducing effort is the most effective way of maximizing the conservation and stock objectives for both species. The management strategy that is best at maximizing the harvest objective depends on species. For example, increasing effort and the amount of area open to fishing (decreasing area closures to pre-RAP) achieves the highest harvest of Coral Trout. Reducing the selectivity of the gear combined with changing the MLS leads to the best harvests of Red Throat Emperor, but the worst harvests of Coral Trout. Reducing effort would lead to higher CPUE of Coral Trout, and reducing the selectivity of the gear combined with changing the MLS leads to the highest CPUE of Red Throat Emperor. The economic and harvest benefits for Red Throat Emperor of reducing gear selectivity and the MLS should be balanced against the poor performance of strategies that involve these factors on the conservation and stock objectives. For the satisfaction objective, which involved having a good chance of catching a fish >50 cm, the best strategies involved reducing effort.

Once again, care must be taken in interpreting the absolute values in Table 6.2. This is because the purpose of evaluating management strategies using an MSE is to make comparisons among strategies, and not to make bold claims that a particular management strategy will lead to a particular outcome.

Table 6.2. Summary of performance indicators for different objectives from the last five years of the projection period (2021-2025) under different management strategies and the effort allocation model. Colours blue: the highest value for a column, green the second highest value, red the lowest value and orange the second lowest value (CT : Coral Trout, RTE Red Throat Emperor, SB spawning biomass, AB available biomass, TB total biomass).

Strategy					Objective											
					Conservation		Stock				Harvest		Economic		Satisfaction	
Effort	Spatial closure	Seasonal Closure	MLS	Indicator (reference):	SB on closed reefs (unfished)		AB on open reefs (2000)		TB on open reefs (2000)		Retained (quota)		Comm. CPUE mean (94-96)		Rec. Big fish (>50cm)	
					CT	RTE	CT	RTE	CT	RTE	CT	RTE	CT	RTE	CT	RTE
0.5	Pre-RAP	3 X 9	38cm		**0.96**	**0.88**	**1.66**	**1.51**	**1.41**	**1.18**	0.70	**0.49**	**1.24**	**0.88**	**0.26**	**0.02**
0.5	RAP	3 X 9	38cm		**0.95**	**0.89**	**1.66**	**1.56**	**1.41**	**1.21**	0.67	**0.49**	**1.19**	0.87	**0.26**	**0.02**
0.5	50%	3 X 9	38cm		**0.96**	**0.89**	1.45	1.49	1.29	**1.18**	**0.57**	**0.46**	1.01	0.82	**0.26**	**0.02**
1.0	Pre-RAP	3 X 9	38cm		0.92	0.81	1.36	1.22	1.22	1.09	1.05	0.78	0.93	0.70	0.23	**0.01**
1.0	RAP	3 X 9	38cm		0.91	0.83	1.35	1.23	1.22	1.09	1.00	0.76	0.88	0.67	0.23	**0.01**
1.0	50%	3 X 9	38cm		0.93	0.83	1.14	1.20	1.09	1.08	0.80	0.73	0.71	0.65	0.23	**0.01**
1.5	Pre-RAP	3 X 9	38cm		0.87	0.75	1.15	1.00	1.08	1.00	**1.25**	0.96	0.74	0.57	0.20	**0.01**
1.5	RAP	3 X 9	38cm		**0.86**	0.79	1.13	1.04	1.08	1.03	**1.20**	0.94	0.71	**0.56**	0.20	**0.01**
1.5	50%	3 X 9	38cm		0.89	0.77	0.94	1.02	**0.96**	1.01	0.92	0.91	**0.54**	**0.53**	0.21	**0.01**
< 1.0	RAP	Sept-Nov	38cm		**0.95**	**0.88**	**1.63**	1.45	**1.39**	1.17	0.77	0.58	1.05	0.79	**0.28**	**0.02**
1.0	RAP	None	38cm		0.88	0.82	1.31	1.18	1.19	1.07	1.05	0.81	0.84	0.65	0.23	**0.01**
1.0	RAP	Re-dist	38cm		0.92	0.82	1.31	1.18	1.19	1.07	1.05	0.81	0.83	0.64	0.22	**0.01**
1.0	RAP	3 X 9	None		0.88	0.78	**1.12**	1.08	1.09	1.03	1.04	0.85	0.92	0.75	0.15	**0.01**
1.0	RAP	3 X 9	35cm		0.90	0.80	1.19	1.10	1.14	1.05	1.03	0.83	0.91	0.74	0.18	**0.01**
1.0	RAP	3 X 9	Slot		0.87	0.79	1.14	1.04	1.19	1.07	0.68	0.71	0.60	0.63	**0.04**	**0.01**
	RAP	3 X 9	35cm	red. Sel.	0.87	**0.73**	1.15	**0.93**	1.11	**0.95**	1.00	**0.98**	0.88	0.87	0.17	**0.01**
	RAP	3 X 9	Slot	red. Sel.	**0.79**	**0.53**	**0.91**	**0.67**	**0.98**	**0.73**	**0.66**	**1.17**	**0.59**	**1.04**	**0.02**	**0.01**

6.3. Effort model comparison

The results from the effort models were quite similar for the main performance indicators (Table 6.1, 6.2). The main difference was in the regional discard rates (Table 6.3). The source of these differences lies in the faithfulness with which effort remains in a region. The allocation of effort in the vessel dynamics model was more restricted in the movement among regions than the effort allocation model. Since the effort allocation model allocates effort to reefs with the highest CPUE, effort was allocated preferentially to reefs outside of the southern region. This applied particularly to low effort management strategies, because under reduced effort all of the highly ranked reefs still received an effort allocation, but the lower ranked ones, such as those in the southern Capricorn-Bunker region, did not.

Because the CPUE calculation for the effort allocation model puts a high weighting (0.85) on historical CPUE compared with more recent ones, the movement of effort away from the southern region was gradual. As a result, the populations in the southern region recovered accordingly, resulting in an increasing number of smaller fish.

It is important to note that retention rate over the whole Marine Park did not differ greatly between the effort models. This indicates that regional distributions of effort have strong implications for regional performance indicators, but that the differences become less important at the larger scale that covers the whole Marine Park.

Table 6.3. Proportion of the total catch that is discarded in the northern and southern GBR for the last five years of the projection period (2021-2025) under different management strategies, for the different species (Coral Trout CT and Red Throat Emperor RTE) and effort models (VD: vessel dynamics model, EA: effort allocation model).

Strategy													
Spatial closure	Effort	Seasonal Closure	MLS	Indicator:	Northern discards (proportion of total catch)				Southern discards (proportion of total catch)				
				Species:	CT		RTE		CT		RTE		
				Effort model:	VD	EA	VD	EA	VD	EA	VD	EA	
Pre-RAP	0.5	3 X 9	38cm		0.02	0.02	0.02	0.02	0.02	0.09	0.03	0.06	
Pre-RAP	1.0	3 X 9	38cm		0.01	0.02	0.01	0.02	0.01	0.06	0.02	0.04	
Pre-RAP	1.5	3 X 9	38cm		0.01	0.02	0.02	0.03	0.01	0.03	0.02	0.02	
RAP	0.5	3 X 9	38cm		0.02	0.02	0.02	0.02	0.02	0.12	0.02	0.08	
RAP	1.0	3 X 9	38cm		0.01	0.02	0.01	0.02	0.01	0.05	0.02	0.04	
RAP	1.5	3 X 9	38cm		0.01	0.02	0.02	0.03	0.01	0.03	0.02	0.04	
50%	0.5	3 X 9	38cm		0.02	0.02	0.02	0.02	0.02	0.07	0.03	0.04	
50%	1.0	3 X 9	38cm		0.01	0.02	0.01	0.02	0.01	0.03	0.02	0.02	
50%	1.5	3 X 9	38cm		0.02	0.03	0.02	0.03	0.01	0.02	0.02	0.02	
RAP	<1.0	Sept-Nov	38cm		0.01	0.03	0.01	0.03	0.01	0.08	0.01	0.09	
RAP	1.0	None	38cm		0.01	0.02	0.01	0.02	0.01	0.03	0.01	0.03	
RAP	1.0	Re-dist	38cm		0.01	0.02	0.01	0.02	0.01	0.05	0.01	0.04	
RAP	1.0	3 X 9	None		0	0	0	0	0	0	0	0	
RAP	1.0	3 X 9	35cm		0.02	0.02	0.01	0.01	0.01	0.06	0.01	0.01	
RAP	1.0	3 X 9	Slot		0.06	0.05	0.04	0.02	0.05	0.07	0.02	0.05	
RAP	1.0	3 X 9	35cm	red. Sel.	0.03	0.03	0.01	0.02	0.03	0.08	0.01	0.02	
RAP	1.0	3 X 9	Slot	red. Sel.	0.06	0.05	0.02	0.02	0.05	0.11	0.01	0.03	

7. Discussion

The effect of multi-species targeting is especially relevant on the GBR where fishers harvest, either by targeting or as incidental by-product, multiple species that have different spatial distributions and population dynamics, and where prominent management strategies include area and spawning closures that directly affect the distribution of fishing effort. Because the potential effects of closures and other management strategies on the harvest, spatial distribution of effort and effect on fish stocks other than those of Coral Trout are unknown, there is a need to develop ways to address the effectiveness of alternative management strategies. This project provided a formal context within which to evaluate a range of management strategies related to the harvest and conservation of common Coral Trout and Red Throat Emperor, the two major target species of the CRFFF.

Management Strategy Evaluation (MSE) is a framework for environmental and natural resource management that couples a computer model of a resource (fish), to the human activities that affect the resource (fishers), and imposes on these activities management options. This allows many management options (strategies) to be implemented and reviewed or evaluated for their effectiveness *before they are implemented in reality* (Sainsbury et al. 2000). The process is more comparative than absolute, seeking to show the likely consequences of each strategy and highlight the trade-offs in performance among the strategies, in their attempt to achieve a range of sometimes conflicting objectives. MSE accounts for a range of uncertainties related to the resource, and its exploitation, and may even address potential uncertainty in resource monitoring and assessment as well as in the implementation of management strategies. The MSE approach provides a way of formalising many models and testing the robustness of proposed management strategies across a range of such models. In many ways, we have approached this model uncertainty in the CRFFF of the GBR in the current MSE work by introducing a second species, with different population dynamics, to the ELFSim model in an effort to show the effects of the proposed management strategies on the two species. We have also shown the effects of different effort models on the proposed management strategies.

The population models for the two species differed in their hypothesised migration patterns. In general, the implications of the management strategies differed between the species indicating that the success of a management strategy at achieving the management objectives depends on the species being targeted and the model used to describe their population dynamics.

Two effort models were used in the simulations. The difference between these models was the scale at which they operated. The model developed initially for the single species MSE (Mapstone et al. 2004), but adapted in this work to Coral Trout and Red Throat Emperor, relied on fleet aggregate behaviour and assigned commercial fishing effort based on historical reef CPUE. The recently developed vessel dynamics model consisted of individual fishing vessels operating at a daily time step and relied on historical commercial fishing decisions. In general, the performance of management strategies between the two effort models was similar, indicating that the performance of the strategies was robust to the uncertainty in how the commercial fleet operates. Although in the current work there may be little benefit given the increased computation cost of treating harvest at the relatively small individual operator and daily time scale, the utility of the vessel dynamics model should not be underestimated for future management strategy evaluations involving quota and quota trading among operators. These are management arrangements that would be difficult or impossible to address with the earlier effort allocation model.

Although similar, the results based on the two effort models differed substantially in terms of how effort shifted among regions. The effect of this is marked in terms of regional discard rates for the commercial sector (i.e., higher under the effort allocation model).

Prior work involving ELFSim has focused on area closures and effort control strategies for Coral Trout. The current results apply not only to Coral Trout, but also to Red Throat Emperor. Furthermore the strategies evaluated consist not only of different effort control strategies and area closures, but also seasonal spawning closures, which in effect are treated in this project as effort control strategies, and changes to the MLS.

Although many of the management arrangements in the CRFFF have changed dramatically with the move to Individual Transferable Quotas, since the start of this project, we have addressed issues that are of substantial interest to the stakeholders within this MSE. First, we have addressed the implications of the RAP area closures. Previous examination of area closures (Mapstone et al. 2004) examined three levels of area closure: the then-current area closures, which comprised about 16% of reef habitat, a 30%, and a 50% area closure. At the time the 30% area closure was a candidate of several possible RAP closure options. In the current work we examined the actual and current RAP area closures, plus the previous pre-RAP (16%) and the 50% closures. The added knowledge of performing simulations for the pre-RAP and 50% closure strategies was that we could assess the effect of the different closures on Red Throat Emperor, as well as on Coral Trout.

As management strategies in their own right, area closures tended to have conservation benefits, particularly with the more sedentary Coral Trout. Qualitatively, the results for Coral Trout were similar to those from previous work (Mapstone et al. 2004) even though how the 30% closure strategy was implemented differed slightly. The results for Red Throat Emperor, however, differed from those for Coral Trout. The most obvious difference was that the area closures were less effective for Red Throat Emperor than for Coral Trout. The most likely reason for this is that the two species exhibit different population dynamics: Coral Trout are assumed to distribute spatially in the larval stage only, and when they settle do not move among reefs; Red Throat Emperor are also assumed to be advected during the larval stage, and initially settle on a reef but then move among reefs throughout demersal life. Further, spawning by Red Throat Emperor was assumed to be restricted to the southern portion of the GBR based on previous research (Williams 2003). The results of the modelling reported here might be expected to be broadly indicative of general differences between species that migrate after settling on a reef and those species that do not. It is widely recognised that the effects of marine reserves and area closures on migratory stocks such as Red Throat Emperor are less effective than on more sedentary species (Roberts and Sargant 2002).

It is important to note that the biological parameters for both species were homogenous in space in the simulations. Other research has provided evidence that both species may have regional-specific growth and mortality (Williams 2003, Bergenius 2006, Leigh et al, 2006). Spatial differences in biological parameters could have been implemented using ELFSim, even though the implications of spatially-different biological parameters for migrating species need to be better understood and validated, before this feature is invoked for Red Throat Emperor.

Reducing effort was a more robust management strategy with respect to the conservation objectives than closing areas to fishing because the two species exhibit different migration behaviours. In general, changes in effort had a large effect on the ability to achieve management objectives, as found previously (Mapstone et al. 2004). For example, increasing effort by 50% had a disproportional effect compared to increasing the amount of areas closed to fishing from 30% to 50%. Current effort levels more than a year after the introduction of the ITQ system in the CRFFF are thought to be at about the 1996 levels, including the onset of technology creep. The results we have shown bracketed the likely extremes of annual effort.

Different effort levels had little effect on the status of closed areas, again particularly for the more sedentary Coral Trout. Changing effort levels had a more marked effect on the spawning biomass in the closed areas for the more mobile Red Throat Emperor.

Spawning biomass levels in the closed areas did not reach pre-exploitation levels for a significant amount of the time, and the objectives of achieving spawning biomass in the closed areas above unfished levels either 100% of the time or even 50% of the time could not be achieved by any of the management strategies that were explored. There were several reasons for this. First, it is unlikely that even an unexploited population would maintain its status above the carrying capacity for a majority of the time. Second, while the areas open to fishing might benefit from the areas closed to fishing in subsidising reproduction, this comes at a slight cost to the populations on the closed reefs, making it less likely that the populations in the protected areas make a full recovery to pre-exploitation levels. This applies especially to Coral Trout, which are actually protected in the closed areas, but not Red Throat Emperor which move in and out of them. Third, infringement, which may especially affect relatively small area closures (Little et al. 2005), was also applied to the closed reefs at a rate of 5% of the reef's attractiveness. Thus, areas that were putatively closed to fishing were actually subjected to some fishing pressure.

Another major issue that we have addressed with this project concerns the effect of the seasonal spawning closures. The primary means of addressing this was as simply a tool for reducing effort. The importance of spawning seasonal closures is increased if the catchabiliy of Coral Trout and Red Throat Emperor increased during them. However, previous analyses (Mapstone et al. 2001, Mapstone unpublished data) have shown that catchability does not increase significantly during the spawning season for Coral Trout and the increase in catchability of Red Throat Emperor during the spawning season is at best marginal. In general, similar to the other effort reduction strategies, the three month removal of effort also had conservation and stock benefits, and tended to reduce the ability to satisfy management objectives related to harvest. The absence of spawning seasonal closures had a similar effect as increasing effort, although it was somewhat 'muted' because the amount by which effort was increased was less than the difference in effort between the current management strategy and the 1.5x 1996 effort strategy. Further research is being planned to develop the ability to evaluate the potential effects of spawning disruptions caused by line fishing, in an effort to judge the potential efficacy of seasonal spawning closures.

Finally, we have also addressed the implications of changing the size restrictions in the fishery. Results showed that reducing the MLS of either species had an effect similar to increasing effort. In general, such management options increased the harvest, but led to lower levels of spawning and available biomass. The management strategy that involved a reduction in MLS to 35 cm had a marginal effect, but if coupled with a change in gear to target those smaller fish, exaggerated the effect substantially. The management strategies that involved a maximum legal size were based on the premise that large individuals contribute a disproportionate amount of spawning potential to the population. This effect, however, was not part of the model and so the management strategy that coupled a maximum legal size with a reduced MLS of 28 cm, led to less chance of achieving the conservation objectives. Lowering the MLS reduced the proportion of time that charter and recreational fishers would retain a 'big' fish.

As a result of this research, we have highlighted the consequences of different options for managing the CRFFF. These have been put forth in a manner that is comparative rather than prescriptive, stressing the trade-offs among the many diverse objectives held for the fishery. Such a process aids in making the decisions that must be made, in a frank, transparent and hopefully easily understood manner by all who value the Great Barrier Reef.

8. Benefits and adoption

Because of the diverse spatial nature of the GBR, the MSE approach will continue to play an integral part to the stakeholders of the CRFFF. This includes engaging stakeholders for input into potential alternative management strategies and objectives, as well as informing them of the effect of these management strategies. The model software and general approach that has been established will, with continued effort and enthusiasm, be one of the principal mechanisms for managing the CRFFF. The operations of ELFSim for management purposes should gradually move to a management body, while the scientific research operations will continue in parallel.

The outputs of the research are being presented in a variety of fora. The models developed will be presented with a user-accessible Graphical User Interface for demonstration purposes and to assist in discussion of model assumptions with stakeholders. (It should be noted, however, that the models are unlikely to be amenable to user-application, in the sense of user software, because of the set-up requirements and run-times for formal evaluations of management strategies.) Formal description of the models and their underlying assumptions has been and will continue to be published in internal reports, reports to ReefMAC, and international refereed journals. In addition, lay-descriptions of the project and the models will be published in industry magazines and the Fishing & Fisheries Newsletter and presented at a range of stakeholder venues (industry meetings, advisory committees, peak bodies) as requested. Results from application of the models will be published in the same range of formats.

Extension of results will focus on specific stakeholder workshops and be coordinated through the Fishing and Fisheries Liaison program. In addition, the following publications will be used to report progress and outcomes from the task: Fishing and Fisheries Project Newsletter (Previously ELF Newsletter); industry magazines (e.g., SUNFISH NQ, The Queensland Fishermen); and management agency newsletters. It is expected that formal presentations of the project will be made to ReefMAC, GBRMPA’s Fisheries Issues Group, The Fishing and Fisheries Project Steering Committee (comprises senior representatives from stakeholder groups), and public meetings in major fishing ports.

9. Further development

There are several areas for further development of this research. Notably, a project is in progress that implements an ITQ component in the ELFSim model (FRDC project 2004-030), and will subsequently evaluate management strategies involving TACs.

Further research projects are being developed to evaluate the potential effects of spawning disruptions by line fishing, in an effort to judge the potential efficacy of seasonal spawning closures. The implementation of an assessment model within ELFSim is also a potentially important and topical area of research, as current assessment methods used in the fishery could be evaluated for their accuracy and effectiveness at supplying management information. This would allow the development and evaluation of management decision rules and feedback mechanisms in the MSE process.

Although this project is focused on just two species, management concerns are approaching the issues of multi-species targeting with general principles in mind. Consequently, we expect the resultant models to be readily extensible to other species for which sufficient information is available with which to parameterise targeting behaviour by fishers and population dynamics of the stocks.

Discard mortality rates, determined from the post-release project (FRDC 2003-019) will be incorporated into the model. The effect of these rates should be examined as they will make the outcomes of management strategies more certain. There is also a need to re-examine the selectivity curves assumed for the fishery, and their potential effect on the efficacy of proposed management strategies.

Improved knowledge of the effect of large fish, and their contribution to spawning is an important issue that has gained scientific credibility (Berkeley et al. 2004, O'Farrell and Botsford 2006). Incorporating such knowledge into the model will aid in more accurate evaluation of management strategies, such as those involving maximum legal sizes. In addition, the model currently ignores the effect of male biomass on reproductive output. Projects that examine the potential effect of a reduction in the sex-ratio of the spawning population on fertilization rates should be examined, and, if found to be substantial, included in ELFSim. Similarly, the effect of fishing disrupting spawning and the rate of sex change needs to be examined, and the results incorporated into ELFSim if necessary.

Connectivity is becoming accepted as a critical issue for the management and conservation of living resources on the GBR. Source-sink relationships between reefs, larval dispersal, self-seeding and larval subsidy are all significant elements in understanding and modelling the population dynamics of reef fish populations, especially in relation to area closures or management practices that concentrate fishing effort. As a result determining the sensitivity of management strategies to different models of larval migration is an important area of future research. Such models include the parametric form used in the current research, as well as the actual results from hydro-dynamics models determined for example by Bode et al. (2006), or results from other larval migration models proposed for the GBR.

The vessel dynamics model could, with appropriate data, be improved by differentiating between vessels that target live product and vessels that target dead product, as well as mobile vessels that operate from more than one home port. More focus should also be placed on the effect of management strategies on the social system. There is a need to investigate the inverse of this by investigating the potential effect that social structure and systems has on the effectiveness of a management strategy, through perhaps the mechanism of information sharing. Nonetheless, there is currently a great need for social and economic indicators in the MSE process.

Further Development

As the relationship of the fishery with the broader social environment increases, more attention should be paid to the recreational sector. With more data, a more dynamic recreational fishing model could be developed.

10. Planned outcomes

The planned outcomes of this project are:

i) an improved understanding of the influence of multi-species harvest and targeting behaviour on the distribution of fishing effort and the effect on target species; and
ii) a formal evaluation of alternative management strategies for line fishing for the two major target species of the CRFFF.

All stakeholder groups benefit from this research through better understanding of the potential effects of fishing on major target species and more informed and transparent management. The major outcome of this task will be more realistic effort models that better reflect the decision making behaviour of the commercial sector. Such models are more likely to predict the response of the commercial fleet to changes in the state of the fishery (e.g., management arrangements, stock status), for which there is little or no experience. The formal MSE including both major harvested species will provide a greater understanding of the potential effects of multi-species targeting on the distribution of fishing effort and effectiveness of alternative management strategies, such as area closures and effort controls.

The outcomes of this project will make a significant contribution to the general assessment and evaluation of tropical multi-species fisheries on the GBR and elsewhere. More generally, the models will provide a substantial contribution to the development of approaches to modelling spatial effort dynamics in multi-species fisheries. This will provide a foundation on which to examine the broader, but related, issue of movement of effort among different fisheries in multi-fishery systems. This issue is particularly pertinent for fisheries operating within the GBR as most fishers hold multiple endorsements and a significant proportion of fishers actively operate across different fisheries (e.g., net, line, crab). The ability of fishers to move between fisheries provides the real potential for factors which influence one fishery (e.g. stock status, economic return, seasonal levels of activity, management status, etc.) to directly effect participation and the level of effort in other fisheries. Understanding the interaction among fisheries would provide the basis for more holistic evaluation of alternative strategies for managing fishing in the GBR. This project is a first step in developing the fundamental approaches to formally modelling multi-species and multi-fishery systems.

Future workshops will provide for the transfer of the outcomes of this research to the management/stakeholder groups in a form that will allow them to be used directly to inform policy.

11. Conclusion

The research has built upon the simulation model ELFSim that is the basis for management strategy evaluation in the CRFFF. In addition to the current model of the primary target species Coral Trout, we developed a large scale, spatially explicit model of the secondary target species, Red Throat Emperor, population dynamics, including spatially restricted spawning and age-specific migration. We have also examined data describing the decisions of where, when and how fishers operate, and determined the effects of different factors such as reef size and distance on their decision making. These results were used to inform a model of individual vessel fishing behaviour.

In consultation with stakeholders, management objectives and strategies were evaluated in ELFSim. Closing areas to fishing was a good measure for addressing conservation concerns of the sedentary Coral Trout, but less so for the more mobile Red Throat Emperor. Lowering effort was the more robust strategy across both species for conservation concerns. Trade-offs among conflicting management objectives were highlighted by the effect that although reducing effort increases the chances of achieving the conservation objective, it reduces the likelihood of achieving the harvest objective. Furthermore, the results showed a difference in the effectiveness of management strategies on the different species, and the importance that management not judge the effectiveness of a management strategy on only a single species like Coral Trout.

Compared to a previously developed effort model, the results from the newly developed model of individual fishing vessel behaviour differed little. Future work must be careful to capture the distribution of effort, and its movement among regions, as the regional distribution of effort could have great effect on regional performance indicators. Performance indicators measured at coarser spatial scales are probably more robust or insensitive to regional distributions of effort.

12. References

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Appendix A. Derivation of Equation 3.6

Consider a population at pre-exploitation equilibrium and denote the pre-exploitation value of a quantity by a subscript '0' (for example S_0^r is the (female) spawner biomass on reef *r* at pre-exploitation equilibrium). The number of zero-year-olds at pre-exploitation equilibrium on reef *r* is defined by the summation over growth group of Equation (3.4):

$$N_{0,0}^r = \sum_k K^k \left[st\ \tilde{f}^r\ S_0^r + (1-st)c^r\ BL_0^r \right] = st\ \tilde{f}^r\ S_0^r + (1-st)c^r\ BL_0^r \qquad \text{(A.1)}$$

From the definition of *st* it follows that $N_{0,0}^r = \tilde{f}^r\ S_0^r$. Substituting $\tilde{f}^r\ S_0^r$ for $N_{0,0}^r$ and $\sum_{r'} \tilde{f}^{r'}\ S_0^{r'}\ \Omega^{r',r}$ for BL_0^r (see Equation (3.6)) in Equation (A.1) yields:

$$\tilde{f}^r\ S_0^r = st\ \tilde{f}^r\ S_0^r + (1-st)c^r \sum_{r'} \tilde{f}^{r'}\ S_0^{r'}\ \Omega^{r',r} \qquad \text{(A.2)}$$

Solving Equation (A.2) for c^r then yields:

$$c^r = \frac{\tilde{f}^r\ S_0^r - st\tilde{f}^r\ S_0^r}{(1-st)\sum_{r'} \tilde{f}^{r'}\ S_0^{r'}\ \Omega^{r',r}} = \frac{(1-st)\ \tilde{f}^r\ S_0^r}{(1-st)\sum_{r'} \tilde{f}^{r'}\ S_0^{r'}\ \Omega^{r',r}} = \frac{N_{0,0}^r}{\sum_{r'} N_{0,0}^{r'}\ \Omega^{r',r}} \qquad \text{(A.3)}$$

Appendix B. Relationship between steepness and Equation 3.9a

Steepness is defined as the ratio of the expected number of one-year-olds when the spawner biomass is reduced to 20% of the pre-exploitation level to the number of one-year-olds at pre-exploitation equilibrium. Assume (without loss of generality) that the number of one-year-olds at pre-exploitation equilibrium is 1 and that there is only a single reef (or equivalently that the level of fishing mortality is the same across all reefs and the biological parameters are also the same across all reefs). The number of one-year-olds as a function of the fully-selected fishing mortality, $R(F)$, is given by:

$$R(F) = \frac{S(F)}{S(0)} \alpha\, e^{-\beta U(F)/U(0)} \tag{B.1}$$

where $S(F)$ is the spawner biomass when the fully-selected fishing mortality is *F*:

$$S(F) = R(F) \sum_{a=1}^{x} \sum_{k} f_{L_{k,a}}\, w_{L_{k,a}}\, N_a^k(F)(1 - P_{L_{k,a}}) \tag{B.2}$$

$U(F)$ is the number of 'juveniles' as a function of *F*:

$$U(F) = R(F) \sum_{a=1}^{J} \sum_{k} N_a^k(F) \tag{B.3}$$

$N_a^k(F)$ is the number of *a*-year-old animals in growth group *k* when fishing mortality is *F*, given that the number of one-year-olds in growth group *k* is K^k:

$$N_a^k(F) = \begin{cases} K^k & \text{if } a = 0 \\ N_{a-1}^k(F)\, e^{-M_{a-1} - S_{L_{k,a-0.5}} F} & \text{if } 0 < a < x \\ N_{x-1}^k(F)\, e^{-M_{x-1} - S_{L_{k,x-0.5}} F} / (1 - e^{-M_x - S_{L_{k,x+0.5}} F}) & \text{if } a = x \end{cases} \tag{B.4}$$

α, β are the parameters of the stock-recruitment relationship, and

$S_{L_{k,a}}$ is the selectivity of the fishery on animals of age *a* in growth group *k*.

The use of a Ricker-like relationship for the mortality between ages 0 and 1 is based on the assumption that this mortality is due to competition between settling animals and the 1+ population already on the reef.

Now, evaluating Equation (B.1) at the pre-exploitation level yields:

$$1 = \alpha e^{-\beta} \quad \text{or} \quad \alpha = e^{\beta} \tag{B.5}$$

Substituting Equation (B.5) into Equation (B.1) then yields:

$$R(F) = \frac{S(F)}{S(0)} e^{-\beta(U(F)/U(0) - 1)} \tag{B.6}$$

Denoting $S(F)/R(F)$ as $\tilde{S}(F)$ and $U(F)/R(F)$ as $\tilde{U}(F)$, it is possible to solve Equation (B.6) for $R(F)$:

$$R(F) = \ell n[\tilde{S}(F)e^{\beta} / \tilde{S}(0)]/[\beta\tilde{U}(F)/\tilde{U}(0)] \quad \text{(B.7)}$$

The algorithm used to find the value for β (and hence through Equation B.5 the value of α) is:

a) Guess a value for β and calculate the value for α from Equation (B.5).
b) Find the value for *F* such that the ratio $R(F)\tilde{S}(F)/S(0) = 0.2$ - a bisection method is used for this purpose.
c) Compare $R(F)$ with the pre-specified value for steepness.
d) Repeat steps a) – c) until $R(F)$ equals the pre-specified steepness.

Equation (3.9a) is then obtained from Equation (B.6) after replacing the ratio $S(F)/S(0)$ by the product of the spawner biomass and the survival from age 0 to age 1 at pre-exploitation equilibrium.

Appendix C. Natural mortality for Coral Trout from age data for "green" reefs

The value assumed for the rate of natural mortality, *M*, for adult Coral Trout in previous applications of ELFSim was 0.3 yr^{-1} (Mapstone et al. 2004). This value appears to differ from that implied by fits to the data collected from the ELF Experiment (0.5 – 0.73 yr^{-1}). This Appendix examines the data for unfished reefs (i.e., reefs that are "green" throughout the ELF Experiment and reefs that were "green" before they were pulsed fished). Figs C.1-C.3 show the age data by year for the unfished reefs. Regressions of log-numbers on age were used to estimate the rate of natural mortality (under the assumption that selectivity is flat and there is no fishing-induced mortality). Ages for which the relative frequency was zero were ignored when conducting the regression. The minimum sample size for inclusion in the regression was 2 and sensitivity was examined at the age-at-full-recruitment (i.e., 4 years – Fig. C.1; 3 years – Fig. C.2; and 5 years – Fig. C.3).

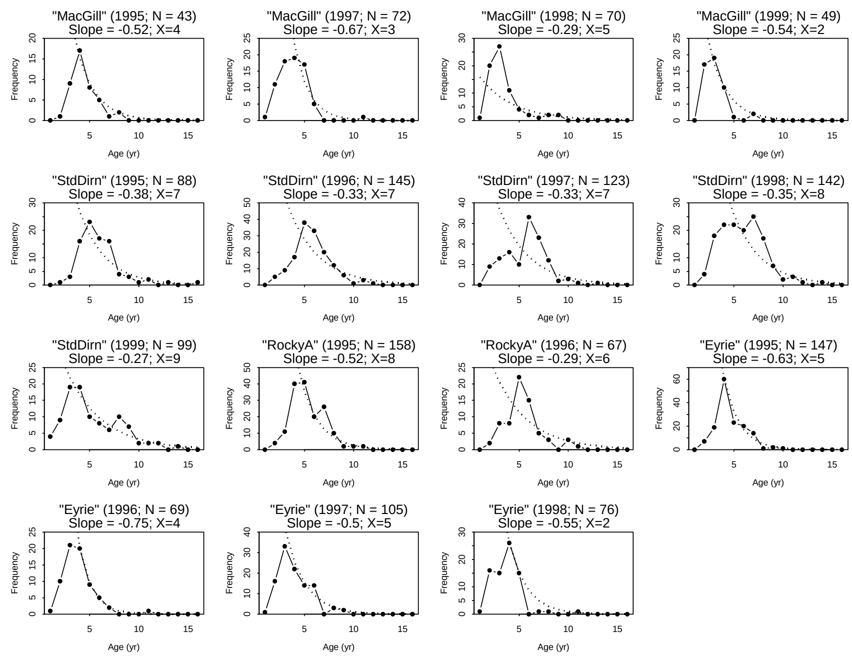


Fig. C.1. Age-composition by year for reefs closed to fishing. The estimates of *M* (negative slope) are based on regressions with a minimum age of 4 years. X denotes the number of ages included in the regression.

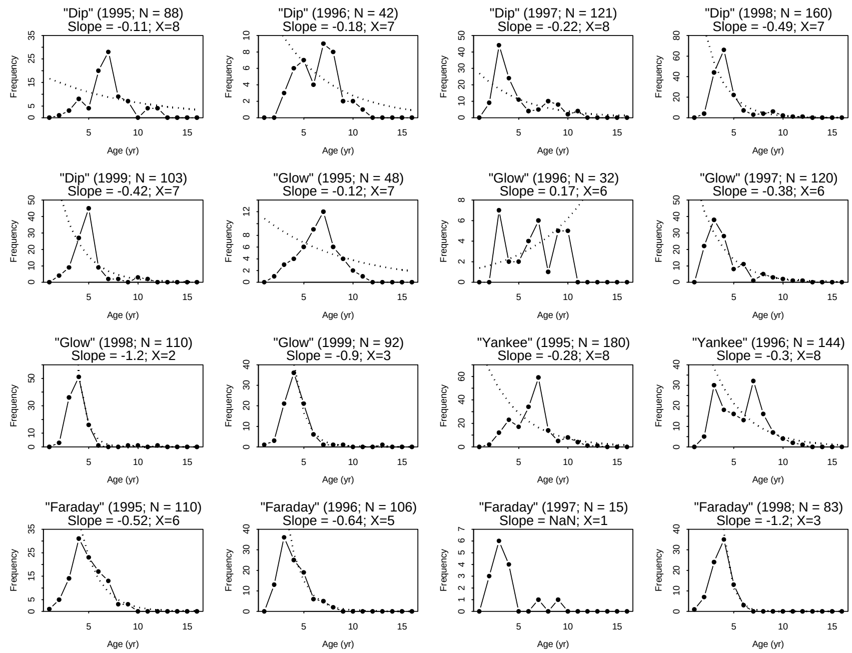


Fig. C.1 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 4 years. X denotes the number of ages included in the regression.

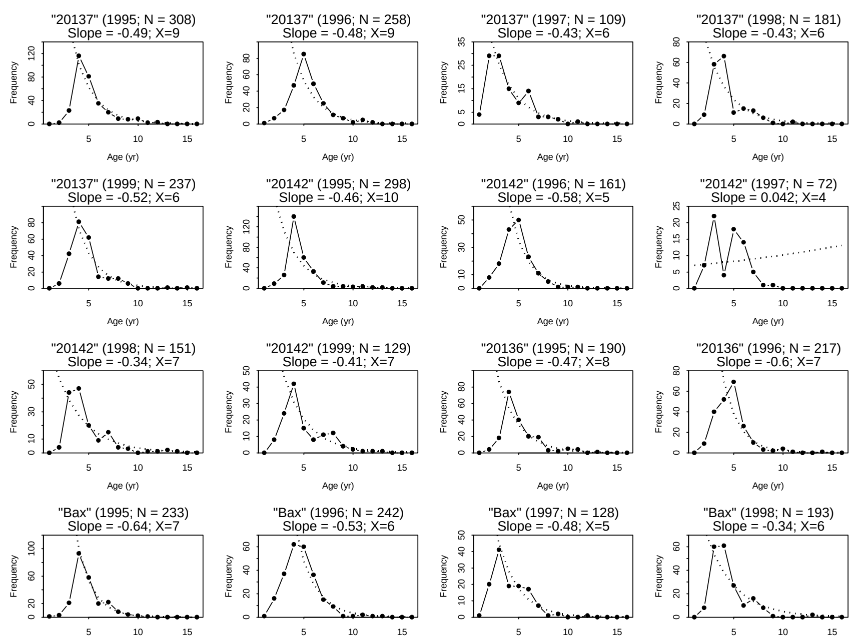


Fig. C.1 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 4 years. X denotes the number of ages included in the regression.

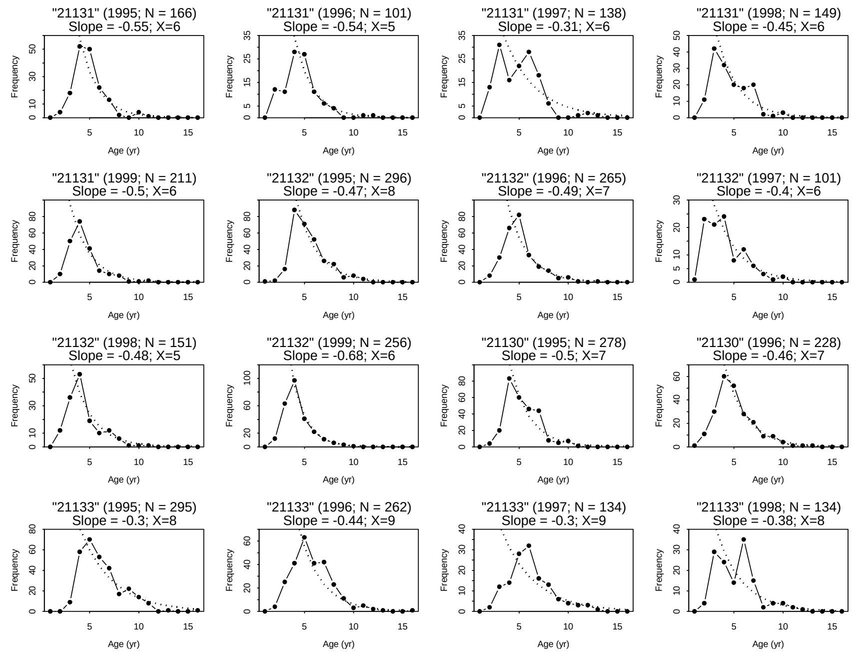


Fig. C.1 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 4 years. X denotes the number of ages included in the regression.

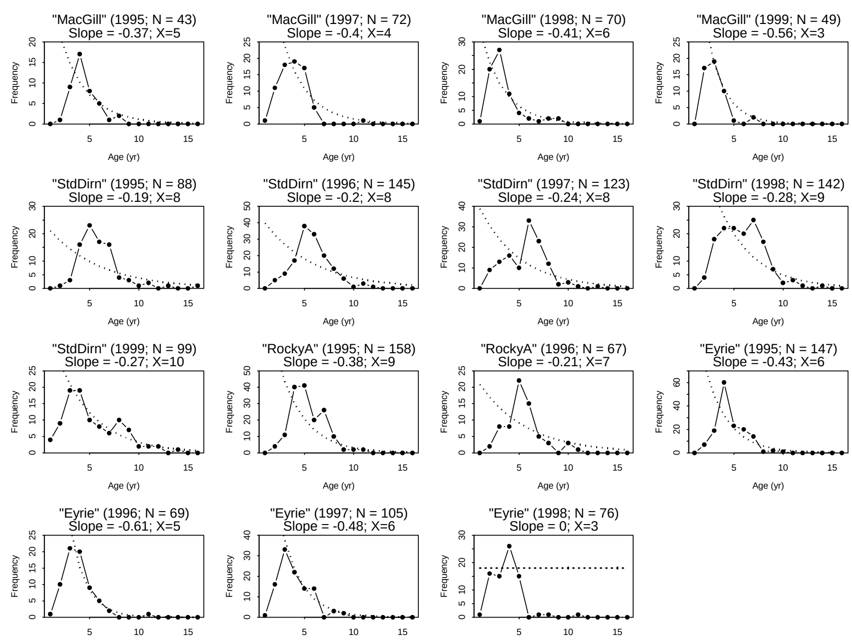


Fig. C.2. Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 3 years. X denotes the number of ages included in the regression.

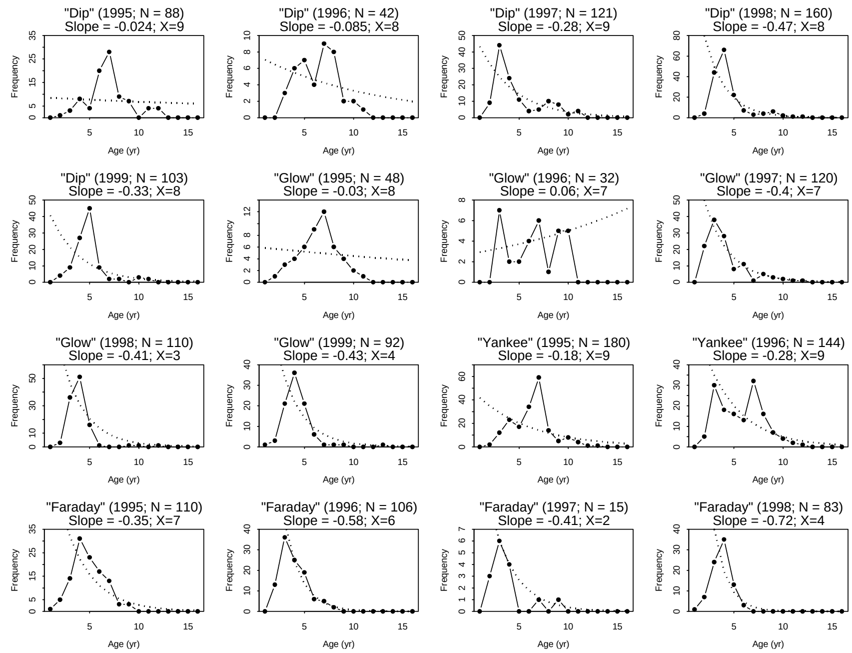


Fig. C.2 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 3 years. X denotes the number of ages included in the regression.

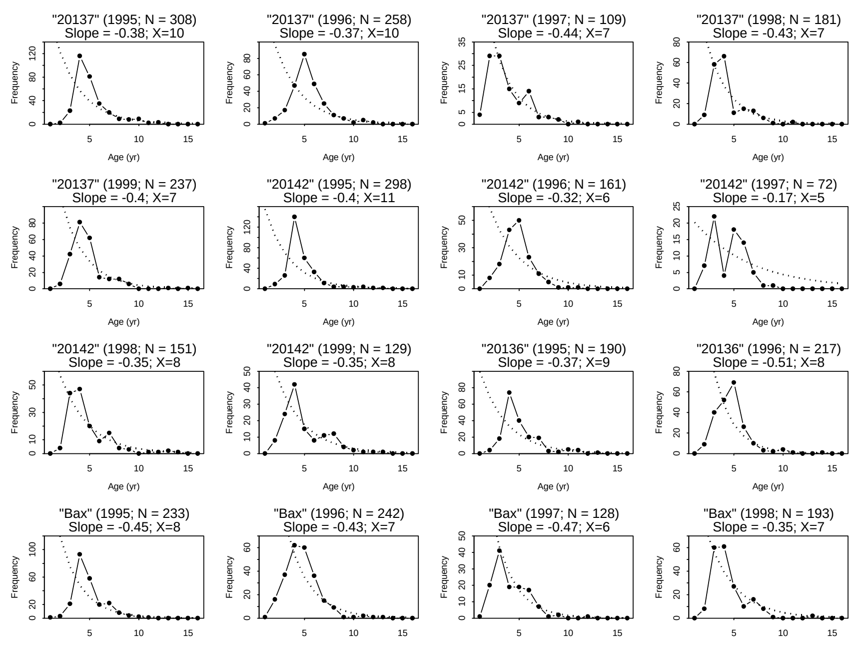


Fig. C.2 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 3 years. X denotes the number of ages included in the regression.

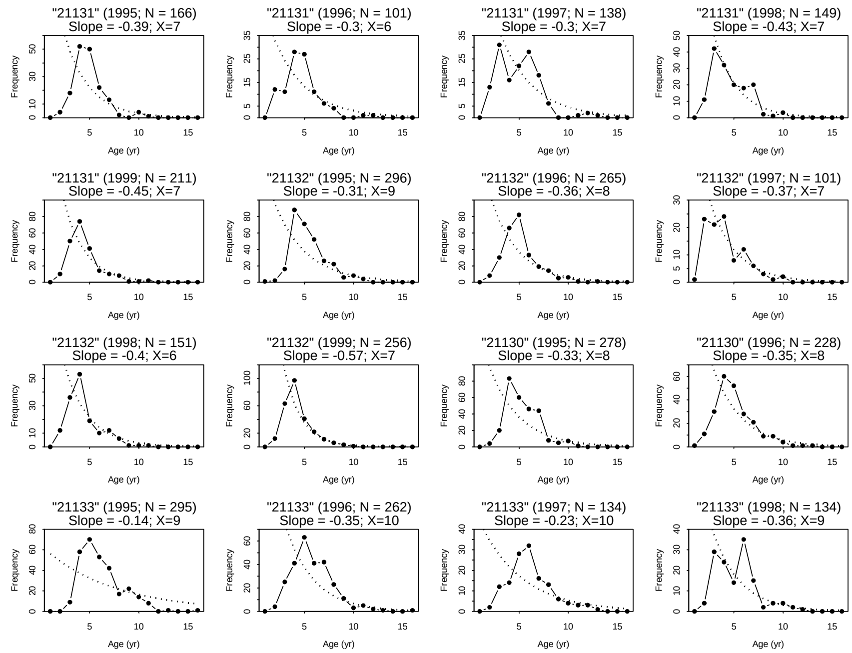


Fig. C.2 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 3 years. X denotes the number of ages included in the regression.

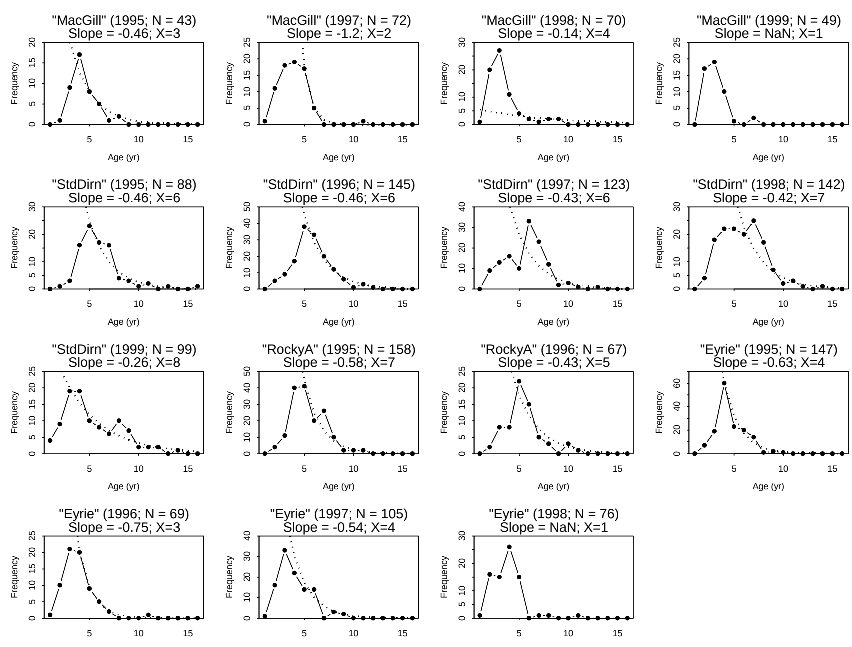


Fig. C.3. Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 5 years. X denotes the number of ages included in the regression.

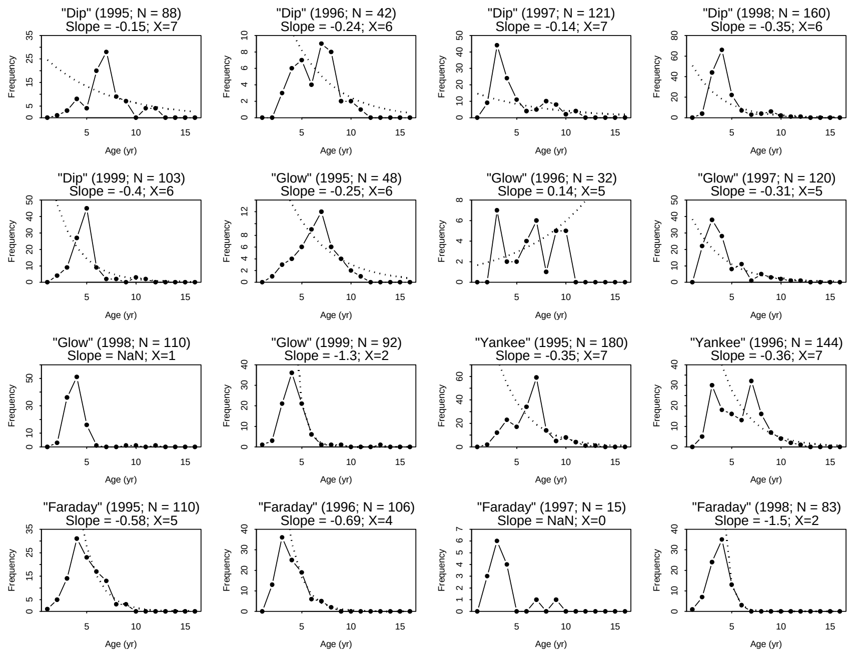


Fig. C.3 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 5 years. X denotes the number of ages included in the regression.

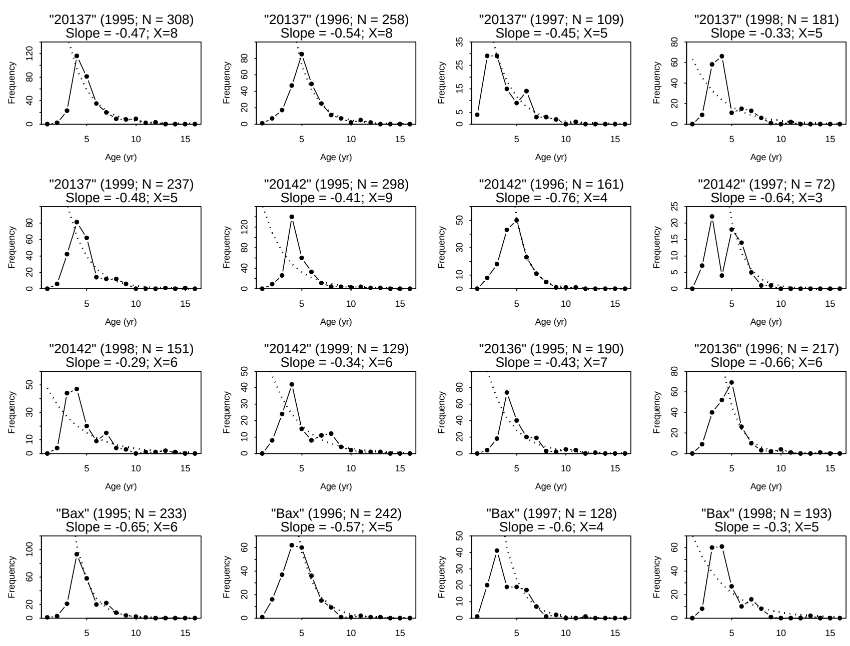


Fig. C.3 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 5 years. X denotes the number of ages included in the regression.

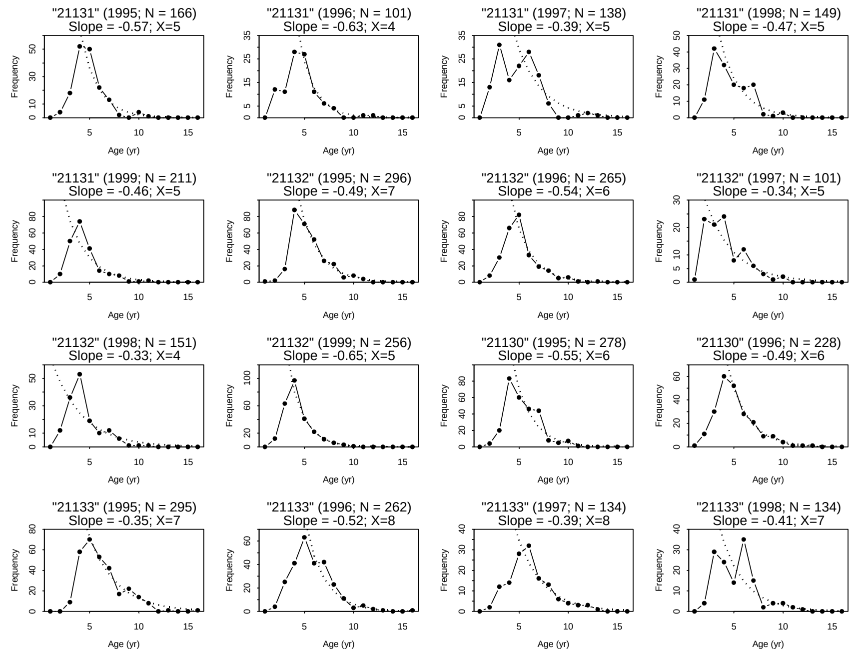


Fig. C.3 (continued). Age-composition by year for reefs closed to fishing. The estimates of *M* (slope) are based on regressions with a minimum age of 5 years. X denotes the number of ages included in the regression.

Some of the age-compositions were clearly incompatible with the assumption of an exponential decline in numbers above some age-at-recruitment (e.g., StDirn 1997; Glow 1995 and 1996; 20142 1997). However, in general, the data were supportive of the model applied. Table C.1 summarises the results in Figs C.1-C.3 by the minimum, median and maximum slopes. The slopes are least negative for an assumed age-at-recruitment of 3 years. However, the age-compositions in Figs C.1-C.3 suggest that fish of age 3 are not fully selected to the fishing gear. The estimates of *M* for the Lizard, Mackay and Storm Cay clusters centre about 0.4-0.5 yr^{-1}, while those for Townsville were centred at somewhat less negative values about 0.3 yr^{-1}. However, the fits to the data for Townsville are rather poorer than to the data for the other clusters. For the purpose of ELFSim therefore we set the rate of natural mortality for Coral Trout aged 2 and older to be 0.45 yr^{-1}.

Table C.1. Range of estimates of natural mortality *M* (minimum, median, maximum) from unfished (i.e., green) reefs. The reefs considered are restricted to those for which at least four data points are available on which to estimate a slope. The number of reefs used when calculating the range is indicated in parenthesis.

Cluster	**Age-at-recruitment (years)**		
	3	**4**	**5**
Lizard	0.61/ 0.37/ 0.19 (13)	0.75/ 0.37/ 0.27 (12)	0.63/ 0.45/ 0.14 (10)
Townsville	0.72/ 0.31/ 0.17 (14)	0.64/ 0.29/ -0.17 (12)	0.69/ 0.33/-0.14 (12)
Mackay	0.51/ 0.30/ 0.17 (16)	0.64/ 0.48/ -0.04 (16)	0.76/ 0.47/ 0.29 (15)
Storm Cay	0.57/ 0.36/ 0.14 (16)	0.68/ 0.47/ 0.30 (16)	0.65/ 0.48/ 0.33 (16)

Appendix D. Growth curves for Coral Trout and Red Throat Emperor

It is necessary to specify a growth curve (and the variability about the growth curve) to use ELFSim. In ELFSim, length as a function of age is modeled by means of the von Bertalanffy growth curve:

$$\ell_a = \ell_\infty(1-e^{-\kappa(a-t_0)}) + \varepsilon \qquad \varepsilon \sim N(0;\sigma^2) \tag{D.1}$$

The values for the parameters of this model are estimated using an approach that accounts for the effect of gear selectivity on the data available to estimate the growth parameters, estimates the rate of natural mortality *M*, and makes use of the information contained in the ages for which age estimates based on sectioned otoliths are available. It can also be used to estimate the parameters of the selectivity ogive (i.e., the relationship between selectivity and length or age).

The probability of capturing an animal of length ℓ is the product of the probability that it has length ℓ, $P(\ell)$, and the probability that it has been captured given that it has length ℓ, $V(\ell)$. The functional form of *V* (logistic) is assumed to be known exactly. Therefore, if the values for the parameters of *V* are also assumed to be known exactly (the case for common coral trout), it is only the functional form of *P* and the values for its parameters that have to be determined from the data. The likelihood function for a single datum is of the form:

$$L(x\,|\,\underline{\phi}) = \frac{V(x)\,P(x\,|\,\underline{\phi})}{\int V(y)\,P(y\,|\,\underline{\phi})dy} \tag{D.2}$$

Notice that the denominator is a scaling constant, such that $\int L(x\,|\,\underline{\phi})dx = 1$. The total likelihood to be maximized to estimate the parameters of the growth model is the product of Equation (D.2) over all data points. Given Equation D.1, it is assumed that length-at-age is normally distributed about its expected value, i.e.:

$$P(\ell\,|\,a,\underline{\phi}) = \sum_k \frac{K^k}{\sqrt{2\pi}\sigma} e^{-\frac{(\ell-\hat{L}_{k,a})^2}{2\sigma^2}} \tag{D.3}$$

where $\hat{L}_{k,a}$ is the model-estimate of the length of an animal of age *a* in growth group *k* (determined from a von Bertalanffy growth equation where the values of ℓ_∞, κ and t_0 may be assumed to differ among growth groups):

$$\hat{L}_{k,a} = \ell_\infty^k(1-e^{-\kappa^k(a-t_0^k)}) \tag{D.4}$$

K^k is the proportion of the population in growth group *k*.

The growth model is fit to the entire age-length data set, i.e. not conditioning on the number of fish in each age-class. This involves modifying Equation D.2 so that $\int L(x\,|\,\underline{\phi})dx = 1$ over all age- and length-classes. It also requires that Equation D.3 be modified so that it is the joint probability for the number of animals of age *a* in length-class ℓ rather than the number of animals in length-class ℓ given that the animals are all age *a*. Such a calculation needs to take account of the relative number of animals of age *a* in the population, i.e.:

$$P(\ell,a\,|\,\underline{\phi}) = N_a \sum_k \frac{K^k}{\sqrt{2\pi}\sigma} e^{-\frac{(\ell-\hat{L}_{k,a})^2}{2\sigma^2}} \tag{D.5}$$

where N_a is the relative number of animals of age *a* in the population.

It does not seem unreasonable that numbers-at-age can be assumed to decline exponentially with age given that the samples on which the analyses of this appendix are based were collected from unfished reefs over several years, i.e.:

$$N_a = \begin{cases} 1 & \text{if } a = 1 \\ N_{a-1}\, e^{-M} & \text{otherwise} \end{cases} \qquad \text{(D.6)}$$

where M is the instantaneous rate of natural mortality.

The most recent data for Red Throat Emperor and common Coral Trout were analysed to:

a) estimate growth and selectivity parameters, and the rate of *natural mortality* for Red Throat Emperor;
b) examine whether *M* for common Coral Trout differs among reefs; and
c) examine whether the values for the growth parameters for common Coral Trout differ among reefs.

No attempt was made to determine whether *M* and the values for the growth parameters for Red Throat Emperor differ among reefs because Red Throat Emperor are known to move among reefs, thereby violating the assumptions that underlie the estimation method. The analyses were restricted to "nominally green" reefs [the data from the green-closed reefs (all years), the green reefs pulsed fished in 1997 (i.e., data for 1995 and 1996), and the green reefs pulsed fished in 1999 (i.e., data for 1995–98)]. Table D.1 summarises the ageing data used in the analyses.

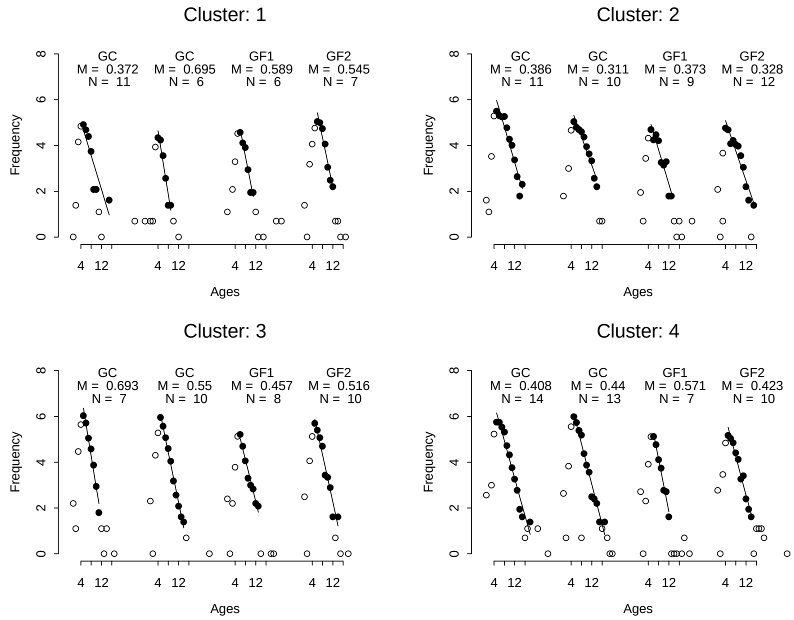
Table D.1. Summary of age data for common Coral Trout and Red Throat Emperor and the subset of the data used in these analyses (GC – "Green closed", "BHF – Blue hard-fished", "GF – Green fished").

Reef	Treatment	Coral Trout		Red Throat Emperor	
		Number of ages	Number ages used	Number of ages	Number ages used
R12	GC	591	591	0	0
R2	BHF	745	0	0	0
R4	GF1	903	377	0	0
R11	GC	258	258	0	0
R6	GF2	822	723	0	0
R21	BHF	624	0	0	0
R23	GF1	684	407	233	132
R9	BHF	349	0	104	0
R13	GC	1008	1008	360	360
R24	BHF	430	0	84	0
R14	GF2	528	434	176	143
R3	GC	621	621	213	213
R15	BHF	708	0	203	0
R7	BHF	723	0	312	0
R22	GF2	1072	891	346	213
R20	GC	1031	1031	392	392
R10	GC	826	826	465	465
R16	GF1	1117	535	327	123
R17	BHF	685	0	261	0
R18	GF2	814	676	282	175
R8	GC	1094	1094	492	492
R19	GC	1271	1271	344	344
R1	GF1	1125	563	233	95
R5	BHF	869	0	96	0

The likelihood function (Equation D.2) depends on natural mortality. Fig. D.1 therefore shows the results of a simple catch curve analysis for common Coral Trout (Fig. D.1a) and Red Throat Emperor (Fig. D.1b). The data for the "nominally green" reefs were pooled across years and the age-at-recruitment was taken to be the age at which the catch-at-age is maximised. The estimates of M (negative of the slope of the catch curve) vary substantially among reefs. This is perhaps not surprising given the low sample sizes for some reefs, particularly for Red Throat Emperor. One result, not unexpected given the results of previous research (Williams 2003), is that the slope of the catch curve for Red Throat Emperor is greatest in the Mackay cluster.

Although Williams et al. (2003) found differences in growth rates among geographical areas for Red Throat Emperor, the analyses here pool the data from all areas. This is because the population dynamics model for Red Throat Emperor allows for movement and associating a growth curve with fish location is a complexity we have chosen to avoid.

(a) Common Coral Trout



(b) Red Throat Emperor

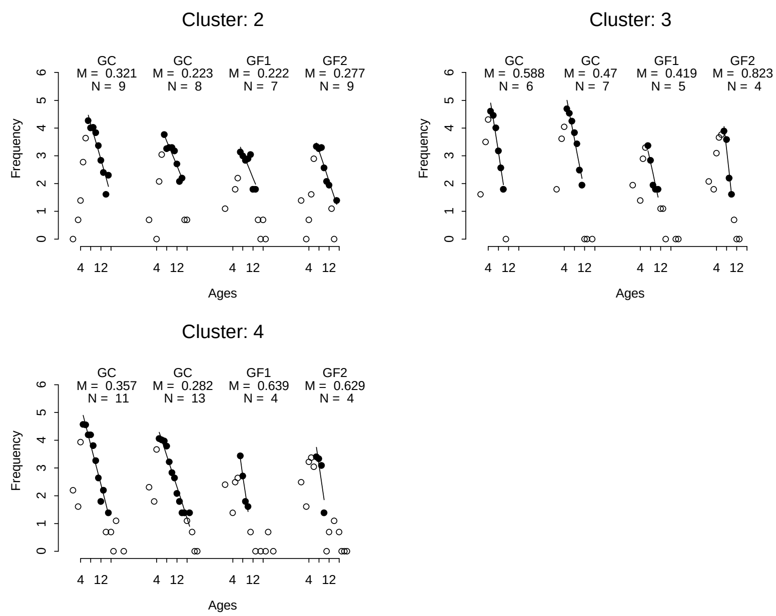


Fig. D.1. Results of the simple catch curve analysis. The closed circles represent the data points included in the analyses, while the open circles indicate those data points not included in the regression because of small sample size or age was less than assumed age-at-recruitment.

In principle, growth might differ among the sexes. Fig. D.2 shows fits of sex-specific and sex-aggregated growth curves to the data for males and females (these fits ignore the effect of size-selectivity – the curves are merely ways to summarise the data). Allowing for sex-specificity in growth leads to a significant (*p*=0.021; log-likelihood ratio test) improvement in fit. However, the actual difference in length-at-age is relatively slight so the analyses of this Appendix are based on pooling data across sex (which also substantially increases the number of data points on which a growth curve can be based because sex is available for less than half of the samples).

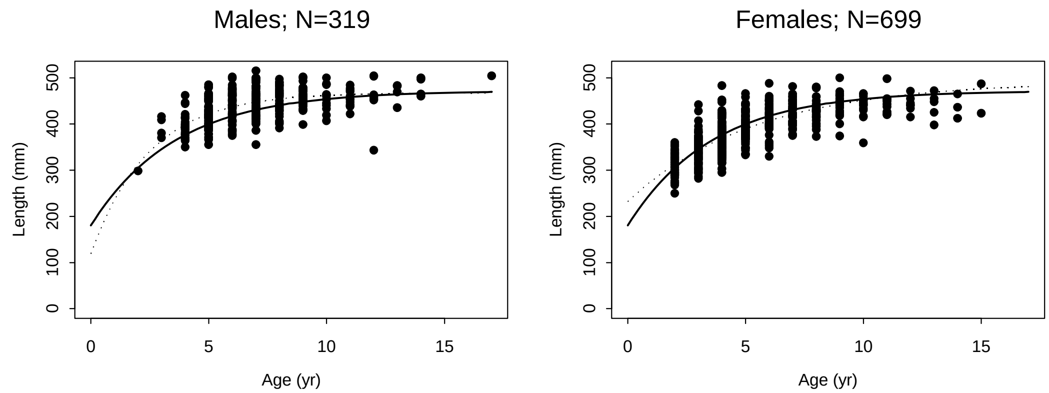


Fig. D.2. Length versus age for Red Throat Emperor. The solid line is a fit to both sexes simultaneously and the dotted lines are fits to the sex-specific data.

The version of the model that is fitted to the data for Red Throat Emperor assumes one growth group, ignores spatial variation in growth, and estimates a logistic selectivity curve. Growth groups are ignored because preliminary analyses (not shown here) indicate that the data do not support the additional complexity associated with growth groups. Table D.2 lists the values of a variety of model outputs (values for the parameters of the growth curve, those of the selectivity pattern, the rate of natural mortality *M*, and the negative of the logarithm of the likelihood function) for four fixed values of *M*, as well as for the maximum likelihood estimate for *M*.

Table D.2. Sensitivity of the results for Red Throat Emperor to how *M* is treated.

M	ℓ_∞ **(mm)**	**κ (yr^{-1})**	t_0 **(yr)**	**σ**	L_{50} **(mm)**	L_{95} **(mm)**	***M*** **(yr^{-1})**	$-\ell nL$
Estimated	454.67	0.310	-0.757	32.42	475.81	572.33	0.566	15215.27
0.3 yr^{-1}	471.91	0.350	-0.265	32.84	350.00	424.60	0.3	15323.16
0.4 yr^{-1}	470.07	0.325	-0.444	33.31	393.37	486.11	0.4	15243.09
0.5 yr^{-1}	462.53	0.312	-0.624	33.08	439.79	537.99	0.5	15221.57
0.6 yr^{-1}	450.69	0.310	-0.789	32.11	490.79	583.53	0.6	15221.44

The maximum likelihood estimate of *M* is 0.566 yr^{-1}. However, this value of *M* includes both natural mortality and the effect of movement on the age-structure of Red Throat Emperor on the sampled reefs. In addition, given movement of fish among reefs, the age-structure on the “nominally green” reefs cannot necessarily be assumed to be that of an unfished population. An additional problem with the analyses with high *M* is that the age-at-50%-recruitment (L_{50} in Table D.2) is larger than ℓ_∞. Therefore, rather than estimating *M*, it is assumed for this analysis and for the purposes of ELFSim to be equal to 0.4 yr^{-1} (see Fig. D.3 for the estimated growth curve).

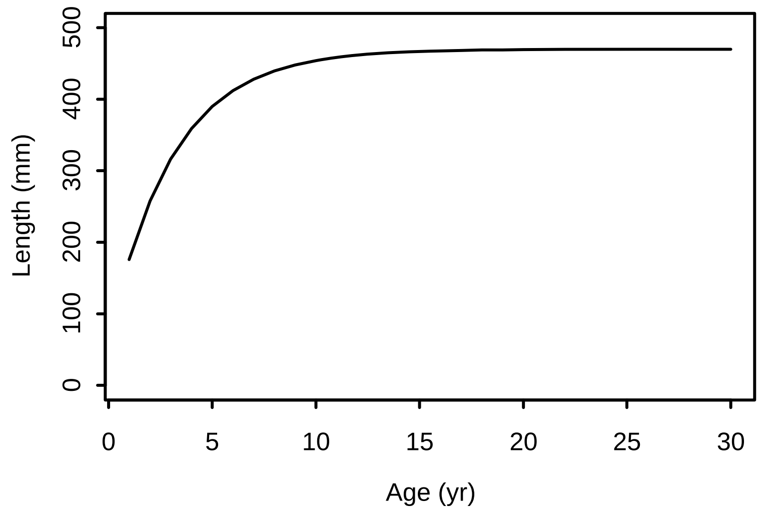


Fig. D.3. Estimated growth curve (length versus age) for Red Throat Emperor.

Fig. D.4 shows the age-compostion data (the ages for which age-estimates are available) for Red Throat Emperor and the fit of the model (marginalizing Equation D.5 over length) to these data, while Fig. D.5 shows the relative frequency of ages in the length-at-age data for Red Throat Emperor and the fit to these data based on Equation D.5. The fit to the age-composition of the ageing sample is good while the fits to the length-at-age distributions are generally adequate. An exception to this is age 2. However, the sample size for age 2 is relatively small (*N*=95). Fig. D.6 shows selectivity as a function of length and age.

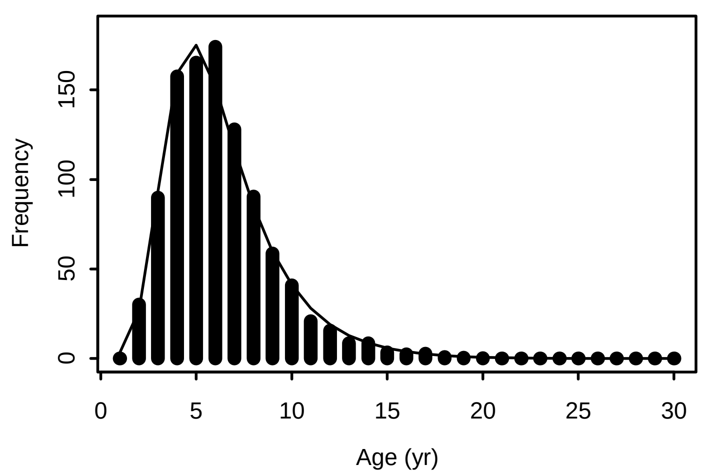


Fig. D.4. Observed (solid bars) and model-predicted (line) catch numbers by age for Red Throat Emperor based on a model in which M=0.4 yr^{-1}.

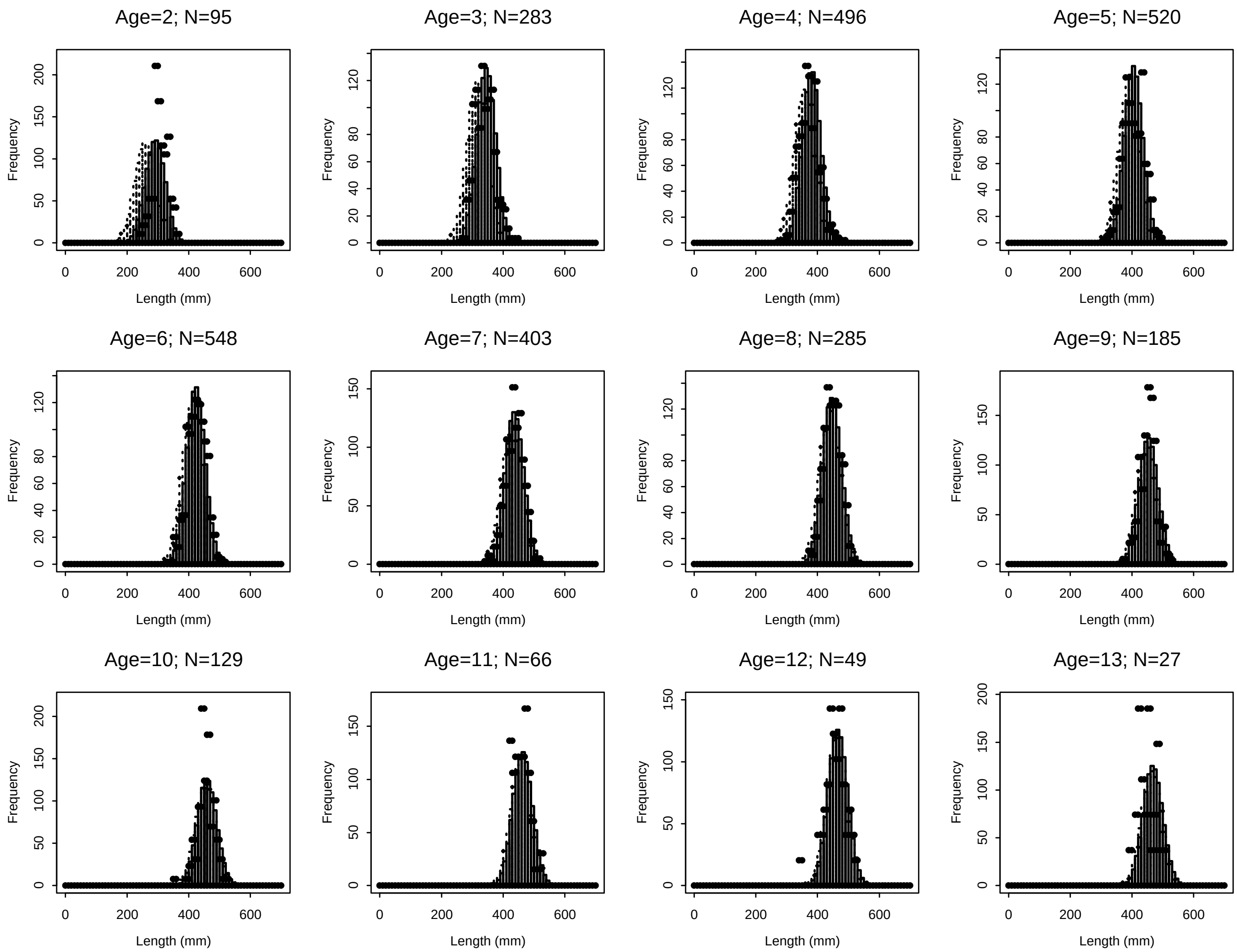


Fig. D.5. The fits to the length-at-age data for ages 2-14 for Red Throat Emperor. The solid dots indicate the observed length-frequency of each age-class , the dotted bars the population length-at-age distributions according to Equation D.5, and the solid bars the catch length-at-age distributions according to Equation D.5 after accounting for selectivity. The model predictions are based on the version of the model with M=0.4 yr^{-1}.

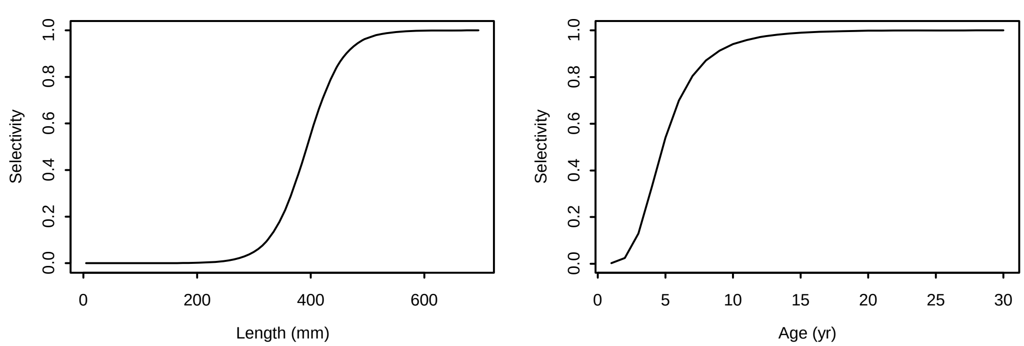


Fig. D.6. Selectivity as a function of length and age for Red Throat Emperor.

The version of the model applied to the data for common Coral Trout is based on the assumptions that: a) there is only one growth group; and b) selectivity as a function of age is governed by a logistic curve with L_{50} = 322 mm and L_{95} = 375 mm. The models considered when analysing the data for common Coral Trout assume:
a) the growth curve and *M* are independent of reef (model 00);
b) growth is cluster-specific and *M* is independent of reef (model 10);
c) growth is reef-specific and *M* is independent of reef (model 20);
d) growth is cluster-specific and *M* is cluster-specific (model 11);
e) growth is reef-specific and *M* is cluster-specific (model 21);
f) growth and *M* are reef-specific (model 22);
g) growth is independent of reef but *M* is cluster-specific (model 01);
h) growth is independent of reef but *M* is reef-specific (model 02).

The eight models are nested, with model 00 being the most parsimonious model and model 22 being the most general model. The results of fitting the eight models are shown in Table D.3, which lists the point estimate of *M*, the value of the negative log-likelihood at its minimum, and ∆AIC and ∆BIC for the eight alternative models. Perhaps not unexpectedly given the large number of data points, the model is selected using AIC is that in which the growth curve parameters are reef-specific and *M* is either reef- or cluster-specific.

Table D.3. Negative log-likelihood, natural mortality M, ∆AIC and ∆BIC for each of the eight models.

Model	Number of parameters	*M* (yr^{-1})	$-\ell n L$	∆AIC	∆BIC
00	5	0.453	57170.1	2032.2	1404.6
10	14	0.452	56787.7	1249.4	723.8
20	50	0.459	56276.6	155.2	37.6
11	17	0.446 / 0.406 / 0.499 / 0.452	56760.5	1189	697.4
21	53	0.494 / 0.405 / 0.498 / 0.451	56243.8	83.6	0.0
22	65	Many	56214.0	0	52.4
01	8	0.458 / 0.453 / 0.507 / 0.411	57126.4	1938.8	1345.2
02	20	Many	56970.3	1602.6	1145.0

The remainder of this section focuses of the model which estimates reef-specific growth and reef-specific *M*. Table D.4 lists the estimates of *M* by reef and Fig. D.7 plots *M* by reef against latitude and longitude. Although Table D.4 and Fig. D.7 suggest relationships between *M* and latitude and longitude, the relationships among these quantities are not statistically significant at the 5% level.

Table D.4. Estimates of the rate of natural mortality for common Coral Trout by reef based on model 22. The values in parenthesis for each cluster are the mean and standard deviation of the reef-specific natural mortality rates (treatment codes: GC – Green control; GF1 – Green reefs fished in 1997; GF2 – Green reefs fished in 1999).

Reef	Treatment	*M* (yr^{-1})	Reef	Treatment	*M* (yr^{-1})
Lizard cluster (0.520, 0.076)			Mackay cluster (0.412, 0.025)		
R12	GC	0.470	R22	GF2	0.458
R4	GF1	0.517	R20	GC	0.540
R11	GC	0.629	R10	GC	0.500
R6	GF2	0.465	R16	GF1	0.493
Townsville cluster (0.498, 0.033)			Storm Cay cluster (0.458, 0.045)		
R23	GF1	0.436	R18	GF2	0.439
R13	GC	0.397	R8	GC	0.403
R14	GF2	0.431	R19	GC	0.487
R3	GC	0.384	R1	GF1	0.501

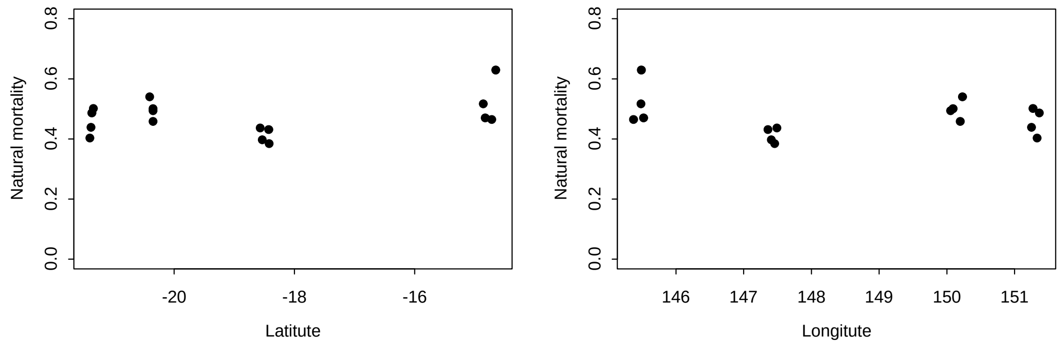


Fig. D.7. Natural mortality versus latitude and longitude for common Coral Trout.

The focus for the remaining calculations examine whether the growth curve differs among clusters in a quantitatively meaningful way. The calculations reported here are based on models 10 and 20 (*M* independent of reef and cluster- and reef-specific growth). These models were selected for further analysis because their results are not confounded by reef- or cluster-specific estimates of natural mortality. Figs D.8 and D.9 plot the cluster-specific and reef-specific growth curves (note that there are only four curves for each cluster in Fig. D.9 because growth curves are not estimated for the two “blue” reefs in each cluster (Table D.1)).

The cluster-specific growth curves (Fig. D.8) suggest that the length at age 30 is largest in the Mackay cluster, with the length at age 30 being lowest in the Townsville and Storm Cay clusters. Although the fits to the length-at-age distributions and the age-composition information (Fig. D.10) for this model are adequate, it is not very clear how to allocate growth curves to reefs.

The applications of ELFSim in this report are based on the following common growth curve for common Coral Trout:

$$\ell_a = 54.05(1 - e^{-0.339(a-0.367)}) + \varepsilon \qquad \varepsilon \sim N(0; 61.7^2) \qquad \text{(D.2)}$$

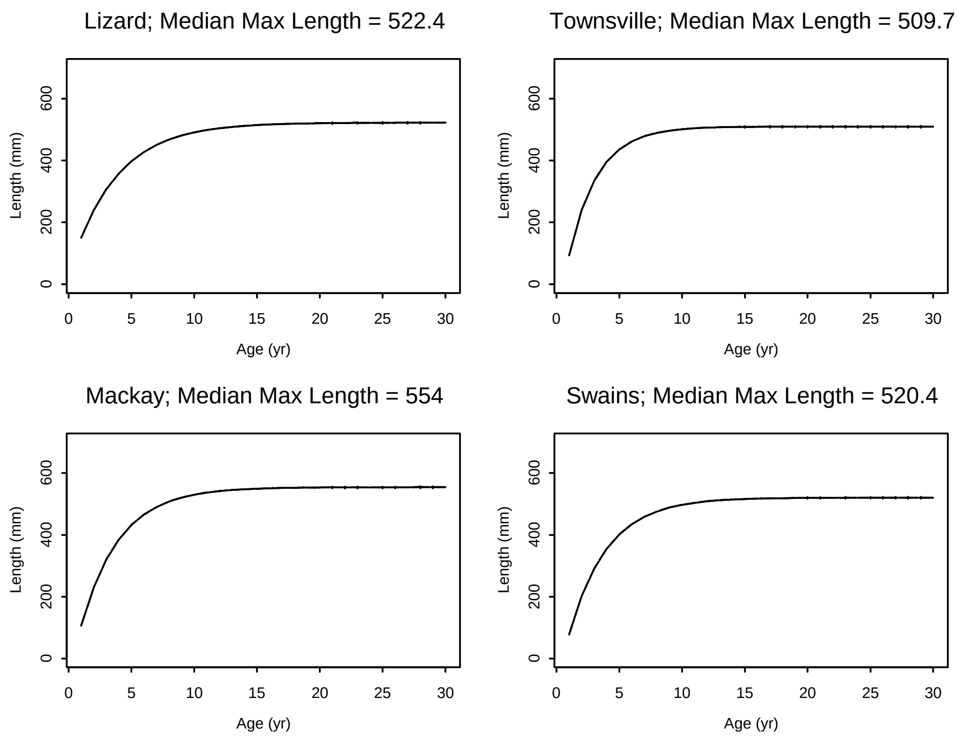


Fig. D.8. Growth curves of common Coral Trout by cluster based on an analysis which assumes that growth is cluster-specific.

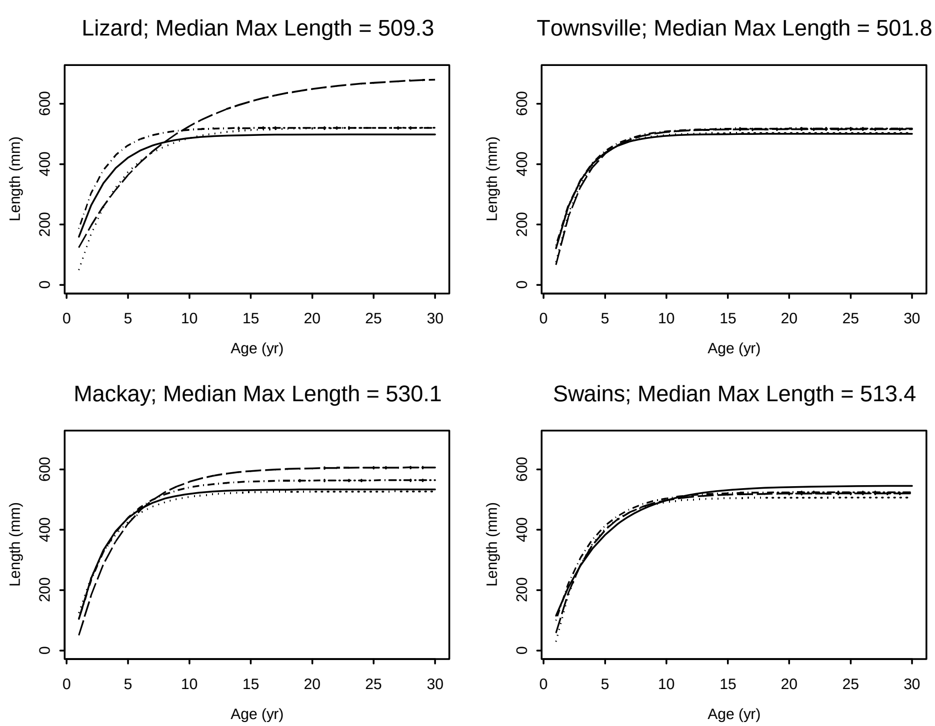


Fig. D.9. Growth curves of common Coral Trout by cluster based on an analysis which assumes that growth is reef-specific. The four curves for each cluster are based on data for each of the four green reefs.

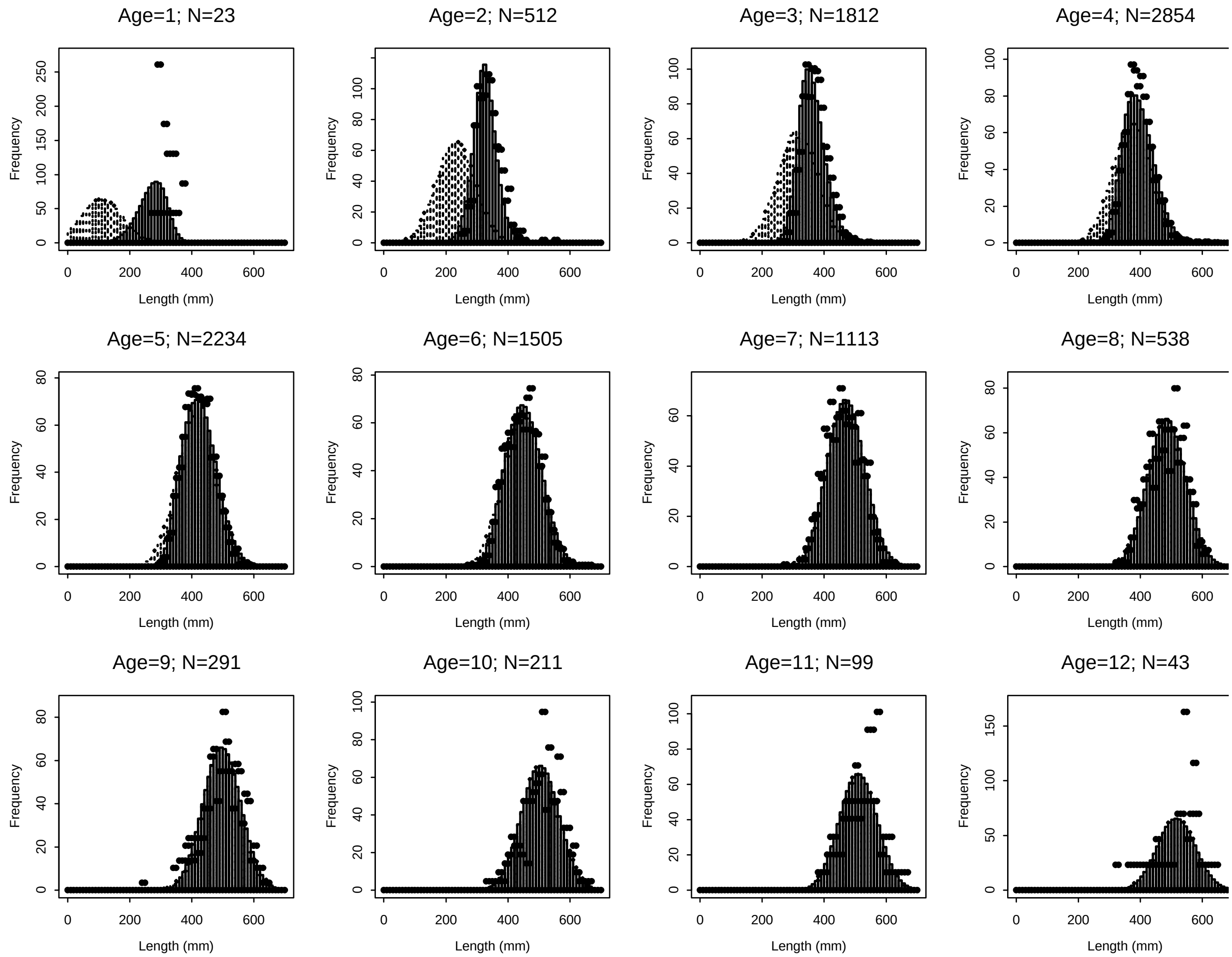


Fig. D.10. The fits to the length-at-age data for ages 1-12 for common Coral Trout. The solid dots indicate the observed length-frequency of each age-class , the dotted bars the population length-at-age distributions according to Equation D.5, and the solid bars the catch length-at-age distributions according to Equation D.5 after accounting for selectivity. The results in this figure are based on a model which assumes that growth is cluster-specific.

Appendix E. Length-weight relationships

These analyses explore whether the (fork) length-weight relationships for common Coral Trout and Red Throat Emperor differ spatially to a sufficient extent to warrant having reef-specific length-weight relationships in ELFSim. The data on which such relationships could be based are the length-weight measurements from the 24 experimental reefs. The data for the experimental reefs were first restricted to records for which length and weight are available and then any weights in excess of 10 kg were excluded as errors. The resultant data sets are summarised in Fig. E.1 and Table E.1. There are clearly outliers in Fig. E.1, but these are few in number compared to the total number of data points.

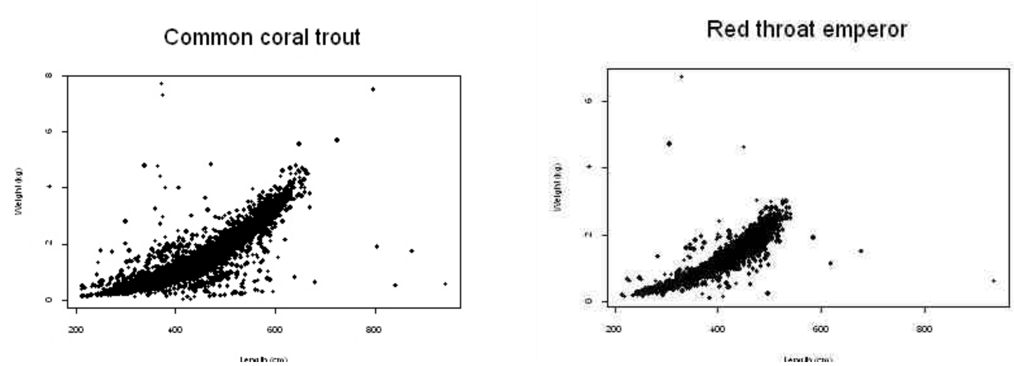


Fig. E.1. Data points used in analyses of length-weight relationships for Coral Trout and Red Throat Emperor.

There are very few data points for Red Throat Emperor for the reefs in the Lizard cluster. The analyses for Red Throat Emperor in this Appendix consequently ignore the data for the Lizard cluster.

Table. E.1. Data points used in analyses of length-weight relationships for Coral Trout and Red Throat Emperor by reef.

Reef	Name	Coral Trout	Red Throat Emperor	Reef	Name	Coral Trout	Red Throat Emperor
Lizard Cluster				Mackay Cluster			
R12	Sth Direction	1122	0	R15	Liff	1177	348
R2	Rocky Islets B	1154	0	R7	Boulton	1599	533
R4	Rocky Islets A	1239	1	R22	Bax	2226	654
R11	MacGillivray	298	0	R20	20-142	1084	320
R6	Eyrie	1760	2	R10	20-137	1567	681
R21	14-133	1138	2	R16	20-136	1661	370
Townsville Cluster				Storm Cay Cluster			
R23	Yankee	1033	351	R17	21-139	1327	426
R9	Knife	672	195	R18	21-133	1498	518
R13	Glow	1255	400	R8	21-132	1355	481
R24	Fork	857	208	R19	21-131	2201	443
R14	Faraday	1323	321	R1	21-130	1273	202
R3	Dip	1501	320	R5	21-124	1391	149

Four models were fitted to the data in Fig. E.1. The most general of these assumes that the parameters of the length-weight relationship are reef-specific (although the residual variance is the same across reefs), i.e.:

$$W = b_1^r L^{b_2^r} e^{\varepsilon}; \qquad \varepsilon \sim N(0;\sigma^2) \tag{E.1}$$

The other three models are special cases of this model in which b_1, b_2 or both b_1 and b_2 are assumed to be independent of reef. The assumption of reef-specific residual variance does not effect the point estimates of b_1 and b_2.

Table E.2 lists the AIC values and the adjusted R^2 for each model and species. The model selected by AIC involves different b_1 and b_2 parameters for each reef. Given the enormous number of data points in Fig. E.1, it is hardly surprising that the model in which b_1 and b_2 are independent of reef is rejected in favour of a more complicated model

Table. E.2. AIC and R^2 values for the four length-weight models.

Model	AIC	ΔAIC	R^2
Common Coral Trout			
Reef-specific b_1 and b_2 values	-27560.66	0	0.9130
Reef-specific b_2 values	-27461.75	98.91	0.9126
Reef-specific b_1 values	-27462.27	98.39	0.9126
b_1 and b_2 are independent of reef	-27112.90	447.76	0.9116
Red Throat Emperor			
Reef-specific b_1 and b_2 values	-7506.05	0	0.9077
Reef-specific b_2 values	-7463.43	42.62	0.9066
Reef-specific b_1 values	-7461.96	44.09	0.9066
b_1 and b_2 are independent of reef	-7339.17	166.88	0.9045

The ultimate aim of this analysis was to examine whether covariates (e.g., latitude and longitude) exist that explain the data, as well as reef (which cannot be used to assign length-weight relationship parameters to each reef in ELFSim). This was, however, deemed unnecessary because plots of the length-weight relationships by reef (Figs E.2 and E.3) suggest that although the inter-reef differences may be (highly) statistically significant, they are qualitatively inconsequential.

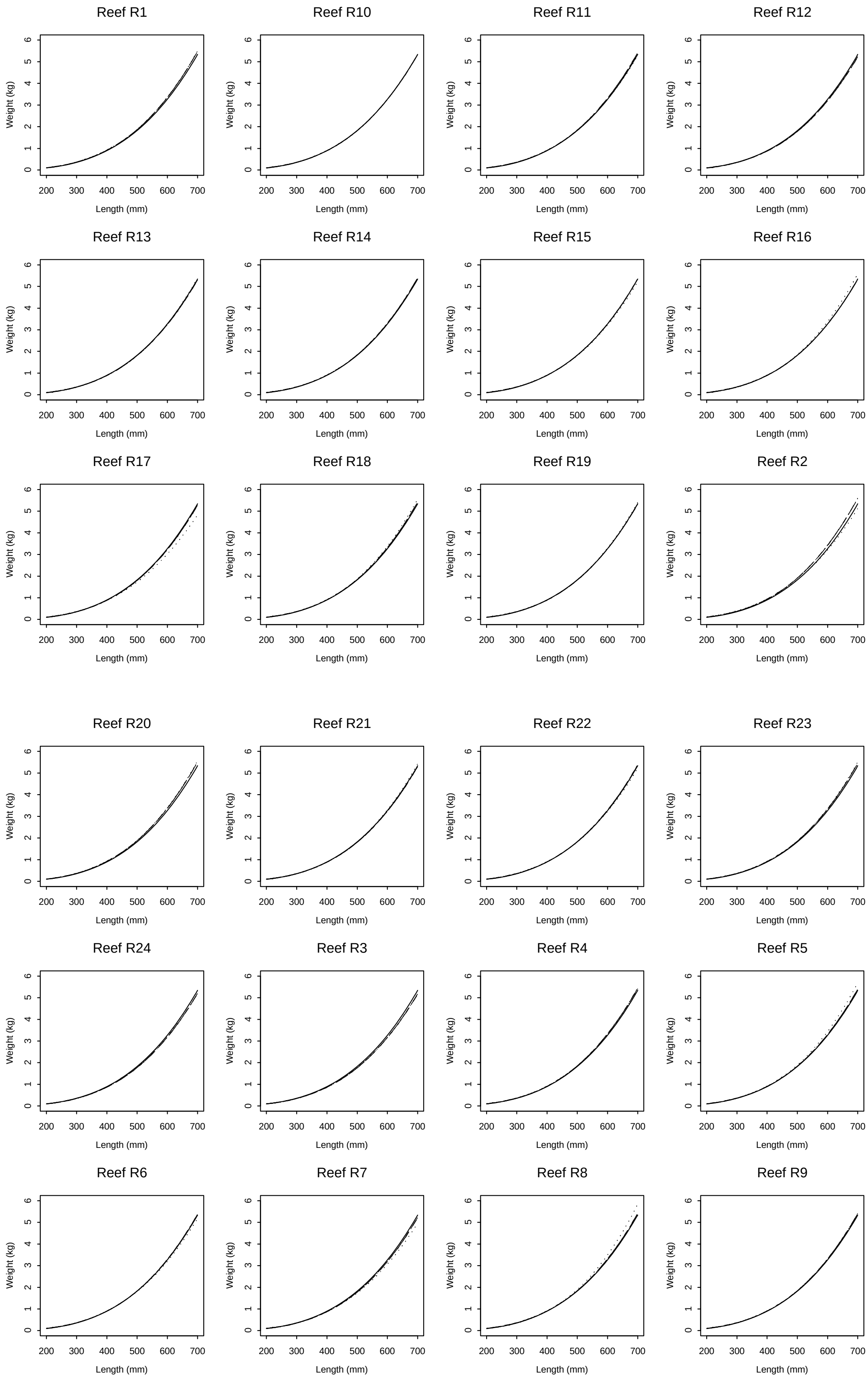


Fig. E.2. Length-weight relationships for Coral Trout for the 24 experimental reefs. Results are shown for the four models outlined in the text and in Table E.2.

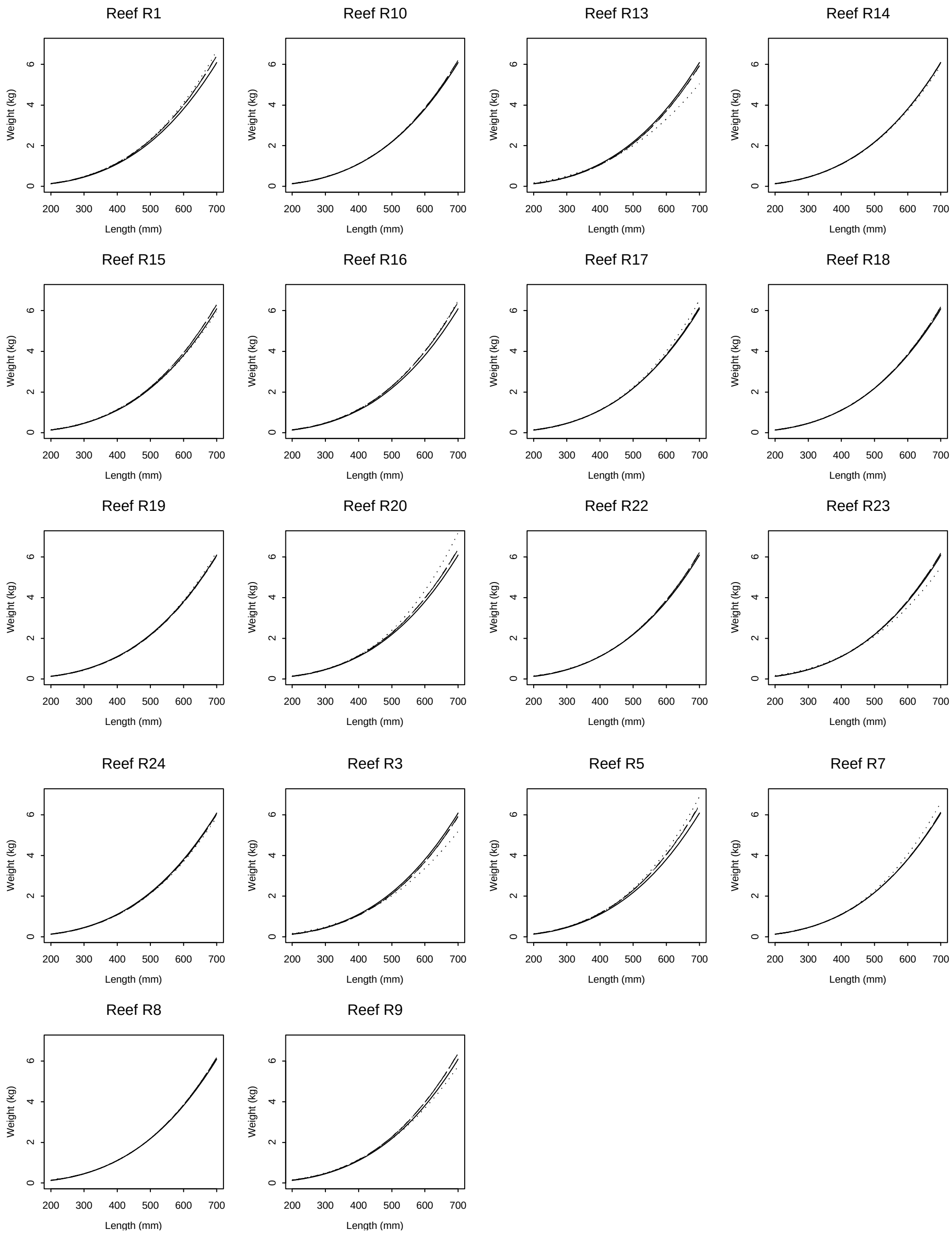


Fig. E.3. Length-weight relationships for Red Throat Emperor for 16 of the 24 experimental reefs. Results are shown for the four models outlined in the text and in Table E.2.

Table. E.3. Estimates (with standard errors in parentheses) for the values for the b_1 and b_2 parameters of the length-weight relationship.

Species	$\ell n b_1$	b_2
Common Coral Trout	-19.2317 (0.0335)	3.1914 (0.0056)
Red Throat Emperor	-18.1728 (0.0713)	3.0497 (0.0119)

Fish lengths in ELFSim are measured in cm, not mm, and so the *a* parameter of the allometric relationship is converted by the equation $\ln b_1^{'} = \ln b_1 - \ln 0.1$, where $b_1^{'}$ is the b_1 parameter used by ELFSim.

Appendix F. Skipper interview

F & F Vessel Movement and Targeting Interview

Date:	Time:	Interviewer:	ID:

A. General background

First, I'd like to ask you a few questions about your fishing history, why you started commercial fishing, and why you have stayed in the fishing industry.

A1. In what year did you start commercial fishing? ____________________

A2. Are you a full-time skipper?

Yes

No **If No, what other occupations do you have?** ____________________

What percentage of your work time is spent skippering? __________

A3. In what year did you first enter the reef line fishery? ____________________

A4. Did you enter the reef line fishery from another fishery?

Yes **If yes, from which fishery?** ______________________________

No

A5. What percentage of your fishing effort is devoted to bottom reef line fishing (e.g., for trout, cod, emperor etc, not mackerel)? __________________

If not 100%, **What other fisheries do you fish in?** ______________________________

How much time is devoted to them (months/year)? __________________

A6. What were the most important reasons for why you started commercial fishing?:
(Use the options below to prompt if necessary. Tick all that apply.)

For the lifestyle (e.g., being your own boss, working outdoors, etc.) ___________

For financial reasons (e.g., expected it to be profitable) ___________

For tradition reasons (e.g., come from a fishing family) ____________

Other (explain) ____________________________________

A7. What are the most important reasons why you continue to fish commercially?
(Use the options below to prompt if necessary. Tick all that apply.)

For the lifestyle _______________

Because it is profitable ____________________

Because of financial commitments (e.g., boat, gear) made to fishing _________

No other trade or profession from which to make a living ___________

Other (explain) _____________________________________

A8. Do you fish for live product?

No ——→ **Go to A11**

Yes

A9. In what year did you start fishing for live product? _______________________________

If A9 = A1 then go to B1

A10. What were the most important reasons why you decided to enter the live fishery?
(Use the options below to prompt if necessary. Tick all that apply.)

Expected increase in profitability __________

Expected fewer competitors in the live fishery ____________

Everyone else was changing to live_____________

The cost of upgrading gear/vessel was affordable __________

Other (explain) ____

Go to B1

A11. Would you say you are not likely, moderately likely, or very likely to enter the live fishery in the next five years?

Not Likely Moderately Likely Very Likely

B. Ports and primary vessel

The next few questions are about what ports you use and the characteristics of your primary vessel and its dories.

B1. What is your present home port (i.e., the port where most of your operations occur)? _____

B2. How long have you operated out of this home port? ______________________________

B3. Have you always had the same home port for your reef line fishing operations?

Yes

No **If No, what other home ports have you had, and when did you leave them?**

Port	When did you leave?

B4. Over the past year, have you used any other ports during your fishing operations (e.g., for offloading catch, emergency repairs, etc)?

No

Yes **If Yes, please list other ports you used, the number of times you used them, and why.**

Port	Number of times used last year	Months of the year used	Reason for use (e.g., offload catch, emergency repairs, etc)

B5. Concerning the primary vessel you currently use, what is the:

Length (m)	**Main engine(s) (KW or HP) ***	**Fuel capacity (l)**
Draft (m)	**Main consumption (l hr^{-1})**	**Fuel normally carried (l)**
Beam (m)	**Auxiliary (KVA or HP)**	**Outboard fuel normally carried (l)**
Age	**Auxiliary consumption (l hr^{-1})**	
Hull material	**Steaming speed (knots)**	
Live tank capacity – Kilograms of fish :	**and/or Litres:**	
Refrigeration capacity – Kilograms of fish:		**Freezer or Icebox:**

*please circle the units used.

B6. How many dories does your endorsement permit you to operate? ___________________.

B7. How many dories do you operate on an average trip? ____________________

B8. Dory characteristics (If all the dories are the same, enter only one line below.)

Dory	Length (m)	Outboard (HP)	Hull material	Live tank capacity (l)	Average fuel/day (l)	Range (nm) (average)	Range (nm) (maximum)
1							
2							
3							
4							
5							
6							

C. Financial and contractual arrangements

Next, I'd like to ask you about some of the financial and contractual arrangements that you use in your fishing business.

C1. Concerning the primary vessel:

Are you: The owner? ☐ Leasing the vessel? ☐ Contract skipper? ☐

C2. Concerning the fishing licence / endorsement:

Are you: The owner? ☐ Leasing the vessel? ☐ Contract skipper? ☐

C3. Which of these endorsements does the license have?

☐ L1 ☐ L2 ☐ L3 ☐ L8

☐ Trawl ☐ Net ☐ Inshore beam trawl ☐ Crab

☐ Bait ☐ Spanner crab ☐ Gill net – barramundi ☐ DPIE export permit

☐ Other (please specify) ____

C4. If you are (or have) a contract skipper, what is the arrangement? (tick appropriate option)

% value of landed catch_______ % of profit________ Price per kg_______ Fixed salary_______ Other _____ (please specify)

C5. What payment system or contract arrangements do you generally use for dory men on your boat?

Product	Payment method (e.g., %individual's catch, price per kg)
Live trout	
Dead trout	
Dead other cods	
Mixed A	

Mixed B	
Other	
Any other contract arrangements? E.g., provision of food, gear or bait?	

D. Fishing operations

Next, I'd like to ask you few questions about your fishing operations at sea. For the purpose of these questions, we are defining a trip as the time from when you leave port or a mother ship, fish, then return to port or the mother ship to offload catch.

D1. How many fishing trips did your vessel make over the past 12 months? ________________

Was this more, less, or about the same as in the previous year? more less same

If more or less, why (e.g., weather, experience, maintenance, etc)? ______________________

D2. Thinking about all of your trips over the past 12 months, how many trips were:

1-3 days	4-6 days	7-9 days	10 days or more

D3. On average, is your fishing effort evenly distributed throughout the year or are there periods when you fish more or less than others?

Yes (evenly distributed)

No **If not evenly distributed please describe how it varies:**

D4. Over the past 12 months, how many days did your vessel spend in port? _______________

Was this more, less, or about the same as in the previous year? more less same

If more or less, why (e.g., weather, experience, maintenance, etc)? ______________________

D5. Do you ever use mother ships? No Yes

If Yes: Over the past 12 months, how many times did you use a mother ship to:

a) refuel and/or reprovision while at sea ?_________________

b) offload catch? ___________________

When using a mother ship, how long will you generally remain at sea before returning to port?________________

How many times will you meet the mother ship to offload and/or reprovision during this time?_______________

What locations do you use to meet the mother ship? _________________

D6. In the past 12 months how many trips did you cut short due to:

Bad weather? _____________________

Low crew morale? _____________________

Fuel shortage? _______________________

Bait shortage? _______________________

Accident or health problems? ________________________

Gear failure? ______________________

Other? ________________

D7. On an average trip, what is the total number of crew (including the skipper)? ____________

D8. On an average trip, what percentage of your total catch comes from the skipper and/or crew fishing directly from the primary vessel? ___________ %

D9. What is the minimum time required in port to unload and reprovision your vessel? ______

D10. What depth ranges do you normally fish for:

Product (if targeted)	Depth						
	0-10 m	11-20 m	21-30 m	31-40 m	41-50 m	51-60 m	>60 m
Live trout							
Dead trout							
Dead other							
Red throat							

D11. What would you say is a good day's catch an average day's catch, and a bad day's catch (for the dories and mother boat combined) for:

	Good day			Average day			Bad day		
	Kg	$	Fish	Kg	$	Fish	Kg	$	Fish
	(Indicate units used)			(Indicate units used)			(Indicate units used)		
Live trout									
Dead trout									
Dead other									

We expect that a lot of your fishing behaviour (such as time spent on each reef, how you react to the presence of other boats, and how tides influence your choice of reefs to fish, etc.) probably depends a lot on the size of the reef in question. The next few questions will ask about your fishing behaviour on small and large reefs.

D12. What do you consider a 'small' reef? less than _____ nm across.
What do you consider a 'large' reef? greater than _____ nm across.

D13. If you start fishing a <u>small</u> reef and experience <u>poor CPUE</u> there, how long would you normally keep fishing there before moving the primary vessel to another reef? (etc. fill in table below)

	Poor CPUE	Average CPUE	Good CPUE
Small reef			
Large reef			

D14. On a scale of 1 to 4 (where 1 = never, 2= Rarely, 3=Frequently, 4 = always), when the primary vessel is anchored on a <u>small</u> reef that has average CPUE, how often do the dories fish on other nearby reefs? (tick appropriate boxes below)

	Never	Rarely	Frequently	Always
Small Reef				
Large Reef				

D15. Would you say you never, rarely, frequently, or always follow the practice of fishing big reefs on big tides and little reefs on little tides?

Never Rarely Frequently Always

D16. Are there any skippers whom you share details about your fishing locations and CPUE?

No

Yes **If yes, how many? ___________________**

How many of these work for the same boat or fishing business as you? _________

How many operate from the same Home Port as you? ____________

D17. Are there any skippers who share details about their fishing locations and CPUE with you?

No

Yes **If yes, how many?___________________**

How many of these work for the same boat or fishing business as you? _________

How many operate from the same Home Port as you? ___________

D18. Would you say you never, rarely, or frequently receive misleading information from other fishers?

Never Rarely Frequently

E. Decision making

E1. We'd like to use some hypothetical scenarios to understand how your choice of which reefs to fish is influenced by expected catch and travel time. We realise that the decision of which reef to fish is complicated, but your answers to these questions will help us model these decisions.

Imagine you have finished fishing a reef and are ready to move to another. You have a choice between two reefs of similar size. The first reef is an hour's steam away and you expect average catch there.

Imagine the second reef is two hours away but you expect the catch to be 50% better than the first reef. All else being equal, which reef would you go to?

First reef (1 hour, average catch) ☐
Second reef (2 hours, 50% better catch) ☐

→ Now, imagine the second reef is four hours away with a 50% better catch than the first reef. Which reef would you go to?

First reef (1 hour, average catch) ☐
Second reef (4 hours, 50% better catch) ☐ → **Go to E2**

→ OK, imagine the second reef is now four hours away but with 100% better catch than the first reef. Which one would you go to?

First reef (1 hour, average catch) ☐ → **Go to E2**
Second reef (4 hours, 100% better catch) ☐ → **Go to E2**

→ Now imagine the second reef is two hours away but with a 100% better catch. Which one would you go to?

First reef (1 hour, average catch) ☐ → **Go to E2**
Second reef (2 hours, 100% better catch) ☐

→ OK, imagine the second reef is now four hours away but with 100% better catch. Which reef would you go to?

First reef (1 hour, average catch) ☐
Second reef (4 hours, 100% better catch) ☐

These next questions are designed to help us understand how the presence of other primary vessels and dories influence your fishing activity.

E2. Imagine you arrive at or approach a <u>small</u> reef that you plan to fish and there are other commercial reef line <u>primary vessels</u> already fishing on the reef. If you expect average CPUE on this reef, how many other <u>primary vessels</u> would have to be there to deter you from fishing on this reef? (etc, fill in table below).

	Small Reef	Large Reef
Primary vessels		
Dories		

E3. Imagine you're fishing a small reef and other commercial reef line vessels arrive. How many primary vessels would have to arrive to cause you to leave this reef? (etc, fill in table below).

	Small Reef	Large Reef
Primary vessels		
Dories		

E4. On a scale of 1 to 3 (where 1=not important; 2= moderately important; and 3=very important), how important is each of the following factors in determining whether or not you fish a particular reef?

	Not Important	Moderately Important	Very Important
The number of fish you caught on previous visits to that reef	1	2	3
Tidal flow (amount of run)	1	2	3
Weather conditions	1	2	3
You've heard from other fishers that it's good	1	2	3
It's close to other reefs you plan to fish	1	2	3

E5. Over the past 12 months, did you fish any reefs that you had not fished before?

No

Yes **If Yes, how many? ________________**

Of these, how many did you fish on subsequent trips? ________________

E6. On a scale of 1 to 3, how important is each of the following factors in determining whether or not you will fish a reef that you haven't fished before:

	Not Important	Moderately Important	Very Important
Information you have received about the reef from other fishers	1	2	3
How good the reef looks on the chart	1	2	3
The distance of the reef from other reefs you fish	1	2	3
The presence of other reef line boats or dories on the reef	1	2	3
Other ____	1	2	3

F. Distribution of fishing effort

Next, I'd like to get some background information on the general areas and reefs you fish so we can understand how effort is distributed across the fishery. This information is important to us because it will give us important information about fishers' actual movements within the fishery. For this I'd like to get you to mark some of your fishing locations and trips on these charts. This information that you give us about your fishing locations will be used for modelling purposes only. This

<u>information will not be published in a way that might reveal your fishing locations to others, and this information will in no way be shared with other fishers.</u>

F1. What are the usual boundaries of the region you fish? (Mark on chart)

F2. In the last 12 months, how have you distributed your fishing effort over this region? (Mark on chart)

F3. Do you fish regular routes? Yes No

F4. Please mark on the chart the tracks of up to 3 trips you have taken over the past 12 months.

F5. For each track, record on the chart or below:

Date (month) of trip
Each reef/ fishing location (numbered sequentially)
Date of each reef (if possible)
Duration of trip (number of days)

G. Targeting behaviour and catches

Next, I'd like to get some information about your catches, and how you decide what species and product to target on any particular trip.

G1. Over the past 12 months, what was the percent of your catch by weight for:

Live trout	
Dead trout	
Red Throat Emperor	
Spanish mackerel	
Other	

Do these percentages vary by season? Yes No

If Yes, how?

____

____

____

G2. What size range do you prefer to catch when targeting:

Live trout ____________________**cm or kg** **Dead trout** ________________________**cm or kg**

G3. Are there any occasions when you specifically target Red Throat Emperor?

No

Yes **If yes, under what circumstances?** ____

G4. Are there any occasions when you specifically target Spanish mackerel?

No

Yes **If yes, under what circumstances?** ____

G5. Are there any occasions when you specifically target any other species?

No

Yes **If yes, what species and under what circumstances? ______________________________**

G6. Are there any occasions when you specifically harvest (keep) only trout?

No

Yes **If yes, under what circumstances? ____**

(If fisher is not in the live industry, <u>go to G9</u>)

G7. Are there any occasions when you specifically fish for dead product only?

No

Yes **If yes, under what circumstances? ____**

On how many trips over the past 12 months did you fish for dead product only? ______

G8. All else being equal, how low does the price of live fish have to be for you to stop fishing for live product in favour of dead product? ______________

G9. To the best of your knowledge, do the dory fishermen ever discard marketable catch to accommodate a more valuable product from:

a) the hook Yes No

b) the icebox Yes No

c) the live well Yes No

If Yes: What species are discarded by dory fishermen? ________________________________

And in favour of what species? ________________________________

G10. Do you ever discard marketable catch from the freezer to accommodate a more valuable product you are catching (i.e., high grading)?

No

Yes **If Yes, on what percentage of trips does this occur**? ________________

What species do you discard? ____

And in favour of what species? ____

G11. With the new quota rules, do you think the number of marketable fish discarded by you and your crew will:

Increase a lot Increase a little Stay the same Decrease a little Decrease a lot

H. Management opinions

Next, I'd like to ask your opinions on the health of the GBR and its fisheries.

H1. On a scale of 1 to 5 (where 1= under fished and 5=over fished) what is your opinion of the present status of the reef fish stocks in your usual area of operation?

Under fished		Moderately fished		Over fished
1	2	3	4	5

H2. On a scale of 1 to 5 (where 1= very little effort and 5=too much effort) what is your opinion of the present level of commercial reef line fishing effort in the GBR Reef Line Fishery?

Very little effort		Moderate effort		Too much effort
1	2	3	4	5

H3. On a scale of 1 to 5 (where 1= very little effort and 5=too much effort) what is your opinion of the present level of recreational reef line fishing effort in the GBR Reef Line Fishery?

Very little effort		Moderate effort		Too much effort
1	2	3	4	5

H4. Do you consider <u>overfishing</u> to be no threat, a minor threat, or a major threat to the Great Barrier Reef line fishing industry? (etc. fill in table below)

	No threat	Minor threat	Major threat	Don't know
Overfishing	1	2	3	4
Poor management	1	2	3	4
Pollution	1	2	3	4
Land run off of nutrients	1	2	3	4
Tourism	1	2	3	4
Other________________________________	1	2	3	4

Next I'd like to ask a few questions about GBRMPA's Rep Areas Program and how it is likely to affect you.

H5. What percentage of the area you currently fish is scheduled to become 'green' under the proposed RAP? ________________

If 0%, go to H7

H6. I'd like to know what will likely happen to your fishing activity the new green zones are implemented. In response to the proposed green zones, how likely will you be to:

	Not Likely	Moderately Likely	Very Likely
Extend your fishing area to somewhere new	1	2	3
Concentrate your efforts in the remainder of your area	1	2	3

Move your fishing operation altogether	1	2	3
Change to another fishery	1	2	3
Stop fishing	1	2	3
Other ______________________________	1	2	3

H7. Do you expect the new green zones to have any effect on <u>your access to productive fishing areas</u>? If yes, will <u>your access to productive fishing areas</u> increase or decrease?

	Decrease	No Effect	Increase
Your access to productive fishing areas	1	2	3
The number of other commercial fishers who fish the reefs/areas you fish	1	2	3
The number of other recreational fishers who fish the reefs/areas you fish	1	2	3
The profitability of your business	1	2	3
The long term sustainability of the reef line fishery	1	2	3
The long term sustainability of the GBR in general	1	2	3

H8. How many reef line fishers do you think fish green zones on occasion?

None   A few   A lot   All

H9. Do you think that fishers who fish green reefs are not likely, moderately likely, or very likely to get caught?

Not likely   Moderately likely   Very likely

(**If <u>not likely</u> to get caught): Do you think low chance of getting caught is a big reason, small reason, or not a reason why some fishers fish green reefs?**

big reason   small reason   not a reason

H10. Would you expect CPUE on green reefs to be better, the same, or worse than CPUE on blue reefs?

better   same   worse

(**If <u>better</u> CPUE expected): Do you think better CPUE is a big reason, small reason, or not a reason why some fishers fish green reefs?**

big reason   small reason   not a reason

H11. Do you think the penalties for fishing green reefs are too small, too large, or about right?

too small   too large   about right

(**If too small): Do you think small penalties is a big reason, small reason, or not a reason why some fishers fish green reefs?**

big reason   small reason   not a reason

H12. Do you think that most reef line skippers have good knowledge, moderate knowledge, or poor knowledge of which reefs are green reefs?

good knowledge moderate knowledge poor knowledge

(If <u>poor</u> level of knowledge): Do you think that lack of knowledge about which reefs are green reefs is a big reason, small reason, or not a reason why some skippers fish green reefs?

big reason small reason not a reason

H13. When the amount of green zones increases substantially under the proposed RAP management plan, do you think the amount of fishing activity in green zones will:

Increase a lot Increase a little Stay the same Decrease a little Decrease a lot

Next, I have a few questions about the new reef line plan (i.e., the new quota system, size limits, spawning closures, no-take restrictions on some species, etc.) that is about to be implemented by that Queensland government and how it is likely to affect you. For these questions, focus on the new quotas and no-take restrictions etc., not the new green zones.

H14. Do you expect the reef line plan to have any effect on <u>your access to species you presently target</u>? If yes, will <u>your access to species you presently target</u> increase or decrease?

	Decrease	No Effect	Increase
Your access to species you presently target	1	2	3
The number of other commercial fishers who fish the reefs/areas you fish	1	2	3
The number of other recreational fishers who fish the reefs/areas you fish	1	2	3
The amount of discarding or high grading that occurs in the reef line fishery	1	2	3
The profitability of your business	1	2	3
The long term sustainability of the reef line fishery	1	2	3
The long term sustainability of the GBR in general	1	2	3

H15. Do you support or oppose each of the following regulations under the Reef Line Plan?

	Oppose	Neutral	Support
The transferable quotas scheme	1	2	3
The 9 day spawning closures	1	2	3
The 38cm minimum size for Coral Trout	1	2	3
The 38cm minimum size for Red Throat Emperor	1	2	3
The 50cm minimum size for blue spot trout	1	2	3
The 80cm maximum size for blue spot trout	1	2	3
No take provision for Maori wrasse	1	2	3
No take provision for barramundi cod	1	2	3
No take provision for red bass	1	2	3
No take provision for Queensland grouper	1	2	3
No take provision for potato cod	1	2	3

H16. Are there any other aspects of the new Reef Line Plan that you strongly support or oppose?

H17. Has your license been allocated a quota of Coral Trout under the new reef line plan?

Not sure

No

Yes **If yes, do you think your allocation was**

1 Less than you were entitled to
2 About what you were entitled to
3 More than you were entitled to
4 Not sure

H18. Has your license been allocated a quota of Red Throat Emperor under the new reef line plan?

Not sure

No

Yes **If yes, do you think your allocation was**

1 Less than you were entitled to
2 About what you were entitled to
3 More than you were entitled to
4 Not sure

H19. Has your license been allocated a quota of Spanish mackerel under the new reef line plan?

Not sure

No

Yes **If yes, do you think your allocation was**

1 Less than you were entitled to
2 About what you were entitled to
3 More than you were entitled to
4 Not sure

H20. Has your license been allocated a quota of 'other' under the new reef line plan?

Not sure

No

Yes **If yes, do you think your allocation was**

1 Less than you were entitled to
2 About what you were entitled to
3 More than you were entitled to
4 Not sure

H21. Are you not likely, moderately likely, or very likely to buy or lease quota over the next 2 years?

Not likely   moderately likely   very likely   not sure

H22. Are you not likely, moderately likely, or very likely to sell quota over the next 2 years?

Not likely   moderately likely   very likely   not sure

H23. Do you expect to still be in the reef-line fishery in 5 years?

Yes

No   **If no, why not? ____**

I. Demographics

I1. What is your age ____________

I2. What is your marital status? married   single   other________________

I3. How many people, including yourself, live in your household? ________________

I4. Do you receive the Fishing and Fisheries newsletter published by the CRC Reef Research Centre?

Yes

No   If no, would you like to receive more information about by subscribing to the F&F Newsletter?

If yes, record address to send newsletter on a separate sheet

I5. Do you have any suggestions as to what might be priorities for future research on the GBR Reef Line Fishery?

I6. Would you be interested in participating in a follow-up interview at a later date?

Yes   No

Appendix G. Management strategy evaluation workshops

CRC Reef Fishing & Fisheries FRDC Multi-species Project
Management Strategy Evaluation Stakeholder Workshop
16-17 August 2004

MINUTES

Thank you

On behalf of the CRC Reef Research Centre's Fishing and Fisheries (F&F) Team, I would like to thank you for your participation in the FRDC funded Multi-species Management Strategy Evaluation Stakeholder Workshop. Your time, expertise and knowledgeable discussion made this workshop of immense benefit, not only to the research we are conducting, but to the management process for the Great Barrier Reef (GBR) Reef Line Fishery.

We hope that this workshop was also of benefit to you by providing a firm background to our research and the Management Strategy Evaluation (MSE) process.

The lively discussions and thoughtful comments over the two days of the workshop have helped us immensely in guiding the future MSE for Red Throat Emperor.

The management objectives identified by you at this workshop will be instrumental in providing a framework for future evaluation of management strategies that we hope to identify at a future stakeholder workshop.

Gavin Begg
F&F Project Leader

INTRODUCTION

This document records the ideas and discussions that emerged at the Multi-species Management Strategy Evaluation Stakeholder Workshop on the 16th-17th August 2004 at the Museum of Tropical Queensland, Townsville.

This document is not meant to be an exhaustive record of all the discussion that occurred over the two days of the workshop, but a synopsis of the main opinions expressed by various stakeholders present. The opinions recorded here may not be those agreed upon by all the stakeholders at the workshop, or by CRC Reef, but were brought up by one or more stakeholders at the workshop, and have been recorded here as a record of the discussions. For further information about the presentations made by researchers at the workshop, please refer to the workshop manual distributed at the workshop or contact the researchers. Contact details can be found at the back of this document.

The workshop was aimed at introducing stakeholders to recent advances in ELFSim, and to discuss with them the scope of scenarios that they would like to see evaluated. Stakeholders were asked to identify features of the Reef Line Fishery that are important to them, how they would like to see the fishery in the future, and what management objectives and potential management strategies that they believed are of interest. The information derived from the workshop will form the framework to test new management strategies that will be discussed at a future workshop.

PRESENTATIONS

Welcome

Presenter – David Williams and Gavin Begg

This workshop is part of the FRDC-funded Multi-species Research Project being conducted by the CRC Reef F&F team and CSIRO. It builds on previous research of the Effects of Line Fishing (ELF) Project and previous stakeholder workshops conducted in 1999 and 2000, when a MSE for Coral Trout was developed and completed.

David Williams

Welcome to the stakeholder workshop, the third of its kind. This workshop was not intended to be a forum to debate current management arrangements. It is, however, to provide to you, the stakeholders of Queensland's reef line fishery, information about CRC Reef Reseach Centre's research that will help make more informed decisions about management of the fishery.

This workshop comes from a long term, collaborative research project between CRC Reef and CSIRO Marine Laboratories to develop management strategy evaluation (MSE) tools for the reef line fishery on the Great Barrier Reef (GBR). The workshop is intended to give researchers information on management objectives for the fishery that can be tested with these tools. In this respect, we do not wish to reinvent the wheel, but to build on the previous workshops and research. Previous MSE research conducted by our team has included common Coral Trout only. We now wish to extend this to include the second most important reef fish species of the fishery; Red Throat Emperor.

Gavin Begg

Welcome to this Multi-species Management Strategy Evaluation (MSE) Stakeholder Workshop and thank you for your participation, especially to those who travelled long distances to attend.

The focus of previous MSE research as part of the F&F Project has been on common Coral Trout as the most targeted fish species in the reef line fishery. CRC Reef and CSIRO researchers developed tools to conduct an MSE for Coral Trout with help and guidance from stakeholders at previous workshops in 1999 and 2000.

The 1999 workshop was aimed at introducing the MSE concept to stakeholders. It also identified management objectives and indicators (means of measuring those objectives) that stakeholders felt were important to them for the sustainable use of the GBR line fishery. This feedback helped researchers develop the ELFSim models that enabled a MSE to be conducted for the fishery.

The 2000 stakeholder workshop aimed to further develop the MSE concept and to identify management objectives and strategies that stakeholders agreed were important for the GBR reef line fishery that in turn could be tested with ELFSim.

ELFSim includes components for modeling fishing effort and biology of Coral Trout, as well as a management component for MSE. It models the whole GBR system and the three main fishing sectors (recreational, commercial and charter). The management strategies addressed by ELFSim are mainly focused on area closures and effort control strategies.

This current stakeholder workshop is to update the research we have done with Coral Trout and more importantly to now extend this model to include Red Throat Emperor. To do this, we now need to gain feedback on important management objectives and strategies that are relevant for Red Throat Emperor and can be tested with ELFSim.

The extension of ELFSim to include Red Throat Emperor is aimed at providing a MSE for the reef line fishery of the GBR that recognizes the multi-species nature of the fishery, and the importance of this species to the fishery. The inclusion of Red Throat Emperor is important to make the model more relevant to the fishery and more useful to stakeholders in making management decisions for the fishery.

We are not all going to agree on everything said at this workshop, but this is not necessary to make the workshop a success. What we hope to do is through discussion among stakeholders identify those features that are important for the management of the GBR reef line fishery.

DISCUSSION:

Vern Veitch: Why Red Throat Emperor? There are many other species that are of importance to many fishers that may be better candidates for inclusion in ELFSim.

Gavin Begg: Red Throat Emperor is important to most sectors of the fishery with respect to fishing on the reef (as compared to coastal fishing), and is the second most important commercially targeted species. We also need to consider what the MSE tools can do and the data required. The models need a lot of biological information to calculate realistic projections of the fishery in the future. Historically, Red Throat Emperor and Coral Trout were identified as important species for the fishery and consequently as a priority species for research, hence why we now have this information for these species. This is not to say that other species in the fishery do not have importance to us and indeed we are continuing research into a range of other fish species. When we have sufficient biological and fisheries information on other species identified as important to stakeholders we will be able to include these into ELFSim also.

Mark Elmer: There are currently proposals for research on other species being considered now, and if these are funded, the results from this may be of use in future MSE research.

Biology, fishery and management

Presenter – Ashley Williams

Common Coral Trout and Red Throat Emperor are the two most targeted fish species in the GBR Line Fishery. Together they make up the majority of reef fish catch in both the commercial, charter and recreational fishing sectors. Efficient management of fish species such that fishing remains sustainable in the long term is highly reliant on a sound knowledge of the biological characteristics of the species being managed. These characteristics include information on growth, reproduction and age. Our current knowledge of the biology of these species is good in some areas, but poor in others. Here we present what we know about the biology of common Coral Trout and Red Throat Emperor, as well as identifying what we don’t know and how this information may affect their management.

DISCUSSION:

The Fishery
Bill Sawynok: Red Throat Emperor is a very different target species for the recreational sector. It tends to be more important to the charter fishers with clients interested in catching their bag limit. Recreational fishers targeting trout are more interested in catching fewer larger fish rather than catching their bag limit. Recreational fishers mainly target Bar-cheeked Trout that tend to be more prevalent in the inshore reef areas that are more accessible to them. This indicates that objectives may change with different sectors.

Bill Edwards: Charter fishers are not actually targeting Red Throat Emperor, but they are interested in their clients taking a reasonable bag limit of fish. That may be Red Throat Emperor, Coral Trout or another species; the species is not relevant. Red Throat Emperor is only one species that they catch.

Richard Hack: There are also regional differences in the charter sector. For example, charter fishers in the southern GBR tend to do drift fishing targeting red emperor.

John Heard: For the commercial fishery, Red Throat Emperor could become a major target at any time if prices increase.

Reproduction
John Heard: Do Red Throat Emperor spawn three times before reaching 38 cm?

Ashley Williams: Red Throat Emperor probably spawns once or twice before reaching their legal size of 38cm.

Les Pollard: Are there any differences in the survival rates of larvae spawned from large and small fish? Current market forces prefer common Coral Trout under 2 kg, hence larger fish are being released. Will this practice have an effect on reproductive output?

Gavin Begg: There is some research on differences in fecundity and larval survival between smaller, younger fish and larger, older fish for other species. Larger, older fish tend to produce larger eggs and larvae that have a greater chance of survival than those produced from smaller, younger fish. It has also been found that those fish that have spawned a few times tend to produce larvae with greater survival characteristics. Another consideration for fish such as common Coral Trout and Red Throat Emperor is that larger, older fish have changed to being male. This is another important consideration for effective management. It is important to know this type of information for a fish stock before considering management strategies.

Barry Goldman: There is a lot of evidence from ecological studies that health of populations of fish are seriously compromised by lack of older individuals.

Ashley Williams: Red Throat Emperor tend to spawn at the same time over their whole GBR distribution, from Gladstone to Townsville.

Danny Brooks: Are Red Throat Emperor more susceptible to fishing in aggregations around spawning time compared with feeding aggregations?

Ashley Williams: Anecdotal evidence from fishers indicate the occurrence of aggregations of Red Throat Emperor, but it is unclear if these are spawning aggregations, feeding aggregations or even if they are aggregations of Red Throat Emperor at all. However, there is no evidence for increased CPUE at this time.

Martin Russell: Common Coral Trout need a critical mass of males to females for an efficient spawning event. If there are too many large males compared to females than they may fight rather than spawn, and hence the reproductive output from such aggregations will be reduced.

Terry Must: Where does the information on Coral Trout aggregations come from?
Ashley Williams: Information on common Coral Trout spawning behaviour is from Melita Samoily and Beatriz Ferreira's research on reefs off Cairns.

Richard Hack: Thousands of wire netting cods are present in certain areas of the Capricorn-Bunkers that tend to come with Red Throat Emperor. Red Throat Emperor tend to come on the bite after spawning time, with most catches being on a full moon at night.

John Heard: With regard to sex ratio, is it important to have an equal amount of males to females at spawning time?

Ashley Williams: This will vary with the species depending on whether they pair or group spawn. We don't really know ideal sex ratios for Red Throat Emperor and common Coral Trout, but we can assume that sex ratio's on reefs closed to fishing reflect the most ideal ratios for a population. For Red Throat Emperor on closed reefs these tend to be slightly female biased.

Les Pollard: Catches of Red Throat Emperor at spawning time are mostly females.

John Heard: If this is the case, that there is a slight female bias, is this due to natural mortality, and is it actually the most efficient sex ratio?

Gavin Begg: In some fisheries around the world, fishing pressure has led to stocks that reproduce at younger, smaller fish and can change sex earlier (if they change sex).

Ashley Williams: Fishing pressure on stocks can also change sex ratios.

Gavin Begg: For common Coral Trout, they seem to very flexible with respect to reproduction and may change sex at a variety of ages and sizes. Some common Coral Trout actually seem to begin their life as males, and others seem to stay as females all their life.

Management

Vern Veitch: The model needs to be able to consider the number of undersized fish that are caught and released, and those that do not survive release. In shoal areas, some fishers can catch 20 under- to legal-sized fish and many released fish do not survive.

Richard Hack: With the new size limit at 38 cm, commercial fishers have reported throwing back 30% of the catch of Red Throat Emperor.

John Heard: Do Red Throat Emperor spawn before reaching 35 cm, and if so, shouldn't that be the minimum legal size?

Gavin Begg: The minimum legal size for both Red Throat Emperor and common Coral Trout are considered to be quite robust and provide a buffer to maintain stability in the fishery.

David Williams: Minimum legal sizes are generally set at a size at which 50% of the population are sexually mature.

Danny Brooks: Fisheries management, however, considers many other factors than just scientific information to set management strategies such as size limits.

Gavin Begg: For example, reef fish are a little different as they change sex, therefore size limits need to be considered differently to other species of fish that don't change sex. There is a lot about sex ratios for reef fish that we don't know, which is one reason why size limits need to be conservative.

Bill Edwards: ReefMAC did not recommend the minimum legal size of 38 cm for Red Throat Emperor based only on scientific information, but more for ease of compliance.

John Heard: We need to reduce the mortality of released fish.

Bill Sawynok: Post release mortality of fish is due to barotrauma or deep gut hooking. Adoption of other fishing practices can reduce the incidence and severity of both of these and hence increase survivorship of released fish.

John Heard: Were the results from the MSE for Coral Trout considered for the Representative Areas Program?

Gavin Begg: RAP was set for a different reason other than fisheries management. However, the closures for RAP when tested with ELFSim were shown to be reasonable.

Mark Elmer: Fisheries management is about a viable, stable fishery into the future, not about closing down the fishery.

Kath Kelly: Results from the MSE for Coral Trout with various area closures for the whole GBR shows a direct relationship between the amount of reef closure and reef fish populations. Is this an assumption of the model?

Rich Little: No it is not an assumption of the model, but the results derived from the model.

John Heard: For 100% area closure of the Marine Park to fishing there is complete recovery of fish stocks to unfished levels in a short time. Is this considered to be realistic?

Rich Little: The recruitment variable (numbers of juveniles settling on reefs) used in the model are very conservative, hence it is considered that this would be a realistic time frame for the recovery of fish stocks given complete closure of the Marine Park to fishing.

Gavin Begg: For common Coral Trout the minimum legal size is quite conservative and hence recovery of common Coral Trout populations is around 10 years. Previous ELFSim evaluations for common Coral Trout on the GBR indicates that the effect of area closures is less efficient at meeting management objectives compared to fishing effort restrictions.

Phil Cadwallader: The RAP had different objectives than fisheries management and is therefore not changeable.

Richard Hack: The commercial fishery may be closed from February to July due to operations reaching their catch quotas and therefore effectively will force effort restrictions in the fishery.

Terry Must: Today, commercial fishermen are only fishing about 60% of the reef area as the rest is too deep for live fishing.

Fish biological model

Presenter – Rich Little

The Coral Trout model of ELFSim is based on the assumption that Coral Trout comprise many local populations each associated with a single reef, linked via larval dispersal. This assumption is based on research indicating that adult fish do not move between reefs. The operating model of Red Throat Emperor differs, however, in that fish over 1 year of age are able to move between reefs. In both models, account is taken of the age-, sex-, and size-structure of the population on each reef. The number of animals settling each year on a reef is determined by the annual egg production on that reef, 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, as well as variation in the relationship between fishing effort and fishing mortality.

The software framework that implements the model has been called the “Effects of Line Fishing Simulator” or ELFSim for short. ELFSim is a decision-support tool designed to evaluate options for managing Coral Trout, and now Red Throat Emperor, in the Reef Line Fishery on the GBR. It contains several components, including visual outputs and run management, but the most important components are a spatially-structured biological model (common Coral Trout and Red Throat Emperor) and a model of fishing behaviour.

ELFSim operates at a monthly time scale and each simulation consists of two parts. In the first, which operates historically from 1965 to 1998, the biological component uses information from previous research to determine the population size (and its age-, sex- and size-structure) on each reef given the documented amount of past fishing. In the second part, which projects the reef populations forward in time from 1998, the biological component is subjected to simulated fishing pressure, which is in turn subject to various management strategies. Stakeholders are then able to evaluate these management strategies by examining biological and economic performance indicators outputted from the model.

Management strategies available for testing include area closures, gear selectivity and minimum legal size. The amount of annual fishing effort that will operate in the projection period can also be set. Because ELFSim operates at a monthly time scale, the annual projected effort is divided among months based on what we know about monthly fishing patterns from past fishing records. Fishing is simulated in the projection period by allocating effort to 6x6 nautical mile grid cells, the scale at which commercial catch and effort data are reported. Within each grid cell, effort is then allocated to reefs proportionally, according to reef perimeter. The amount of effort on each reef is then used to determine reef-specific catch, which then is used by the biological model to update the fish populations throughout the simulation.

DISCUSSION:

Phil Cadwallader: Does ELFSim include such shoal areas?

Rich Little: The reefs included in ELFSim are those that are identified on the GBRMPA mapping systems and a number of ‘virtual’ reef areas identified by catch of fish in areas that do not have an identified reef.

John Heard: Does the model take into account unusual weather events?

Rich Little: Weather events can be taken into account. There are oceanographic models of the GBR that includes information about weather patterns from many years which should encompass such events.

John Heard: Hooks used in the commercial fishery catch a lot of smaller fish as well. There may be some poor assumptions on hook selectivity in the model.

Rich Little: Due to minimum size limits, small fish are assumed to be caught at some rate and these are released. Some of these released fish survive, and some do not. This is how fishing mortality is approached by the model.

John Heard: Researchers may have estimates of hook selectivity for smaller fish that may not be realistic. A lot more smaller fish are taken by 9.0 hooks.

Rich Little: A high proportion of young fish are female, and older fishes are mainly male. Not all females in the model are able to spawn, but there is an increasing proportion that do as they get older. From information on the numbers of fish of a particular sex and size on a reef the model estimates how much larvae are produced from this reef. We are not certain about what happens to the larvae after that. The model includes information on migration of larvae from spawning reef to settlement reef and how many survive given what information we have on larvae dispersal and survival.

John Heard: If little is known about what happens to the larvae, where they settle and how many survive, how do you know the model is giving realistic answers?

Rich Little: There is some information on reproduction, survival, movement of larvae and settlement. The model uses a range of values for dispersal, survival, etc. The use of ranges allows the model to consider the uncertainty in our knowledge of larval dispersal and survival.

John Heard: Is recruitment and migration of larvae important to the overall management of the whole GBR?

Rich Little: It is important information to have. For example, if you consider that reef closures of source reefs or those that provide relatively more larvae to the system, may be relatively more beneficial to the whole GBR than closing sink reefs (reefs where larvae tend to settle more readily than other reefs).

Kath Kelly: Can the model include some patterns of connectivity between reefs (sink and source reefs)?

David Williams: There is some information on connectivity between reefs in the GBR from CRC Reef/JCU research of Tom Hardy’s group, but the computational time this takes to run these models is very high, and would significantly slow down ELFSim if it were incorporated.

Rich Little: The variable that has the most effect on the outcomes of the model are the starting population size. It is based on the size of the reef and latitude, but this is a broad brush view.

Gavin Begg: There is a large amount of uncertainty in this model, but it is the best information available, and in the future when we do have more information on some of these features we can include these into the model to make it more realistic.

Richard Hack: Wire netting cods come into an area of the Capricorn-Bunkers around Christmas in their 1000's. This is also when the Red Throat Emperor spawn and the aggregations of the two fish species are somehow related. If these cods are eating the small Red Throat Emperor then by protecting these cods with the new size limit at 38 cm their numbers will increase which will possibly have negative effects on Red Throat Emperor numbers.

Gavin Begg: This brings up the importance of ecosystem effects on fisheries. We don't have sufficient information about these types of effects to address them with this model.

John Heard: The stakeholders who are asking the questions in this forum will bias the answers from an MSE as the answer will be gauged at this question.

Mark Elmer: For this fishery, it is quite surprising that the goals of the various stakeholders are actually quite similar to each other. Compared to other fisheries such as the billfish fishery where management objectives for the various stakeholders vary widely and often conflict with each other. This is evident in past F&F MSE stakeholder workshops where there was fairly quick agreement on what objectives should be tested for ELFSim, although the reasons may be different.

Rich Little: As ELFSim models 1000s of individual reefs, the computational time to run evaluations is very high. We are always looking for ways to speed up the model without compromising the information contained in it, but there is still consideration on what can be evaluated due to constraints on computational time.

Fishing effort models

Presenter – Barry Goldman and Nick Ellis

The Effort Allocation model of ELFSim allocates fishing effort to reefs, on a monthly time step, based on historical CPUE and effort history. It is based on the assumption that distribution of CPUE in the past will be a good predictor of the distribution of effort in the future. However, the focus has been on the fish not the fishers. Not modelling the fishing fleet has been a common reason for failure of management strategies to meet their objectives, therefore, we have been working for the last year to develop a complimentary 'vessel dynamics' model to integrate within ELFSim. This may provide a more realistic model of fishing effort that will be more responsive to changes in management and fish populations. The vessel dynamics model will take account of the physical characteristics of the GBR such as reef size and location, presence of other boats, past fishing successes, etc.

DISCUSSION:

Mark Elmer: Although catch quota's have now been introduced to the reef line fishery, effort restrictions are still an important feature of management. For example QDPI&F

still has in place limited entry license restrictions, limits on numbers of fishing platforms (dories), as well as bag limits for the recreational sector. Hence, it is still important to keep effort controls in the model.

Barry Goldman: The vessel dynamics model looks at the movements of individual boats in the fishery that can change the reefs they fish, what fish they are targeting, etc.

Vern Veitch: The vessel dynamics model is based on the commercial fishing fleet. QDPI&F research indicates that recreational fishing in Queensland is about 45% of the total catch of reef fish, and is therefore a significant and important sector in the fishery. Therefore, ELFSim to be most realistic should also consider the vessel dynamics of the recreational fishing fleet. But how can you model the important recreational fishers if you don’t have information on recreational fishing behaviour?

Gavin Begg: There is not as much information available on the fishing behaviors of the recreational fishing sector. Also, it would not be feasible to model 1000’s of individual recreational fishers in the same way as the commercial fleet due to excessive computation time that would be required. RFish information collected by QDPI&F is incorporated in ELFSim.

Vern Veitch: Could remote sensing technology be used to get information on recreational boat trips out to the reef?

Bill Sawynok: At some simple level we should be able to include individual recreational fishing behavior in the model.

Vern Veitch: There are 9000 recreational boats registered in Townsville, however, only 161 of these can go out at any one time due to car parking restrictions in Townsville.

Richard Hack: Could Air Sea Rescue trip sheet data be used to provide information on recreational fishing trips? It would give information on how many boats, how many fishers on each boat, and where they were going fishing on any particular day.

Les Pollard: Fishing operations also need to consider other economic and social factors such as retaining their regular crew for the long term. This is especially the case for larger operations that have a large crew of four or more people. In times of low prices for fish or now when the trout quota has been filled, it is important for an operation to remain fishing, even though they may not actually be making money to ensure that their regular crew has continued employment. Otherwise these crews would be forced to seek jobs elsewhere, and when prices rice again, an operation would be without crew and would not be able to take advantage of the high prices.

John Heard: Market forces may also have a big influence on the behaviour of fishers; how is this included in the model? The model is missing information on market forces. For example, commercial fishers are not taking large fish due to the quota as plate sized fish have higher beach prices. Economically, therefore, it is better to take smaller fish and less large fish to fill your quota.

Richard Hack: The live fishing industry has seen a decrease in the amount of product being filleted. This trend may now be increased due to the introduction of quota as fishers will be focused on gaining the highest price possible for their product, hence they will be focusing on live fish for common Coral Trout and whole iced fish for other species such as Red Throat Emperor. Red Throat Emperor doesn’t really need management as there will be less commercial fishing effort for Red Throat Emperor.

The model needs to consider such influences as market forces on fisher behaviour and effects of this on management.

Les Pollard: For commercial fishers, decisions on what reef to fish on any particular day is mainly based on economics – you need to make a pay. This may be a 100 live common Coral Trout per day for a four dory operation. A catch for a ‘good’ day on a commercial operation may be 150 live trout per day for a 4 dory operation (25 fish per fisher).

Richard Hack: A good day previously was around 300-400 kg of all fish per day (fishing from main boat only), but now more like 250 kg per day.

Richard Hack: Commercial fishers indicated that they are not targeting Red Throat Emperor as much as previously due to decreased quota’s. Logbook records of catch of Red Throat Emperor will not be a good indicator of true CPUE.

Mark Elmer: There will be significant changes to CPUE patterns of Red Throat Emperor as a result of the quota system.

Mark Elmer: Charter fishing was reported in the same grid patterns as for commercial fishers.

George Leigh: Red Throat Emperor CPUE are fairly steady over time from logbook catch records although, there are some slight changes.

John Heard: Red Throat Emperor catches in logbooks is not a good measure to use for the health of the fishery as catch has declined since live fishing has increased. This is because fishers keeping live fish tend to fish differently and don’t want to catch Red Throat Emperor. Hence, the declines in Red Throat Emperor CPUE in recent years that are reported in logbooks are not reflective of Red Throat Emperor populations, but a change in practice to live fishing. CPUE for Red Throat Emperor may increase again with the introduction of catch quotas as fishers may target them when their Coral Trout quotas are filled.

Richard Hack: For ice boats (selling whole reef fish on ice) Red Throat Emperor is the staple catch for these operations.

Gavin Begg: CPUE may not be a good indicator of abundance at all as CPUE can be maintained despite declines in population (hyperstability) for various reasons. The MSE is not necessarily using this as an indicator of abundance, but more as an indicator of the economic aspects of the fishery.

Kath Kelly: CPUE for Red Throat Emperor is not a reliable indicator of abundance compared to those species that are not targeted. If you did want to look at CPUE data may be better to look at the top 30 boats.

Mark Elmer: There will be significant differences in fishing behaviour with new quota regulations in the fishery.

Gavin Begg: When the project started a couple of years ago, the management strategies that were being considered at the time were focused on effort restrictions. This strategy has now changed to catch quotas. Currently, ELFSim can not directly evaluate catch quotas, however, this does not diminish the importance of this project as we can still use the framework to look at Red Throat Emperor, and catch quota’s will be incorporated into the model in the future.

John Heard: The behaviour of commercial fishers has changed now that quota restrictions are in place. For example, an operation that has Coral Trout quota to fill may release caught Red Throat Emperor to maximize the profits for that trip as they don't wish to waste time, and holding space for lesser value product. However, they may target Red Throat Emperor later in the year once their trout quota has been filled, or if the market for trout drops for some reason such as SARS, transport problems, etc.

Richard Hack: Spanish mackerel are being caught at the moment, but they are not taking them as fishermen don't want to fill their small Spanish mackerel quota. Therefore, they are releasing 10 kg mackerel, even though they are thought to not survive release. Additionally, for operations that had to buy catch quota to be viable they must also catch enough to cover those costs. For smaller operations fishing for dead product, buying quota is the same price as for those fishing live, therefore it has an even greater effect with lower prices for product.

Danny Brooks: In response to comments that no one wants Red Throat Emperor quota, QDPI&F is fielding many calls from fishers enquiring how they can find Red Throat Emperor quota to buy.

John Heard: Some commercial operations are holding onto Red Throat Emperor quota for use in case the market for common Coral Trout declines (for example in response to SARS) and they need a fallback product to keep their operations running.

Les Pollard: Boats geared for live fishing tend to have shorter trips (less than 10 days) due to limiting mortality of live fish on board. Hence, you are limited to make a pay for the trip in 10 days. This requires focusing on fish species that will bring in maximum dollars, such as live trout.

Richard Hack: Commercial operations that focus on whole fish on ice are limited to trip lengths of 4 days.

Terry Must: Bowen boats tend to fish shorter trips as they are generally smaller boats. Gladstone boats tend to have longer trips as they have further to travel out to the reef. Mackay has traditionally been a bigger boat port and hence has longer trips compared to Bowen boats.

Les Pollard: An operation would fish one session minimum at a particular spot before making a decision to move on if catch is not economical. They would generally avoid reefs where there are boats fishing already. In previous times there was a gentleman's agreement among commercial fishers that if you came to a reef where a boat was fishing, information would be exchanged between the skippers as to where they had been, and where they were going, and both operations would fish in different areas so as to avoid fishing the same reefs. Since the early 1990's this practice has not been continued with an overall effect of increased effort on reefs. Around a reef that is fishing well, the area of good catches is around 10 miles.

Introduction to Management Strategy Evaluation (MSE)

Presenter – Gavin Begg and Rich Little

Management Strategy Evaluation (MSE) varies from more conventional approaches to fisheries stock assessments in several ways. First, MSE is focused on evaluating the medium to long term performance of management strategies, rather than on short term assessments of regulatory practice. Second, MSE is comparative rather than prescriptive, seeking to compare likely outcomes of a range of management scenarios rather than to prescribe actions that should be taken under an existing regulatory framework. MSE seeks to compare the performance of a range of candidate management strategies in consideration of a diversity of stakeholder objectives, including social, economic and biological. MSE provides a system for comparing the performance of alternative management strategies against different stakeholders' objectives based on a common currency across all or most objectives.

Management Strategy Evaluation requires a number of key elements for successful application. First, it is necessary to have the capacity to simulate the characteristics of the harvested stock or stocks (a biological model), the fishery (an effort model) and the interactions between the two. The model must be a credible representation of the actual biological and fishery system, requiring considerable amounts of biological information and other data. Second, MSE requires the identification of quantitative management objectives, performance indicators and (preferably) target values for those performance indicators. Finally, specification of a range of alternative management strategies or scenarios by which the objectives might be achieved is required. The management strategies compared must be both feasible and likely to be supported by stakeholders to ensure that the MSE process is useful.

Thus, MSE requires not only a credible research base but also the active engagement of a diversity of stakeholders in the formulation of management objectives and strategies.

DISCUSSION:

Bob Grimley: Is the level of compliance considered when looking at objectives?

Gavin Begg: A parameter for infringement is included in the model that can be set at various levels.

Rich Little: Interestingly, evaluations of ELFSim with Coral Trout show that levels of infringement up to 20% in green areas does not seem to have significant effects on results of scenarios (with effort and area closures included). This indicates that these strategies are fairly robust to high levels of infringement.

Phil Cadwallader: GBR managers and surveillance officers would be able to comment on what levels of infringement would be realistic.

Annabel Jones: ELFSim can also provide information back to managers as to what management strategies will be most robust against higher levels of infringement.

John Heard: In a MSE example of maintaining spawning stock biomass (SSB) – how do you measure SSB on the green reefs and what can you do about it if the objectives are not met, given that there is no fishing on green reefs?

Rich Little: It is not necessary to measure SSB on every green reef on the GBR as you can relate information from the reefs that are monitored to those that are not. A further consideration is that there is some connectivity between reefs, so fishing on fished or blue reefs can effect on the stocks on green reefs; therefore, fishing pressure on open reefs could reduce SSB on closed reefs. An objective of a healthy level of SSB on green reefs is not as unachievable as it seems. For example, inclusion of a relative level of SSB (i.e., 80% of SSB on a virgin or unfished reef) in the objective recognizes that green reefs may not have the same levels of fish abundance as they may have prior to any fishing pressure due to illegal fishing and or fishing on open reefs.

Vern Veitch: This raises the need to consider carefully what can be measurable for reef fish stocks, and how many reefs do we need this information from.

Simone Retif: We need to consider export provisions and the legislative framework for the MSE.

John Heard: If the investment warning for the fishery was adhered to, there would not be the problems that we have in the fishery today.

Danny Brooks: Agreed with this statement.

Management objectives

Presenter – Gavin Begg

This section aims to identify a clear set of quantitative management objectives for Red Throat Emperor that are agreed to be of importance to the collective group of stakeholders present at this workshop. Discussion will centre on how stakeholders would like to see the fishery in 10 to 20 years time, and beyond? What management objectives do various stakeholders feel are important to the fishery? These discussions will help guide researchers as to what management strategies to test with ELFSim, and the direction of future research.

Broad objectives identified by stakeholders for Red Throat Emperor

Broad Objective 1

Bill Edwards: For charter fishers to be able to catch Red Throat Emperor above the minimum size limit for 90% of the time (i.e., only throwing 1 out of 10 fish back), up to the bag limit, for 60 to 70% of the time.

DISCUSSION:

John Heard: At the current minimum legal size for Red Throat Emperor this will be unachievable.

Richard Hack: There are regional differences in the Red Throat Emperor fishery. For example, in the Capricorn-Bunker area, 50 to 60% of Red Throat Emperors are under-size. Now that minimum legal size limits for Red Throat Emperor are 38 cm fishers are now releasing 30% of their catch.

Mark Elmer: Discard rates for reef fish are around 50 – 60%. The charter fishing sector may be able to adopt practices to address this problem.

Rich Little: In the southern areas, would you be happy to have around 20% of Red Throat Emperor caught being undersize?

Richard Hack: In the southern areas of the GBR, commercial fishers would be happy with 70% retention of legal sized Red Throat Emperor.

John Heard: For larger operations in northern areas, they would be happy with 5% of undersized Red Throat Emperor in their catch.

Terry Must: Due to the low prices for Red Throat Emperor, fishermen don’t want to fish in areas where there are a lot of undersize fish as you would be using up bait on fish that had to be released. His operation would move from an area if they were catching too many undersize Red Throat Emperor.

Ashley Williams: The Capricorn-Bunkers area may be different to other areas of the GBR for Red Throat Emperor and may need special management considerations.

<u>Broad Objective 2</u>
Commercial fishers: The Red Throat Emperor fishery become and remains an economically viable fishery.

DISCUSSION:
Rich Little: Do commercial fishers want stable catches?

Richard Hack: The fishery is very changeable; there is no stability in the Red Throat Emperor fishery now.

Terry Must: For over 10 years, the catch has been reasonably stable. There has been some variability such as in 1997, but overall it has been fairly stable.

Les Pollard: The fishery is very variable over time. In some years, you can't catch fish for months and this may not be due to there not being any fish in the area. This can change quickly to the situation where catches are good. This has changed a little over recent times though.

John Heard: If fish are not biting in a particular area, commercial fishers will move to somewhere else where they will catch fish. If people go to a reef and not catch fish it should not be concluded from this that there are no fish in that area.

John Heard: Putting a % of catch on an objective for the commercial fishery is not very useful as it is so variable over time. For example in an area, catch would not be stable every year.

Les Pollard: Commercial fishers want sufficient numbers of brood stock of all fish, but also to be an economically viable fishery. Different types of commercial fishing operations will have different levels of what they feel would be economically viable. For example, those that fish for live fish compared with those that sell their product whole on ice. Another example is those operations with no or very few dories and those with multiple dories.

Les Pollard: It is difficult to put a number on how many legal size to undersize Red Throat Emperor a commercial fisher would like to catch when considering the whole GBR as this can vary widely in different areas. In areas where there are a lot of small fish, you will catch more undersize fish. In areas where there are larger fish, you will catch less undersize fish.

Les Pollard: For a live fishing operation that doesn't necessarily target Red Throat Emperor (as they are a lower value product and are difficult to handle) values for a 'good' day are 25 cartons per day (10 kg cartons) for four dories, before the introduction of the green zones in the 1980's. Now, 15 cartons of Red Throat Emperor per day after the Marine Park zoning came into effect is a good day. Today, compared to the same dollar value you would get for Coral Trout fillet, 40 cartons of Red Throat Emperor per day would be required to be economically viable. With prices of common Coral Trout currently, fishermen want to catch more common Coral Trout than Red Throat Emperor. But this may change overnight and Red Throat Emperor may again be targeted. Red Throat Emperor is a buffer for bad times in the trout fishery.

Gavin Begg: Is CPUE a good proxy for economic viability for the commercial fishery?

Les Pollard: For commercial fishing, economic viability is to catch fish in the least amount of time.

Terry Must: In the Bowen area commercial fishers can only target Red Throat Emperor for a couple of months of the year, when they are usually aggregating to spawn. The target for this operation is around 600 kg of Red Throat Emperor per year.

Richard Hack: Isn't the objective of spawning closures being compromised by targeting Red Throat Emperor when they are gathering?

John Heard: Spawning closures are mainly to protect Coral Trout, but it stops other fish being targeted at that time.

Les Pollard: Release mortality of Red Throat Emperor is high, as they are hard to deflate. Commercial fishers need to keep a little bit of Red Throat Emperor quota for by-catch when targeting trout.

Richard Hack: Disagreed with this statement.

Mark Elmer: Red Throat Emperor is a domestic supply product, and as such needs continuity of supply.

Les Pollard: The beach price for Red Throat Emperor is fairly stable throughout the year. For his operation, when targeting Coral Trout, they always catch some Red Throat Emperor (usually about 8 cartons per trip).

Terry Must: Coral Trout will not be available in Australia due to the high demand and prices paid for live fish, now that there is a catch quota on this species. Demand for Red Throat Emperor should increase to supply the domestic market with reef fish. However, fishers will need to target Red Throat Emperor when they can get maximum CPUE to make targeting of Red Throat Emperor economically viable.

Gavin Begg: What years were considered good for Red Throat Emperor catch as a reference for what would be considered as economically viable?

Richard Hack: 2000 was a good Red Throat Emperor year for the southern areas.

Terry Must: 1997 was a good year for the Bowen area (Cyclone Justin).

Richard Hack: In 1997, Red Throat Emperor disappeared from the southern areas.

Les Pollard: There were fairly stable catches of Red Throat Emperor over the years 1993-1995.

Mark Elmer: To take account of the different types of commercial fishing operations would it be possible to use a subset of the boats in the model? For example, could we exclude those smaller non-active boats to ensure that CPUE used for Red Throat Emperor are valid for active boats?

Rich Little: This would complicate the model by adding new types of fishing sectors with different behaviors.

Les Pollard: Without being able to fillet fish, Red Throat Emperor would be totally unviable as a targeted fish product as trip lengths would be too short (if keeping whole fish on ice) to be able to catch a viable total catch for a trip to cover travel costs.

Terry Must: Agreed with this statement.

Julie Pollard: There should be better CPUE for Red Throat Emperor than the early 1990's as there are now more green areas. The extra protected areas should see increased numbers of Red Throat Emperor on the areas left open and CPUE should be better than before. Maybe the objective should be set at around 150% of the 1995-1996 CPUE levels.

Mark Elmer: 150% may be difficult to achieve, maybe a 100 or 110%?

John Heard: Some commercial fishers would be happy with 80% of 1995-1996 catches.

Martin Russell: If CPUE for Red Throat Emperor has dropped from 1995-1996 levels this would indicate to managers a potential decline in stocks and hence there may be cause for concern for this stock.

Mark Elmer: A 80% drop in CPUE would be cause for concern for ReefMAC.

Rich Little: We can evaluate this objective with CPUE levels of 80%, 100% and 150% of 1994-1996 CPUE levels for Red Throat Emperor.

Les Pollard: A number of commercial fishers indicated that they would not reach their TAC in every year for a number of reasons. However, they would want the fishery to be in a healthy state such that they would be able to catch their quota of Red Throat Emperor in every year if they wanted to do so.

Terry Must: Agreed with this statement.

<u>Broad Objective 3</u>
Martin Russell: The Red Throat Emperor stock is not decreasing.

<u>Broad Objective 4</u>
Kath Kelly: Ensure and maintain an economical, ecological sustainable fishery.

<u>Broad Objective 5</u>
Simone Retif: Ensure Red Throat Emperor stocks are maintained at sustainable levels.

<u>Broad Objective 6</u>
Danny Brooks: Sustain SSB of Red Throat Emperor to appropriate levels, although we don't know what that level should be yet.

<u>Broad Objective 7</u>
Danny Brooks: Sustain available biomass (AB) at appropriate levels.

<u>Broad Objective 8</u>
Danny Brooks: Maximise economical viability and ensure satisfaction of fishers.

<u>Broad Objective 9</u>
Anne Clarke: Develop profitable fishing industries in the long term.

DISCUSSION:
Barry Goldman: Some social features to consider. How many people do we want to have in the various fishing sectors? Do we want to keep a stable number of people in the industry?

John Heard: All of the objectives discussed thus far focus on the fish stocks but do not consider the fishers.

Broad Objective 10
Malcolm Dunning: Maintain the available catch distributed across the GBR as they are now. Don't want concentration of fishers in one region.

Broad Objective 11
David Bateman: Maintain a quality trip for recreational fishers.

DISCUSSION:
Bill Sawynok: Most recreational fishers (with boats) don't have boats big enough to get to areas where they can target Red Throat Emperor, and if they do, they wont be targeting Red Throat Emperor, but would target red emperor and Coral Trout. Many recreational fishers also tend to target nannygai these days. Red Throat Emperor is generally considered to be by-catch.

Rich Little: Would recreational fishers like to see the catch composition be mainly common Coral Trout? For example, would two or three common Coral Trout per person per day be considered a 'good' catch?

John Heard: This needs to be considered on a regional basis, as fishermen from different regions will have different expectations.

David Bateman: As recreational fishers aren't trying to make a profit out of fishing, there are other outcomes to a fishing trip than just catching fish. For recreational fishers the important features of a trip are to catch some fish, catch large fish, etc. There are some fishers who will no longer come to north Queensland (with their boats) to fish now that the new area closures are in place. Recreational fishers want to catch eatable fish such as common Coral Trout and red emperor, and catch some big fish (around 4 kg for these species). Recreational fishers will target Coral Trout up to their bag limit, then they may target other fish like Red Throat Emperor to fill their reef fish bag limit. Red Throat Emperor would be the second most targeted fish.

Bill Sawynok: A look through fishing magazines demonstrates the importance of Red Throat Emperor to the recreational fishery. All the photo's in these magazines are of common Coral Trout and red emperor, with very few Red Throat Emperor.

Bill Sawynok: Recreational fishers do consider economic issues such as the price of fuel, etc. For example, it may cost $200 for fuel to get out to the reef, therefore fishers may expect $200-$300 of fish to be caught to make the trip worthwhile.

David Bateman: In saying this, some fishers are turning to more economical gears such as 4 stroke motors and taking out extra people to spread costs.

Bill Edwards: For charter fishers there is some variation as to their expectations from a trip. There will be some who just want to enjoy the experience, but there are others that want to catch lots of fish. This would be the same with recreational fishing trips.

David Welch: Spear fishers would like to be able to catch trophy sized fish. Spear fishing tends to be a very selective fishery. Most spear fishers won't spear a fish unless it is a big fish. With respect to Red Throat Emperor, these are challenging to spear as they are difficult to approach underwater but are good eating. Would like to see more Red Throat Emperor when diving.

Barry Goldman: What is a big fish for Red Throat Emperor?

Bill Sawynok: For Red Throat Emperor it would be a fish over 50 cm.

David Welch: For spear fishers to be able to catch 1 Red Throat Emperor over 50 cm in every 10 Red Throat Emperor retained would be considered satisfying.

Bill Sawynok: For recreational fishers 1 fish over 50 cm each trip would be satisfying.

Broad Objective 12
Bob Grimley: Ensure access to the fishery is fair.

DISCUSSION:
Bob Grimley: We need to include a way of measuring effectiveness of compliance of each strategy evaluated (including cost of enforcement). This may not be a real issue today as enforcement costs are covered by the government. But if costs of compliance were recovered from the fishing sectors, stakeholders would have to consider this.

Conservation Objective
Julie Pollard: The conservation aspects of the fishery are probably being met by the objectives already on the table.

DISCUSSION:
Mark Elmer: Concern that for all the objectives discussed, that the time frames put on them are unrealistic in wanting to meet each objective every year, or 9 out of 10 years. In such a variable environment such as the GBR it may be better to look at more conservative values, like 50% of the time.

MSE Red Throat Emperor

Presenter – Gavin Begg

From the broad objectives identified above the following quantitative management objectives were identified by the stakeholders.

#	Objective	Comm.	Rec.	Charter	DPI&F	GBRMPA
1	9 in 10 RTE are legal size 60% of the time			X		
2	RTE becomes and remains viable economically	X				
	To develop profitable fishing industries			X	X	
3	Maintain available catch across the regions				X	
	Maximise CPUE: commercial CPUE >80% 1994-1996 levels 90% of the time	X				
	Maximise CPUE: commercial CPUE >120% 1994-1996 levels 90% of the time	X				
	Maximise CPUE: commercial CPUE >150% 1994-1996 levels 90% of the time	X				
4	Reduce number of undersize fish caught	X				
	Reasonable change of catching big fish, including RTE		X			
	In South <30% are undersize 90% of the time	X				
	In North <5% are undersize 90% of the time	X				
5	To catch the quota that is available 100% of the time	X				
6	RTE stock is not decreasing					X
	Maintain spawning biomass at appropriate levels				X	
	Maintain available biomass at appropriate levels				X	
	To ensure and maintain ESD					
	To ensure that RTE stocks remain at					

	ecologically sustainable levels		
	Total and spawning biomass over all reefs is not less than current total and spawning biomass (possibly by region) 100% of the time		
	Total and spawning biomass over all reefs is not less than current total and spawning biomass (possibly by region) 50% of the time		
	Total biomass >40% virgin biomass over all reefs (possibly by region) 80% of the time		
7	Ensure satisfaction of fishers	X	X
	Quality experience	X	
	1 RTE retained in catch >50 cm per trip		
8	Maintaining access to fishing areas	X	
	No more net area closures		
9	Effective enforcement		X

NB – Objectives highlighted with shading are those that can be evaluated with ELFSim.

Presenters

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Stakeholders

Name	Institute	Affiliation
Danny Brooks	Queensland Department of Primary Industries and fisheries	Manager
Mark Elmer	Queensland Department of Primary Industries and fisheries	Manager
Anne Clarke	Queensland Department of Primary Industries and fisheries	Manager
Malcolm Dunning	Queensland Department of Primary Industries and fisheries	Manager
Kath Kelly	Queensland Department of Primary Industries and fisheries	Manager
Martin Russell	Great Barrier Reef Marine Park Authority	Manager
Phil Cadwallader	Great Barrier Reef Marine Park Authority	Manager
Simone Retif	Department of Environment and Heritage	Manager
Bob Grimley	Queensland Boating and Fisheries Patrol	Surveillance
John Heard		Commercial fisher
Terry Must		Commercial fisher
Les Pollard		Commercial fisher
Julie Pollard		Commercial fisher
Richard Hack		Commercial fisher
Lynette Hack		Commercial fisher
Vern Veitch	Sunfish	Recreational fisher
David Bateman	Sunfish	Recreational fisher
Bill Sawynok	InfoFish	Recreational fisher
George Leigh	Queensland Department of Primary Industries and fisheries	Scientist
David Welch	CRC Reef/QDPI&F	Scientist
David Williams	CRC Reef Research Centre	Scientist

CRC Reef Fishing & Fisheries FRDC Multi-species Project
Management Strategy Evaluation Stakeholder Workshop
10 November 2004

MINUTES

Thank you

On behalf of the CRC Reef Research Centre's Fishing and Fisheries (F&F) Team, I would like to thank you for your continued participation in the Fisheries Research and Development Corporation (FRDC) funded Multi-species Stakeholder Workshop. Your time, expertise and knowledgeable discussion made this Workshop of immense benefit, not only to the research we are conducting, but to the management process for the Reef Line Fishery of the Great Barrier Reef.

Your input and thoughtful suggestions at the Workshop have helped us immensely in providing relevant potential strategies for managing the fishery into the future.

The management strategies identified by you at this Workshop will be instrumental in providing a framework for future evaluation of management strategies that we will present at a future stakeholder workshop.

Gavin Begg
F&F Project Leader

INTRODUCTION

This document records the ideas and discussions that emerged at the Multi-species Stakeholder Workshop on the 10th November 2004 at the CRC Reef Research Centre, Townsville.

This document is not meant to be an exhaustive record of all the discussions that occurred at the Workshop, but a synopsis of the main opinions expressed by various stakeholders present. The opinions recorded here may not be those agreed upon by all the stakeholders at the Workshop, or by CRC Reef, but were brought up by one or more stakeholders, and have been recorded here as a record of the discussions.

The Workshop was aimed at discussing with stakeholders potential management strategies that they would like to see evaluated for the GBR Reef Line fishery with respect to common Coral Trout and Red Throat Emperor. The strategies identified at the Workshop will provide the actions upon which the management objectives identified at the last workshop can be tested in a MSE.

PRESENTATIONS

Welcome

Presenter – Gavin Begg

Welcome to this Multi-species Stakeholder Workshop and thank you for your participation, especially to those who have travelled from afar to attend.

This workshop is part of the FRDC funded multi-species research project being conducted by the CRC Reef F&F team and CSIRO. It builds on previous research of the Effects of Line Fishing (ELF) Project and previous stakeholder workshops in 1999 and 2000, when a MSE for Coral Trout was developed and completed.

This workshop continues on from the more recent workshop held in August 2004 where we documented a list of management objectives identified by stakeholders as important to the GBR Reef Line fishery for Red Throat Emperor. In this Workshop we hope to identify management strategies that stakeholders feel may be useful to meet these management objectives.

Overview of Coral Trout and Red Throat Emperor biology, fishery and management

Presenter – Gavin Begg

Common Coral Trout and Red Throat Emperor are the two most targeted fish species in the GBR Reef Line Fishery. Together they make up the majority of reef fish catch in the commercial, charter and recreational fishing sectors. Efficient management of fish species such that fishing remains sustainable in the long term is highly reliant on a sound knowledge of the fishery and the biological characteristics of the species being managed. These characteristics include information on age, growth and reproduction. Our current knowledge of the biology of these species is good in some areas, but poor in others. Here we present what we know about the biology and fishery of common Coral Trout and Red Throat Emperor, as well as identifying what we don’t know and how this information may affect their management.

DISCUSSION:

No discussion recorded.

Revision of management objectives for Red Throat Emperor

Presenter – Rich Little

At the previous August 2004 stakeholder workshop a number of management objectives for Red Throat Emperor were discussed. These were revised and listed in Table 1. A total of 13 management objectives were identified and varied across stakeholders from aspects of conservation to exploitation. Notably, the objectives were specified in terms of quantifiable and measurable indicators that can be evaluated within the ELFSim modelling framework.

Clarification was sought on the time periods over which all the management objectives were to be assessed, and the spatial division between the northern and southern GBR for two of the management objectives related to the magnitude of the undersize catch. Two time periods were agreed upon: 1) 2010-2015; and 2) 2020-2025. These were considered to represent both short- and mid- to long-term objectives for the fishery. The spatial division for the northern and southern GBR was agreed to occur at 22°30'; thereby capturing the natural division between the inshore Capricorn-Bunkers reefs in the southern GBR and the more offshore northern reefs of the GBR. Growing evidence from fisher’s reports and independent scientific studies supports this division, with changes in fish population structure across the Capricorn Channel.

Table 1. Management objectives for Red Throat Emperor defined at the Multi-species MSE Stakeholder Workshops. These objectives will be evaluated using the ELFSim models and form the basis of the multi-

species MSE. MLS = minimum legal size (38 cm). Northern – Southern GBR regions separated at 22°30'. Time periods to be evaluated: 2010-2015; 2020-2025.

Management objective (Red Throat Emperor)	Indicator	Stakeholder
9 in 10 Red Throat Emperor caught >MLS 60% of the time	P(retain/total > 0.9)	Charter
Commercial CPUE >80% 1994-1996 levels 90% of the time	$P(CPUE/CPUE_{1994-1996} > 0.8)$	Commercial
Commercial CPUE >120% 1994-1996 levels 90% of the time	$CPUE/CPUE_{1994-1996}$	Commercial
Commercial CPUE >150% 1994-1996 levels 90% of the time	$CPUE/CPUE_{1994-1996}$	Commercial
In northern GBR <5% of catch is <MLS 90% of the time	P(discard/total < 0.05)	Commercial
In southern GBR <30% of catch is <MLS 90% of the time	Fish > 38 cm	Commercial
To catch the quota that is available 100% of the time	P(retain/quota > 1)	Commercial
Total biomass (TB) ≥ TB_{2000} 100% of the time	$P(TB/TB_{2000} > 1)$	GBRMPA
Spawning biomass (SB) ≥ SB_{2000} 100% of the time	$P(SB/SB_{2000} > 1)$	GBRMPA
Total biomass (TB) ≥ TB_{2000} 50% of the time	$P(TB/TB_{2000} > 1)$	DPI&F
Spawning biomass (SB) ≥ SB_{2000} 50% of the time	$P(SB/SB_{2000} > 1)$	DPI&F
Total biomass (TB) > 40% TB_{virgin} 80% of the time	$P(TB/TB_{virgin} > 0.4)$	DPI&F
1 Red Throat Emperor caught each trip > 50 cm	Fish > 50 cm	Recreational

* Total biomass represents fish > 20 cm; also examine available and spawning biomass in blue and green reefs; proportion of recreational retained catch > 50 cm [1 in X number caught to expect RTE > 50 cm (> MLS & > 50 cm in numbers)]; reference virgin year as well as 2000 for relevant objectives.

Many of these objectives are multi-faceted in that they may have goals that are applicable to various stakeholder groups. It was also interesting that a regional (north / south) component to some objectives was identified.

DISCUSSION:

Management objectives

Rick Hack: With regard to the objective to catch 150% of the 1994-1996 catch of Red Throat Emperor, what is the current catch of Red Throat Emperor compared with previous years?

Danny Brooks: It is unlikely that the quota will be met this year.

Rick Hack: The attitude towards commercial fishers by the other fishing sectors has changed a lot lately, where they now feel sorry for us with the new restrictions put in place.

Danny Brooks: What year had the highest CPUE for Red Throat Emperor?

Rick Hack: 1996 was the best year for Red Throat Emperor, even though boats were still chasing Coral Trout.

Rich Little: Also, 1997 was the year of Cyclone Justin when Red Throat Emperor catches were seen to go up and Coral Trout catches down. But there was some regional differences in these patterns.

Ashley Williams: It is around the Capricorn-Bunkers area that you seem to get a significant difference in population characteristics of Red Throat Emperor compared to all other areas of the GBR.

Les Pollard: We tend to avoid areas where we know we are going to catch a lot of undersized Red Throat Emperor.

Rick Hack: In contrast, we cannot move out of these areas where a lot of undersized fish are caught, and so need to consider this issue in the evaluation of potential management objectives and strategies.

Rick Hack: Recently, large areas of sea grass are degrading or have disappeared altogether in areas of the Capricorn-Bunkers. In his experience sea grass beds do not recover in these areas, which may be an important factor for Red Throat Emperor.

Rich Little: Are there incidents of coral bleaching in these areas?

Rick Hack: No.

Les Pollard: Sea grass beds were considered to be of less importance in his area of fishing.

David Bateman: Can the MSE model include cyclones?

Rich Little: The model can include catastrophic events such as cyclones that can include localized depletions. We can also include trends such as global warming.

Indicators

Rich Little: From the objectives given at the last meeting, the related performance indicators are naturally identified, but are these acceptable?

Danny Brooks: How is total biomass measured? Fishers are fishing very differently now with the introduction of the quota and if total biomass is measured from the total catch then it may not be a suitable indicator.

Rich Little: Currently our actual catch records for Red Throat Emperor only go to 2000, therefore we do not include any information for total biomass or catch post introduction of the quota. This is, however, an important point to remember when we do include catch information past 2004.

Rick Hack: Logbook data should not be used to indicate Red Throat Emperor catches as they are influenced by many things. Catches of Red Throat Emperor will now be very different with the introduction of quotas for reef fish.

George Leigh: What is the software capability of ELFSim? Can it test all the objectives indicated at the last meeting?

Rich Little: Most of the things that were identified at the last meeting are achievable with ELFSim.

David Bateman: Can ELFSim take into account various TAC levels as the quota may change in years to come?

Gavin Begg: One of the outputs from ELFSim is total catch, so we can see how this differs from what the quota is at the time. We can do this at the moment. We are now developing ELFSim further so that it includes quota as an input rather than an output. We will then be able to test different quota levels as a management strategy.

Rick Hack: We need to keep in mind what is a suitable time frame for these evaluations.

Les Pollard: I think it would be useful to project these evaluations to the year 2010.

Gavin Begg: As an example, for the Coral Trout projections, reference data (used to set parameters of the model) were used up to the year 1998 and projections were made to the year 2025.

Rich Little: It is up to the stakeholders to determine how long they want the projections to be for the MSE. It should be remembered though that the model takes some time for trends to settle down and become obvious – so longer projections are better. Ideally, you need 5-10 years to see if a management strategy is meeting an objective.

Les Pollard: So projections through to 2020 would be better than to 2010?

Rick Hack: This time frame may not be very helpful as fishers are interested in what we need to do now, and what sort of fishery we are likely to see next year, not in twenty years time.

Martin Russell: It is important to remember that we are probably not going to see the benefit from a management strategy for at least 5-10 years after its implementation.

David Bateman: Up to now we have had to wait a long time to see if a new management strategy was beneficial or not, which is unacceptable. There must be a way to monitor reefs to determine if a new strategy is working in a shorter time frame than previously?

Barry Goldman: This is the benefit of the MSE process as it allows us to evaluate the potential performance of a range of management strategies before they are put in place. This will provide managers with information that will help in their decision making and ultimately see acceptance of strategies that have a better chance of meeting management objectives.

Barry Goldman: Red Throat Emperor take around two years to reproduce and about six years to become fully available to the fishery. This will give an idea of the minimum time the population takes to ‘turnover’, and how long we may want to run the projections.

David Bateman: We need to get updates on how a strategy is going regularly, not just how the strategy will benefit the fishery a long time into the future. We need to have on-going monitoring of the fishery and the management strategies.

Gavin Begg: We will be running these scenarios in the next couple of months. This will give you some information on how the management strategies are likely to perform in the fishery 5-10 or 25 years into the future. We can also rerun these scenarios at a later date to see if the projections change with new information (data) included in the model.

Danny Brooks: I suggest that we run the scenarios for three different time periods to account for three generations of fish.

Rich Little: We can run the projections over a longer time frame (for example to the year 2025), but capture interim outputs throughout this time (for example from the year 2015). Please note that these models are not proposed to tell you where fish stocks are, or how many fish there are in the water. They are meant to indicate what strategies will work better against various management objectives.

Management strategies for Red Throat Emperor

Presenter – Gavin Begg

Strategies are the management tools used to meet management objectives. There are a number of strategies that are already in place for the GBR Reef Line Fishery. These were discussed, and a suite of potential management strategies of interest to stakeholders selected for testing by ELFSim.

A range of alternative management strategies to evaluate against the specified management objectives for the multi-species MSE were identified and agreed upon by the stakeholders at the Workshop. These strategies were considered appropriate for evaluating the management objectives of Red Throat Emperor. The management strategies identified were a combination of area and temporal spawning closures, effort restrictions, and legal sizes.

Initially, four levels of area closures were identified: 1) current closures under the new GBRMPA Representative Areas Program (RAP); 2) closures in place immediately prior to the implementation of RAP; 3) 50% of all reefs closed to fishing; and 4) 100% of all reefs closed to fishing (the latter being included for model validation and for testing trends).

Secondly, three levels of effort restrictions were identified: 1) 1996 fishing effort; 2) 50% of 1996 fishing effort; and 3) 150% of 1996 fishing effort. The 1996 fishing effort level was assumed to best represent current exploitation, although it was acknowledged that fishing patterns will most likely change with the recent introduction of the total allowable commercial catch (TACC).

Thirdly, three levels of spawning closures were identified: 1) current 9 day closures in October, November and December under the new DPI&F Coral Reef Finfish Management Plan; 2) total closures between September to November; and 3) no closures. The three month total closure between September to November was considered by stakeholders to better capture the peak spawning periods of both common Coral Trout and Red Throat Emperor, rather than the current closures which were designed only around common Coral Trout. The three month total closure and no closure strategies, however, are conditional upon the statistical analysis of commercial catch and effort data demonstrating changing catchabilities during the spawning seasons. If catchability is found to increase during the spawning seasons for common Coral Trout and Red Throat Emperor than these strategies will be evaluated. If not, there will be no need for these strategies to be evaluated as they will simply be acting as an additional effort restriction, which is already being assessed.

Finally, four levels of size restrictions were identified: 1) current minimum legal size of 38 cm; 2) minimum legal size of 35 cm; 3) appropriate minimum and maximum legal sizes based on biological principles of first maturity, protogyny and protection of larger males; and 4) no size limits. The appropriate minimum and maximum legal sizes for common Coral Trout and Red Throat Emperor will be determined from biological data collected as part of the Effects of Line Fishing Project.

A total of 15 management strategies, therefore, were identified to evaluate the management objectives for Red Throat Emperor; combining area and temporal spawning closures, effort restrictions, and legal sizes (Table 2). The final strategies to be tested were considered by the stakeholders to be the most appropriate considering the current management regime under which the fishery operates, while acknowledging the time constraints of the model for evaluating multiple management strategies.

Table 2. Management strategies for Red Throat Emperor defined at the Multi-species MSE Stakeholder Workshop, November 2004. These strategies will be evaluated using the ELFSim models and form the basis of the multi-species MSE. RAP = GBRMPA Representative Areas Program (current closures). Base case refers to current management strategies that the reef line fishery is operating under.

Area closure	Effort restriction	Spawning closure	Legal size	Comment
RAP	1996	3x 9 days (Oct-Dec)	Min – 38 cm	Base case – current (2004) strategies
RAP	0.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
RAP	1.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
Pre-RAP	1996	3x 9 days (Oct-Dec)	Min – 38 cm	
Pre-RAP	0.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
Pre-RAP	1.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
50%	1996	3x 9 days (Oct-Dec)	Min – 38 cm	
50%	0.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
50%	1.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
RAP	1996	None	Min – 38 cm	Conditional on catchability analysis (i.e., if *q* differs seasonally)
RAP	1996	Sep-Nov	Min – 38 cm	Conditional on catchability analysis
RAP	1996	3x 9 days (Oct-Dec)	None	
RAP	1996	3x 9 days (Oct-Dec)	Min – 35 cm	Previous size limit
RAP	1996	3x 9 days (Oct-Dec)	Min – Max	Conditional on slot size limits based on biological analysis; minimum to reflect size at first maturity; maximum to reflect sex ratios and size at sex change
100%	Zero effort	NA	NA	No fishing – control strategy

DISCUSSION:

David Bateman: Can the model consider gear restrictions such as one line per fisher in yellow zones?

Gavin Begg: This is basically an effort restriction strategy.

Danny Brooks: You can include restrictions on effort, but can you use controls on catch as a proxy for effort.

Rich Little: The model can not model an Olympic type catch quota where fishers fish without restrictions until an overall quota is reached, nor at this stage any quota based strategy. Also, it is not realistic to consider this Olympic type quota strategy as this would be unlikely to be implemented in the fishery. Further, we can't at this stage use total catch as an input into the model; it is an output.

<u>'Live' boats vs 'dead' boats</u>

Les Pollard: There is no live fishery for Red Throat Emperor; it is really only a dead product issue.

Rich Little: The model is now a multi-species model so it can be used to consider what is happening to Coral Trout, as well as Red Throat Emperor. If live boats do not actively target Red Throat Emperor this may be good for the fishery.

Gavin Begg: One strategy for example may be to restrict live boats from taking Red Throat Emperor.

Les Pollard: I don't agree; although live boats are not targeting Red Throat Emperor they do still catch them. It would be impractical to release these fish if they are caught inadvertently.

Rick Hack: I think it would be great if live boats released Red Throat Emperor, it would be good for the dead product boats.

Rick Hack: Is management going to restrict the sale of filleted product?

Danny Brooks: It is difficult to enforce the new size restrictions if filleting is allowed. Therefore, there will have to be some restrictions on filleting. However, it will not be restricted all together.

Les Pollard: There are licenses for operations that are allowed to fillet fish.

Rick Hack: Live fishing has nearly killed the domestic reef fish market (whole and filleted fish). There are only two 'wet' or 'dead' boats working out of the Gladstone area now.

Rick Hack: I wouldn't like to say that live boats can't keep Red Throat Emperor, as most of them don't target them anyway. Red Throat Emperor is a last resort for live boats.

Rich Little: What % does Red Throat Emperor make of the live catch?

Les Pollard. Red Throat Emperor makes about 50% of the catch of Coral Trout. For example, if we catch about 700kg of trout we would end up with around 400kg of Red Throat Emperor. All Red Throat Emperor is filleted.

Rick Hack: All of our product is sold whole on ice – straight to the shops.

Les Pollard: If we actively targeted Red Throat Emperor we would catch a lot more.

Rick Hack: On an economic basis you would not survive on the catch of Red Throat Emperor alone. To survive we need to take other fish to make a pay.

Les Pollard: We also need to consider mortality rates. We need the mortality of discarded fish to be zero if we are going to be throwing fish back.

Gavin Begg: From a management strategy perspective, it is probably too early to discuss the difference in catch between live and dead boats. However, it may be something to consider for future work with ELFSim.

Management strategies

Martin Russell: It is worth noting the State changes to zoning in State marine park areas.

Rich Little: A base case management strategy that includes the current management strategies of area closures (RAP and State zoning), size limits and effort limited to that in 1996 should be included.

David Bateman: At this stage I don't feel that a change in size limit is necessary.

Rick Hack: I would like to see the difference in the fishery with current area closures compared to those in place prior to RAP.

Infringement
David Bateman: How realistic is the model in predicting outcomes when we approach 100% of the reef closed?

Rich Little: As you get to 90% closure, effort is restricted into a very small area and infringement becomes important. Infringement is included in the model, but we are really not sure of the best way to handle this variable. For example, is infringement at higher levels around the edge of a green zone compared to the middle of the zone? This will also depend on the size of the green zone.

David Bateman: Does 100% closure mean 100% protection?

Gavin Begg: Yes – provided we assume that there is no infringement. This strategy would be of benefit to the conservation management objectives, but would fail to meet objectives of the commercial, recreational or charter boat sectors.

Rich Little: A 100% closure is a good base case scenario to include for model comparison.

James McClellan: How long does it take for fish stocks to fully recover from fishing?

Rich Little: If we protect stocks now, we would expect to see stocks recover to pre-fished levels by the year 2010.

David Bateman: You can change people's attitudes by changing the gear they use. For example, the use of 10/0 hooks.

Rich Little: We can not model gear restrictions as such. We do have some information on hook selectivity, but not for individual gears used.

Spawning season closures
James McClellan: Could we investigate the effect of shifting spawning season closures to when Red Throat Emperor spawn?

Gavin Begg: Coral Trout and Red Throat Emperor spawning seasons do not overlap completely. If you shift the closures to better suit Red Throat Emperor spawning, you risk missing the Coral Trout spawning season. Closures such as these are basically reducing effort – in the case of the current spawning season closures you are removing 28 days of fishing.

Rich Little: If fish are more catchable at spawning time (i.e., higher catchability), spawning season closures will be more efficient at protecting fish than the closures at other times of the year.

Rick Hack: As there is now a quota in place, does this matter, as we will be catching the same amount of fish (up to the quota) as we would if the spawning season closures were not in? The spawning season closures will not change how many fish we will catch.

James McClellan: The spawning season closures were implemented to protect Coral Trout. If you move closures to protect Red Throat Emperor you will miss protection of Coral Trout. Do Red Throat Emperor aggregate to spawn?

Ashley Williams: There is no data to show that Red Throat Emperor aggregate to spawn. There are, however, reports of bigger Red Throat Emperor catches around the time that they spawn, indicating they may be aggregating. This is anecdotal only. There is limited evidence in the catch data that catchability of Red Throat Emperor increases at spawning time.

Rick Hack: We seem to catch most of our Red Throat Emperor after they have spawned, around Christmas.

Terry Must: The spawning season closures don't mean that Coral Trout are spawning at these times.

Ashley Williams: Some Coral Trout have been found to spawn outside the new moons (around which the spawning closures are based).

Martin Russell: There was some discussion of closing the fishery down for three months to cover this variability when Coral Trout spawn.

James McClellan: I would like to see the effect of a 3 month closure.

Ashley Williams: As Red Throat Emperor are spawning from July, a three month closure from September to December would not encapsulate all of the Red Throat Emperor spawning season.

Rick Hack: It doesn't matter what time of the year a fish is caught. If it is caught it can't spawn at the next spawning closure.

Barry Goldman: Spawning season closures are basically an effort control. As long as catchability doesn't change at this time compared to other times of the year it won't matter when the closures occur.

Martin Russell: I would like to look at the difference in catchability throughout the year.

Gavin Begg: We will look to see if there is any significant change in catchability throughout the year and include this information in our scenarios when we evaluate the effect of the spawning season closures.

Size limits
James McClellan: Red Throat Emperor change sex, so a maximum size limit may be beneficial for protecting males?

Les Pollard: There should be no size limit at all on Red Throat Emperor.

Ashley Williams: Based on the biological information we have for this species, if we want to protect females you would look at a minimum size limit of about 28cm to protect around 50% of females from fishing. A maximum size limit of about 50-55cm would protect the males. From a fishery point of view I don't think that maximum size limits would work, however, from a biological point of view, it would protect more males.

Danny Brooks: What is the reason for setting maximum size limits?

Ashley Williams: For a sex changing species like Red Throat Emperor, 100% of the males are able to be fished. If you want a strategy to protect some of these males, a maximum size limit is one way of doing this.

Danny Brooks: A minimum size limit at 38cm should protect some males.

Ashley Williams: I have not seen any males that are less than 38cm. However, if a maximum size limit was introduced, there would be such a limited size range of fish that would be legally able to be taken that an introduction of a maximum size limit may not be effective for this species.

Danny Brooks: Maximum size limits are very difficult with respect to compliance.

Martin Russell: When do Red Throat Emperor change sex?

Ashley Williams: Red Throat Emperor change sex at around 42cm, and 6 years of age.

Martin Russell: Would it be better to increase the minimum size limit to around 42cm?

Danny Brooks: If a maximum size limit was considered, it may necessitate decreasing the minimum size limit to around 28cm – the size at first maturity. If we protected larger fish with a maximum size limit, what proportion of the stock would we be protecting?

Ashley Williams: The proportion of fish protected by a maximum size limit would be small.

Danny Brooks: Maximum size limits are usually implemented for species that have a very distinct range of sizes at which sex change occurs such as for blue spot trout.

James McClellan: The reason I suggested a maximum size limit for Red Throat Emperor is that they are heavily targeted and very few males are protected by current strategies. We need to consider that there is a tourism value in having large Red Throat Emperor in the water. If we consider discard mortality though, it may be better to increase the minimum size limit instead.

Gavin Begg: As we learn more about discard mortality, we can include this information in the model.

Danny Brooks: It would be difficult to argue that a maximum size limit is justified for Red Throat Emperor.

Gavin Begg: We could consider no maximum size limits and test an increased minimum size limit that protects some of the males.

Danny Brooks: Is discard mortality included in the model?

Rich Little: There is a variable for the amount of discard mortality in the model. However, this is the same for all sizes of fish.

Fecundity
David Bateman: Is there information available on fecundity of Red Throat Emperor – do larger females produce more eggs?

Gavin Begg: We don't know the specifics of this for Red Throat Emperor, but we can assume that this is probably so for Red Throat Emperor.

Ashley Williams: Red Throat Emperor are capable of spawning from around 2 years of age, but we don't have any data on the different rates of fecundity at different ages or sizes. Another point to consider is that Red Throat Emperor populations tend to be female biased.

Migration
David Bateman: Do we have any meaningful information on migration of Red Throat Emperor from one reef to anther?

Rich Little: We do have some data on movement.

Martin Russell: Is there any way we can consider juvenile habitats in this process?

Rick Hack: Given the large amount of area closed to fishing in the Capricorn-Bunkers area that may be an important habitat for juvenile Red Throat Emperor, these areas should not require further protection.

Bag limits
Les Pollard: Does the model allow for separate bag limits for recreational fishers?

David Bateman: Can it include individual recreational bag limits? For the recreational fishers, the level of effort seen in 1996 is probably about the same as what we see now.

Rich Little: We can not explicitly model bag limits.

Rick Hack: In the Gladstone area we are seeing a lot of recreational fishers selling their boats. The feeling is that with the new RAP closures it is too far to travel to the open reefs, and so is no longer worth while doing.

Revision of management objectives, indicators and strategies for Coral Trout

Presenter – Barry Goldman
A revision of the management strategy evaluation (MSE) for Coral Trout was provided to stakeholders with an opportunity to determine if the previously agreed to management objectives, indicators and management strategies were still relevant. These components of the MSE were revisited and discussed amongst stakeholders.

The management objectives and performance indicators for common Coral Trout, which were initially agreed to at previous stakeholder workshops in December 1999 and November 2000, were revisited. A total of 19 management objectives were identified for common Coral Trout (Table 3). Similar objectives to those identified for Red Throat Emperor are now considered to be also appropriate for common Coral Trout. Additional management objectives related to the charter and recreational sector (e.g., recreational CPUE >80% 1998-2000 levels) and which were agreed to at the previous stakeholder workshops in 1999 and 2000 were identified as still being appropriate objectives for the fishery because of the greater importance of Coral Trout as a target species for recreational fishers compared to Red Throat Emperor.

Table 3. Revised management objectives for common Coral Trout defined at the Multi-species MSE Stakeholder Workshops. These objectives will be evaluated using the ELFSim models and form the basis of the multi-species MSE. MLS = minimum legal size (38 cm). Northern – Southern GBR regions separated at 22°30'. Time periods to be evaluated: 2010-2015; 2020-2025.

Management objective (common Coral Trout)	Indicator	Stakeholder
9 in 10 common Coral Trout caught >MLS 60% of the time	Fish > 38 cm	Charter
Commercial CPUE >80% 1993-1996 levels 90% of the time	$CPUE/CPUE_{1993-1996}$	Commercial
Commercial CPUE >120% 1993-1996 levels 90% of the time	$CPUE/CPUE_{1993-1996}$	Commercial
Commercial CPUE >150% 1993-1996 levels 90% of the time	$CPUE/CPUE_{1993-1996}$	Commercial
Charter CPUE >80% 1996-2000 levels 90% of the time	$CPUE/CPUE_{1996-2000}$	Charter
Charter CPUE >120% 1996-2000 levels 90% of the time	$CPUE/CPUE_{1996-2000}$	Charter
Charter CPUE >150% 1996-2000 levels 90% of the time	$CPUE/CPUE_{1996-2000}$	Charter
Recreational CPUE >80% 1998-2000 levels 90% of the time	$CPUE/CPUE_{1998-2000}$	Recreational
Recreational CPUE >120% 1998-2000 levels 90% of the time	$CPUE/CPUE_{1998-2000}$	Recreational
Recreational CPUE >150% 1998-2000 levels 90% of the time	$CPUE/CPUE_{1998-2000}$	Recreational
In northern GBR <30% of catch is <MLS 90% of the time	Fish > 38 cm	Commercial
In southern GBR <5% of catch is <MLS 90% of the time	Fish > 38 cm	Commercial
To catch the quota that is available 100% of the time	Total commercial catch	Commercial
Total biomass (TB) ≥ TB_{2000} 100% of the time	TB/TB_{2000}	GBRMPA
Spawning biomass (SB) ≥ SB_{2000} 100% of the time	SB/SB_{2000}	GBRMPA
Total biomass (TB) ≥ TB_{2000} 50% of the time	TB/TB_{2000}	DPI&F
Spawning biomass (SB) ≥ SB_{2000} 50% of the time	SB/SB_{2000}	DPI&F
Total biomass (TB) > 40% TB_{virgin} 80% of the time	TB/ TB_{virgin}	DPI&F
50% of common Coral Trout caught > 50 cm	Fish > 50 cm	Recreational

Furthermore, the management strategies identified for Red Throat Emperor were also considered to be appropriate for Coral Trout. A range of alternative management strategies to evaluate against the specified management objectives for the multi-species MSE were identified and agreed upon by the stakeholders at the Workshop. The management strategies identified were a combination of area and temporal spawning closures, effort restrictions, and legal sizes (Table 4).

Table 4. Management strategies for common Coral Trout defined at the Multi-species MSE Stakeholder Workshop, November 2004. These strategies will be evaluated using the ELFSim models and form the basis of the multi-species MSE. RAP = GBRMPA Representative Areas Program (current closures). Base case refers to current management strategies that the reef line fishery is operating under.

Area closure	Effort restriction	Spawning closure	Legal size	Comment
RAP	1996	3x 9 days (Oct-Dec)	Min – 38 cm	Base case – current (2004) strategies
RAP	0.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
RAP	1.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
Pre-RAP	1996	3x 9 days (Oct-Dec)	Min – 38 cm	
Pre-RAP	0.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
Pre-RAP	1.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
50%	1996	3x 9 days (Oct-Dec)	Min – 38 cm	
50%	0.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
50%	1.5x 1996	3x 9 days (Oct-Dec)	Min – 38 cm	
RAP	1996	None	Min – 38 cm	Conditional on catchability analysis
RAP	1996	Sep-Nov	Min – 38 cm	Conditional on catchability analysis
RAP	1996	3x 9 days (Oct-Dec)	None	
RAP	1996	3x 9 days (Oct-Dec)	Min – 35 cm	Previous size limit
RAP	1996	3x 9 days (Oct-Dec)	Min – Max	Conditional on slot size limits based on biological analysis; minimum to reflect size at first maturity; maximum to reflect sex ratios and size at sex change
100%	Zero effort	NA	NA	No fishing – control strategy

DISCUSSION:

No specific discussion recorded. There was a general consensus that the management strategies identified for Red Throat Emperor were also appropriate for Coral Trout.

Presenters

Name	Organisation	Address	Email
Gavin Begg	CRC Reef Research Centre	JCU, Townsville, 4811	Gavin.Begg@jcu.edu.au
Barry Goldman	CRC Reef Research Centre	JCU, Townsville, 4811	Barry.Goldman@jcu.edu.au
Rich Little	CSIRO Marine Research	GPO Box 1538, Hobart, 7001	Rich.Little@csiro.au

Support staff

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Iesha.Stewart	CRC Reef Research Centre	JCU, Townsville, 4811	Iesha.Stewart@jcu.edu.au
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Stakeholders

Name	Institute	Affiliation
Danny Brooks	Queensland Department of Primary Industries and fisheries	Manager
George Leigh	Queensland Department of Primary Industries and fisheries	Manager
Martin Russell	Great Barrier Reef Marine Park Authority	Manager
Bill Nason	Queensland Boating and Fisheries Patrol	Surveillance
Terry Must		Commercial fisher
Les Pollard		Commercial fisher
Richard Hack		Commercial fisher
Lynette Hack		Commercial fisher
David Bateman	Sunfish	Recreational fisher
James McLellan	North Queensland Conservation Council	Conservationist
David Welch	CRC Reef/QDPI&F	Scientist
Ashley Williams	CRC Reef/QDPI&F	Scientist

Apologies

Name	Institute	Affiliation
Mark Elmer	Queensland Department of Primary Industries and fisheries	Manager
Kath Kelly	Queensland Department of Primary Industries and fisheries	Manager
Anne Clarke	Queensland Department of Primary Industries and fisheries	Manager
Malcolm Dunning	Queensland Department of Primary Industries and fisheries	Manager
Phil Cadwallader	Great Barrier Reef Marine Park Authority	Manager
Simone Retif	Department of Environment and Heritage	Manager
Bob Grimley	Queensland Boating and Fisheries Patrol	Surveillance
Duncan Souter	QSIA	
Julie Pollard		Commercial fisher
Vern Veitch	Sunfish	Recreational fisher
Bill Sawynok	InfoFish	Recreational fisher
Nick Ellis	CSIRO	Scientist
Bruce Mapstone	CRC ACE	Scientist
Mark Elmer	Queensland Department of Primary Industries and fisheries	Manager

Glossary

Biomass — Measure of weight of fish in a stock.

Mature biomass — Biomass of those fish which are reproductively mature.

Available biomass — Biomass of fish above minimum legal sizes, and below maximum legal sizes (where applicable).

Spawning stock biomass — Measure of total weight of all reproductive fish in a stock.

Virgin biomass — Biomass of a fish stock prior to it being fished. This value is often

	estimated from reefs closed to fishing assumed to be representative of a virgin (unfished) stock.
Relative biomass	Biomass of stock in a particular year relative to biomass before fishing started (B/Bo).
Decision table	Synthesis of information from ELFSim which highlights the comparative trade-offs among different management strategies under consideration and (where possible) the likelihood that each strategy (or set of strategies) will meet operational objectives.
Quantitative (operational) objective	Specific quantitative objective against which the performance of management strategies can be assessed.
Management scenario	A set of management strategies proposed for future use.
Management strategy	Specific approach (e.g., area closures) to regulatory framework by which to achieve a management objective.
Performance indicator	A characteristic of the fishery (fish stock, fleet, management system) that is observed in real life and used as an "indication" of the status of the system. eg age-structure, density, catch, effort, CPUE are indicators.
Performance measure	A measure of how close the chosen indicator is to a desired target. That is, the performance measure is the difference between where the system is and where we would like it to be. Calculation of performance measures, therefore, requires clear specification of specific objectives for the fishery and the stock.
Risk	Chance (probability) of an event, usually considered to be an event resulting in a negative outcome.
Robustness (of management strategies)	How well strategies work under uncertainty and how likely strategies are to realise objectives under unforeseen or extreme circumstances.
Catch	All fish caught by a fisher or fishery, including those that are discarded (due to minimum legal size restrictions etc).
Harvest	All fish caught and retained, i.e. does not include those fish that are discarded.
Catchability	How readily fish can be caught. This may vary widely and is dependant on many factors.
Effort creep	Advances in technology that are adopted by fishers (such as gps systems, larger boats, etc) that decrease the effort required to catch fish. These advances increase the effectiveness of the time fishers spend fishing resulting in increased harvest with the same amount of effort. In an environment of declining fish stocks, effort creep can maintain harvest at a stable level and lead to a situation of stable CPUE that may mask a declining fish stock.

Appendix H. Communication and extension

F&F Newsletters; QLD Fishermen

Publications

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 of marine reserves 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.

Little, L. R., Kuikka, S., Punt, A. E., Pantus, F., Davies, C. R., and Mapstone, B. D. (2004) Information flow among fishing vessels modelled using a Bayesian network. Environmental Modelling and Software **19**: 27-34.

Newsletters/flyers/QLD Fisherman

Workshops

Multi-species Management Strategy Evaluation Stakeholder Workshop, 16-17 August 2004.
Multi-species Management Strategy Evaluation Stakeholder Workshop, 10 November 2004.

Fisheries Staff Issues Team Seminar Series Utility of models for fisheries management and their limitations- various experiences in Australia and elsewhere, Andre Punt, Rich Little, 23 August 2005, 2.00pm - 3:30pm, Primary Industries Building, 80 Ann Street Brisbane, Ground Floor, Auditorium 3

15 December 2004 The effects of size and fragmentation of marine reserves and fisher infringement on the catch and biomass of Coral Trout(Plectropomus leopardus) on the Great Barrier Reef of Australia. 2004 World Conference on Natural Resource Modelling, RMIT University, Melbourne, Australia 12-15 December 2004.

May 2004 Conference Paper: Evaluating the size and fragmentation of marine reserves and the effect of fisher infringements in the reef line fishery of the Great Barrier Reef, Australia. Little, L.R.a, Punt, A.E.ab, Mapstone, B.D.cd, Smith, A.D.M.a, Pantus, F.e, Davies, C.R.df, and McDonald, A.D.a .4th World Fisheries Congress , Vancouver, Canada 3-6 May 2004

7 May 2004. Modelling Fisher Interactions in an Agent-based model of fishing behaviour. Seminar at the CSIRO Centre for Complex Systems Science, Gungalin, ACT, Australia

Little, L.R. The biological models of ELFSim. CRC / CSIRO - Multi-species targetting 1st Stakeholder Workshop, Queensland Tropical Museum, Townsville, 16-17 August 2004.

Begg, G. and Little, L.R. Management Stratgegy Evaluations. CRC / CSIRO - Multi-species targetting 1st Stakeholder Workshop, Queensland Tropical Museum, Townsville, 16-17 August 2004.

Little, L.R. Introduction to ELFSim and the effects of area closures and fisher infringements. Seminar to the Fishing and fishing Effects Group of the Reef CRC. 17 July 2004, James Cook University Townsville.

Little, L.R. What is ELFSim? A tutorial on the operational details of the Effects of Line Fishing Simulator. Seminar to the Fishing and fishing Effects Group of the Reef CRC. 29 July 2004, James Cook University Townsville.

The final report of the Effects of Line Fishing Project was published which attracted enormous stakeholder interest and is critical for management. 2003-04 Highlights and

Achievements, CRC Reef Research Centre, CRC Torres Strait and the International Marine Project Activities Centre

Advice was provided to Queensland Fisheries Service to assist in developing management plans for the Coral Reef Finfish fishery.

The results of the ELFSim report were used by James Larcombe in a report (entitled: GBR RAP Reef Line Fishery - Ecological and Fishery Effects) to DEH that was used in their buyout of quota from the Reef Line Fishery. (They did not have anything like this sort of detail for any of the other fisheries affected by the RAP.)

Evaluating the potential implications of the "Larval Subsidy Effect" for management of reef fish populations on the Great Barrier Reef, Australia. Little, L.R., Mapstone, B.D., Smith, A.D.M., Pantus, F., Punt, A.E., Davies, C.R., McDonald. A.D. MODSIM05: Advances and Applications for Management and Decision Making, 12-15 December 2005, The University of Melbourne, Melbourne, Australia.

Bergenius M., Mapstone, B. and Little, R. Consequences of spatial variability in biology to the dynamics of reef fish populations subject to various harvest strategies. ASF 2005 annual conference, Alaska

Indicators used in the Management Strategy Evaluation for the Effects of Line Fishing on the Great Barrier Reef. Little, L.R. CSIRO Workshop on Ecological Indicators for Fishing, Aquaculture and Ecosystem-based Management, 11-12 July 2005, Hobart, Tasmania.

GBRMPA FRAC

GBRMPA FRAC, GBRMPA Seminars

Appendix I. Intellectual Property

No patentable or marketable products or processes have arisen from this research. All results will be published in scientific and non-technical literature. The raw data from compulsory fishing logbooks remains the intellectual property of the Queensland Department of Primary Industries and Fisheries. Raw catch data provided by individual fishers to project staff remains the intellectual property of the fishers. Intellectual property accruing from the analysis and interpretation of raw data vests jointly with the Cooperative Research Centre for the Great Barrier Reef World Heritage Area and the Principle Investigator.

Appendix J. Staff

Principle Investigator:	Gavin A. Begg
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	André E. Punt
	Nick Ellis
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Database Managers:	Gary Carlos
	Aaron Ballagh
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