Evaluating candidate monitoring strategies, assessment procedures and harvest control rules in the spatially complex Queensland Coral Reef Fin-fish Fishery

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Abbreviations

CPUE	catch per unit effort
CRFFF	Coral Reef Fin Fish Fishery (for the purpose of this report, this refers to the Queensland CRFFF only)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CT	coral trout
DAF	Department of Agriculture and Fisheries
(Q)DAFF	(Queensland) Department Agriculture, Fisheries and Forestry (precursor to DAF)
DEEDI	Department Employment, Economic Development and Innovation (precursor to DAFF)
ELFSim	Effects of line fishing simulator
FQ	Fisheries Queensland
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
HCR	harvest control rule
LTMP	long-term monitoring program
MLS	minimum legal size
MSE	management strategy evaluation
MSY	maximum sustained yield
OS	other species
QLD	Queensland
QSIA	Queensland Seafood Industry Association
RQ	reef quota
RTE	red throat emperor
TAC	total allowable catch

Executive Summary

Fisheries management strategies are composed of three important stages:

1. the measurement or collection of data,

2. analysis or assessment using the collected to data to understand the state of the stock and fishery, and

3. a subsequent decision to affect control on the fishery (often through the manipulation of total allowable catch or effort).

It is important to realise that uncertainty or errors are possible in each of these stages. Observation or sampling error for example, can occur in measuring and collecting data in the first stage. Model estimation or statistical analysis can mis-specify or represent the stock in the second stage, and implementation error, representing the ability to implement a prescribed management action like a TAC, applies to the third. One of the purposes of management strategy evaluation (MSE) is to determine the effect of these uncertainties on the management of a fishery, and to identify a strategy, i.e. a combination of measurement, analysis and decision, that minimises the effects of these errors and ultimately achieves the purpose or objective of management.

Appropriate monitoring and data collection, assessment and decision procedures are needed to ensure sustainability and maximum economic benefit from the coral trout stocks in the Queensland Coral Reef Fin Fish Fishery (CRFFF). This is not an easy accomplishment in a fishery that is as spatially complex as the CRFFF, and so in order to determine whether procedures are worth implementing, it is better to try techniques on a virtual fishery before doing so in reality. This project addressed these issues in the CRFFF by evaluating the effectiveness of:

1. several potential monitoring and sampling regimes of the coral trout stock, including the existing Long Term Monitoring Program (LTMP) surveys,

2. different ways of analysing the data collected from a monitoring program, including evaluating the recently developed stock assessment model used to estimate the coral trout status, and

3. evaluating candidate harvest control rules that translate the perceived state of the fishery into a TAC.

Lastly, since quota trading was introduced to the fishery, industry has stressed the fact that the economic conditions of the fishery have changed substantially, and so an update of economic data was urgently needed to ensure the evaluation of the management strategies was relevant and useful.

Background

Coral trout is the key target species in the CRFFF. The fishery spans 14 degrees of latitude between the tip of Cape York and the southern boundary of the Great Barrier Reef (GBR). Currently, approximately 150 out of 367 commercial fishing vessels that are endorsed to take coral reef fin fish target coral trout in the fishery. The fishery is spatially complex and there is significant variation in the distribution and abundance of coral trout and in the distribution of fishing effort across the region of the fishery. This spatial variability has made it challenging to use standard approaches to determining sustainable levels of harvest. At the commencement of this project in 2011, the commercial TAC (1288 t) was based on the historical commercial catch taken by the fishery and had changed little since it was implemented in 2004. The reliance on historical data to determine the TAC has led to questions regarding the potential profitability and sustainability of the fishery, especially given that the initial TAC set in 2004 was referenced to the most productive year recorded for the fishery.

Fisheries Queensland (FQ) within the Department of Agriculture and Fisheries (DAF), through the Long Term Monitoring Program (LTMP), has invested significant resources in fishery-independent monitoring of coral trout at specific reefs throughout the fishery area in an attempt to address the question of sustainable harvest. This information collected complements the information collected from the longer-term commercial logbook data and during the Effects of Line Fishing Research Program.

In a further attempt to address the difficulty in managing the spatial and other complexities of the fishery a management strategy evaluation (MSE) has been developed to simulate the spatially explicit population dynamics of coral trout on over 4000 reefs, the fishing activity on those reefs, and the potential effects of a range of management measures. The MSE represents the ideal platform to test, in a simulated environment, different monitoring strategies, including a fishery independent survey that could be used on the real population. The MSE can also evaluate candidate assessments and decision procedures.

Aims/objectives

This project addressed the following objectives:

1. To identify appropriate spatial and temporal fishery independent and fishery dependent monitoring strategies, and assessment and harvest control rules that use them.

The project used an MSE framework to achieve this by:

a. evaluating the ability of different monitoring strategies at different spatial scales to inform the estimation of the coral trout stock by a recently developed stock assessment model,
b. evaluating the performance of different harvest control rules to achieve implied fishery objectives for the commercial fleet, and

2. To update the economic and fisheries data used to determine cost effective management strategies.

Since the fishery has changed dramatically over the past decade, industry has stressed the fact that the economic conditions of the fishery have changed substantially through the increased focus on sale of live coral trout, a decline in catch rates, and changes to economics as a result of externalities. This project sought to increase the confidence of the results obtained by the model and ensure it portrays an accurate representation of the fishery by updating the model with the latest fishery data; and conducting an economic survey to understand the current economic conditions of the commercial fishing fleet.

3. To give scientists and managers in DEEDI (*) their own ability to compare and contrast methods of data collection and analysis for the CRFFF, in order to aid the identification of appropriate harvest strategies.

ELFSim is expected to inform and aid fisheries management in the future. There is the need therefore for DAF to gain operational capability in its use. This project initiated transfer of the operational capacity of ELFSim MSE model and software to the DAF.

In addition, Fisheries Queensland were interested in investigating the effect of alternative assumptions of fleet mobility (the ability restricting or not vessels fishing across the GBR) on the ability of the fishery to meet an updated statement of stakeholders objectives. We performed simulations to address this issue.

* The Queensland Department of Agriculture and Fisheries (DAF) was formerly the Queensland Department of Agriculture, Fisheries and Forestry (QDAFF), previously the Department of Employment, Economic Development and Innovation (DEEDI), and prior to that the Department of Primary Industries and Fisheries (DPI&F).

Methods

Economic survey

A fleet profile was created that determined three broad classes of coral trout fishers across the GBR region. This formed the basis for sampling the fleet in the economic survey, which captured 29% of the active operators and vessel owners identified.

MSE model

The results of this survey updated the economic data and information used by the simulation model, ELFSim, used for the MSE. ELFSim is a simulation tool composed of three components:

a) The biological component of ELFSim is a population dynamics model that is age-, size- and sex-structured, includes a stochastic stock-recruitment relationship, and accounts for sex change, discard mortality and larval movement among reefs for the primary target species coral trout.

b) The effort dynamics component of ELFSim includes models of how fishers of each of the three sectors (commercial, recreational and charter) distribute their effort spatially.

c) The management component of ELFSim allows the user to specify future management options by sector. In this project, simulated monitoring strategies were implemented and the recently developed stock assessment model for coral trout was coupled to the underlying simulation model.

This simulated monitoring strategies included a structured line survey simulating a vessel survey in September each year. A sample of reefs was visited each year. Seven reefs were selected randomly from a set of regions. The simulated survey vessel operated by fishing a reef on each day of the month in September, collecting CPUE across the reefs as an index of abundance, as well as age and length samples from fish taken from each reef for use in the stock assessment model.

Three other monitoring strategies were used to compared against this survey. These strategies were fisheries dependent and not based on a random sample of reefs, but on the commercial fishing vessel behaviour.

On board observer data collection
A simulated on-board observer sampling program was developed whicih involved specifying a *number of observers* that would be on a number of associated vessels, and the, *observer coverage*, which indicated the proportion or probability that the particular observer is on a trip taken by the vessel. Ages (and lengths) of the fish caught by the (simulated) commercial fishing vessel were collected for each reef, and assigned to a specific “population” in the DAF assessment model.

Port sampling
A third monitoring strategy was developed as a port sampling program which used the same procedure as the *On board observer data collection* above, except the data were aggregated at a higher “port” level across spatial scales used in the DAF assessment model.

Processor port sampling
Lastly, a fourth monitoring strategy was developed to simulate sampling from a processor port. This strategy used the same procedure as the *On board observer data collection* above, except data were aggregated across the broadest spatial scale in the QLD assessment model to represent data collected at the coarsest spatial scale seens as a “processor port” level.

Key findings

Objective:

1. Identify appropriate spatial and temporal fishery independent and fishery dependent monitoring strategies, and assessment and harvest control rules that use them.

Stock assessment evaluation

As part of this objective we evaluated the ability of the Queensland DAF stock assessment to estimate the underlying simulated ELFSim biomass. The stock assessment model was able to estimate relative biomass within about 10%, but mainly by overestimating it.

Assessment of monitoring strategies

The stock assessment evaluation was based on simulated monitoring surveys. Stock assessment estimation using data from this simulated monitoring program, was compared with the estimates based on fisheries dependent collection at three different spatial scales (levels of age frequency data aggregation). In general, there was little effect of the degree of aggregation, and between fishery independent and fishery dependent collected age frequency data. Thus, we did not find the most “appropriate” spatial scale of monitoring in the fishery.

We also examined changes in the sampling rate of the fisheries dependent monitoring strategies, by increasing the sampling rate, either through more observers or increased coverage of a single observer, and found that the accuracy of the stock assessment increased. Whether a monitoring strategy is appropriate however, would come down to weighing their costs.

Harvest strategy evaluation

Although the stock assessment model tended to over-estimate the simulated underlying biomass, which would be expected to result in over-exploitation of the simulated stock, when used with a harvest control rule that targeted the average catch in the fishery between 2006-08, the underlying stock only decreased slightly (less than 10% reduction in biomass) with an increase in catches of about 100t over the current level of TAC in the fishery. Harvest strategy evaluations based on an empirical CPUE indicator and associated harvest control rule resulted in increased stock abundances of 0.70 - 0.80 B_0, well above the 0.48B_0 target which represented the fishery state in 2006-08.

Objective:

2. Update the economic and fisheries data used to determine cost effective management strategies.

Economic survey

The fleet profile and economic survey showed three broad classes of vessels operating in the fishers: (i) a large group of small ***Generalist line fishers***, many of whom were only partially active in 2010-11, and focused on line fishing but only partially in the CRFFF; (ii) a group of ***Dedicated live CT fishers*** with relatively large vessels focused on live CT, and (iii) a group of ***Diversified fishers*** with medium-sized vessels that operate across a range of fisheries including the CRFFF.

Objective:

3. Give scientists and managers in DEEDI (*) their own ability to compare and contrast methods of data collection and analysis for the CRFFF, in order to aid the identification of appropriate harvest strategies.

The stock assessment model and its integration into ELFSim were undertaken by DAF in QLD.

In addition to questions regarding testing monitoring strateging and harvest control rules, fisheries managers were interested in determining the effect of fleet mobility along the Queensland coast, and the implications of spatially restricted vessels on achieving fishery objectives.

The effect of fleet mobility

The ability of vessels to move among regions on the GBR influenced the distribution of effort and the ability of achieving fisheries management objectives at the regional level. Specifically, when vessels were released from fishing their own regional areas, effort tended to shift from the northern regions (Far North and Cairns) to more southerly regions (Mackay and Swains), which resulted in higher catches and profits.

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Implications

Two outcomes result from this research:

1. Managers and stakeholder groups like QSIA will be provided with critical information for cost effective ways of monitoring and analysing the coral trout stock, which could lead to the implementation of harvest control rules for the fishery.

- The fishery has changed substantially since it was last economically surveyed and is likely to change rapidly again as the effect of the mining boom diminishes. It is important to consider this when reviewing the variable, and in particular labour costs to the fishery.
- Stock assessment model estimations based on fisheries dependent monitoring programs were comparable to fishery independent monitoring program. This was also true across a range of spatial scales. This opens up the possibility of exploring the cost effectiveness of spatial and temporal scale of monitoring using monitoring cost data.
- A carefully implemented harvest control rule could provide sustainable and economic benefit to the commercial coral trout sector, although more detailed exploration of CPUE-based rules is required.

2. Fisheries managers and the management agency will develop the skills and capability to do MSE simulation themselves with less reliance on obtaining funds to contract an external research agency. This will allow DAFF to continually evaluate and improve monitoring design, abundance indicators, assessment techniques, and decision rules that are used for calculating TACs.

- The stock assessment model and its integration into ELFSim were undertaken by DAF in QLD, who now have the initial capability of using the model to explore fishery questions. All parties are committed to maintaining this capability in the future. Further research is being planned within FQ (**Further Development**).

Lastly, we stress that the modelling results shown are a first attempt at implementing these management arranagement into a very spatially complex fishery into a simulation framework and exploring their consequence, and that closer examination is needed, under a range of underlying condtions, to make any definitive advice.

Keywords

ELFSim; coral trout; *Plectropomus leopardus*; management strategy evaluation; Great Barrier Reef

1. Introduction

There are three types of harvest quota in the ‘Queensland Coral Reef Fin Fish Fishery’ (refered to as CRFFF here after): coral trout (CT); red throat emperor (RTE); and other species (OS). The OS incorporates approximately 154 other reef fish species, although only a relatively small proportion of these are actively targeted by the commercial fishery or retained for sale if caught. The CT quota covers seven species of coral trout, but the majority of landings consist of the common coral trout (*Plectropomus leopardus*). For this part of the project, the following quota management arrangements were current at that time (2013): quota unit represented one kilogram of fish (live weight equivalent) for all quota types. However, there was some capacity for this to be adjusted if specified catch triggers are reached. The available TACs for CT, RTE, and OS were 1,288,156kg, 615,586kg, and 955,604kg, respectively. As legislated, the commercial RQ TACs should not exceed 1350t for CT, 700t for RTE, and 1011t for OS. However, following an allocation appeals process the CT TAC was adjusted to ~1423t. The Australian Government Department of Environment subsequently bought 135t of CT, 73t of RTE and 109t of OS, in 2004-05, reducing the quantity of quota available to commercial fishers.

The CRFFF is a hand-line fishery operating predominantly on the continental shelf off the Queensland coast (Australia), approximately between latitudes 11 and 30S. The majority of the species whose catch in regulated in this fishery is caught within the Great Barrier Reef Marine Park (GBRMP) and World Heritage Area (GBRWHA), which extends from ~11 to 24.5ºS latitude.

The CRFFF is comprised of three operationally distinct sectors: a commercial sector catching fish for national and international markets; a charter sector in which operators take customers on recreational fishing trips and catch cannot be sold; and a private recreational sector, from which catch also cannot be sold. Fishers in all sectors use similar gear, mainly consisting of single baited hooks on heavy line on rod and reel or hand reel. The CRFF is a multi-species fishery with over 125 species or species groups being taken in various quantities, though the bulk of the catches in each sector comprise groupers (Epinephilinae), primarily coral trout (*Plectropomus spp*.), tropical snappers (*Lutjanidae*), and emperors (*Lethrinidae*) (Mapstone *et al*., 1996, 2004; Higgs 1999, Morgan 1999).

The commercial fishery mainly is a dory (small, shallow-draft boat, ~ 4-7m) fishery with fishing by hand-lines from up to seven dories tendered to 8-19m primary vessels, though some fishing also occurs from the primary vessels. Primary vessels, with their licenced and strictly limited number of attendant dories, generally fish during trips to sea of 1-20 days, with some larger vessels remaining at sea for extended periods punctuated by very short visits to off-loading points. At-sea offloading and transhipment is not allowed.

The main species landed commercially are the common coral trout (*Plectropomus leopardus*, the most common of 7 Plectropomus spp.) and the red throat emperor (*Lethrinus miniatus*) (Mapstone *et al*. 2004, QFS 2002), which together have comprised around 70-80% of landings since consistent records have been kept (from 1988). Approximately 400 vessels were active in the CRFFF up to 1994, though over 1500 licences for commercial line fishing were held, exercising approximately 16,00-18,00 line-days of effort and harvesting less than 3,000 tonnes of demersal species annually (Mapstone et al 1996). All catch was marketed dead, usually frozen, until 1993 but since then increasing proportions of the catch of coral trout has been retained alive and sold to international live reef fish markets, mainly through Hong Kong. This change has resulted in significant change in operational and financial characteristics of the sector and generally increased the proportion of landings comprised of live coral trout, which deliver higher beach prices (seasonally up to $60/kg) and require less on-board post-capture processing. Effort and catch increased substantially as a result (QFS 2002, Williams 2002), reaching nearly 40,000 line-days by over 700 operations and landing over 4,400 tonnes of demersal reef fish in 2001 (from all Queensland waters, QFS 2002).

Management arrangements in the GBR region, the main home of the CRFFF, are complex. Jurisdictions for conservation management and fisheries management vest with the Australian Commonwealth and the Queensland State governments respectively constitutionally, legislatively, and operationally. The GBR Marine Park and World Heritage Area are managed primarily for conservation through a system of area-based management that excludes all line fishing in approximately one third of coral reef habitat. Fishing outside those exclusions is managed by Queensland, consistent with the Off-shore Constitutional Settlement (1981), under the *Queensland Fisheries Act (1994, 1999, 2004)*.

The CRFFF is managed uniformly over its domain. Minimum legal size limits exist for most species covered by the Act and apply to all sectors of the fishery, as do restrictions on the numbers of hooks and lines that can be used by each fisher. Recreational and charter fishers are regulated by per-person 'in possession' species-specific and total bag limits, in addition to the general size and gear limits but there is no license or permitting system for recreational fishers. Commercial fishing prior to 2004 also was managed through limited entry licensing, limits on primary vessel length and the numbers of dories allowed to be used per primary vessel.

Individual Transferrable Quotas (ITQs) and a Total Allowable Catch (TAC) were introduced for the commercial sector in 2004, at the same time as actions also were taken to reduce the latent effort in the sector, limit to 411 the number of operators allocated quota, further constraint entry to the fishery, and buy-back some of the newly allocated quota. There are three types of (commercial) quota in the CRFFF: coral trout (CT); red throat emperor (RTE); and other species (OS), referred to collectively as the reef (fish) quotas (RQ). The OS incorporates approximately 154 other reef fish species, although only a relatively small proportion of these are retained for sale if caught and very few are targeted by the commercial fishery.

The CT quota includes catches of the seven species of coral trout but the majority of landings are common coral trout. One quota unit represents one kilogram of fish (live weight equivalent) for all quota types under current conditions. There is some capacity for this to be adjusted, however, if specified catch triggers are reached. The available (2012) TACs for CT, RTE, and OS are 1,288,156kg, 615,586kg, and 955,604kg respectively.

Coral trout is the key target species in the CRFFF. The fishery area spans 14 degrees of latitude between the tip of Cape York and the southern boundary of the Great Barrier Reef (GBR). Approximately 150 out of 367 commercial fishing vessels that are endorsed to take coral reef fin fish target coral trout in the GBR fishery. The fishery is spatially complex and there is significant variation in the distribution and abundance of coral trout and in the distribution of fishing effort across the region of the fishery. This spatial variability makes it challenging to use standard approaches to determining sustainable levels of harvest. At the commencement of this project in 2011, the commerical TAC (1288 t) was based on the historical commercial catch taken by the fishery and had changed little since the ITQ system was implemented in 2004. The reliance on historical data to determine the TAC has led to questions regarding the potential profitability and sustainability of the fishery, especially given that the initial TAC set in 2004 was referenced to the most productive year recorded for the fishery.

Fisheries Queensland (FQ), through the Long Term Monitoring Program (LTMP), has invested significant resources in fishery-independent monitoring of coral trout at specific reefs throughout the fishery area (Fisheries Queensland 2012) in an attempt to address the question of sustainable harvest. This information collected complements the information collected from the longer-term commercial logbook data and during the Effects of Line Fishing Research Program (Mapstone et al. 2004).

An operating model used as the basis for previous Management Strategy Evaluation (MSE, Little et al 2007, Mapstone et al 2004, 2008), has been developed to simulate the spatially-explicit population dynamics of coral trout on over 4000 reefs, the fishing activity on those reefs, and the potential effects of a range of management measures, in an attempt to deal with the spatial complexity of the fishery. The MSE represents the ideal platform to test, in a simulated environment, different monitoring strategies, including a fishery independent survey that could be used on the real fishery. The MSE can also evaluate candidate harvest control rules which could be used subsequently in a sustainable harvest strategy for the CRFFF.

In this research project we used the MSE model to:

1. evaluate a fishery independent monitoring program, and
2. evaluate a range of methods to identify appropriate harvest control rules for the GBR commercial reef line fishery.

Previous projects evaluated the effect of alternative conditions of effort and area closures (Mapstone et al. 2004, 2008), additional species and vessel behaviour (Little et al. 2007), and the effects of TACs, ITQs and dory ownership constraints (Little et al. 2009a) on the ability of the fishery to achieve a range of objectives and expectations. In this research project we continued this exploration by:

3. investigating the effect of alternative assumptions of fleet mobility (the ability restricting or not vessels fishing across the GBR) on the ability of the fishery to meet an updated statement of stakeholders objectives.

The fishery in recent times has changed substantially through the increased focus on sale of live coral trout, a decline in catch rates, and changes to economics as a result of external conditions. We also sought to increase the confidence of the results obtained by the model and ensure it portrays an accurate representation of the fishery by:

4. updating the model with the latest fishery data; and
5. conducting an economic survey to understand the current economic conditions of the commercial fishing fleet.

Lastly, the model is able to inform and aid fisheries management and as a result of recent management requirements there is the need for the management agency to gain operational capability in its use. This project therefore also initiated:

6. the transfer of the operational capacity of ELFSim to the QLD fisheries management agency DAF.

Objectives

This project addressed the following objectives:

1. To identify appropriate spatial and temporal fishery independent and fishery dependent monitoring strategies, and assessment and harvest control rules that use them.

The project used an MSE framework to achieve this by:

  a. evaluating the ability of different monitoring strategies at different spatial scales to inform the estimation of the coral trout stock by a recently developed stock assessment model,
  b. evaluating the performance of different harvest control rules to achieve implied fishery objectives for the commercial fleet, and
  c. investigating the effect of alternative assumptions of fleet mobility (the ability restricting or not vessels fishing across the GBR) on the ability of the fishery to meet an updated statement of stakeholders objectives.

2. To update the economic and fisheries data used to determine cost effective management strategies.

Since the fishery has changed dramatically over the past decade, industry has stressed the fact that the economic conditions of the fishery have changed substantially through the increased focus on sale of live coral trout, a decline in catch rates, and changes to economics as a result of externalities. Consequently, this project sought to increase the confidence of the results obtained by the model and ensure it portrays an accurate representation of the fishery by updating the model with the latest fishery data; and conducting an economic survey to understand the current economic conditions of the commercial fishing fleet.

3. To give scientists and managers in DEEDI (*) their own ability to compare and contrast methods of data collection and analysis for the CRFFF, in order to aid the identification of appropriate harvest strategies.

Lastly, the model is expected to inform and aid fisheries management, and as a result of recent management requirements, there is the need for QLD DAF to gain operational capability in its use. This project therefore also initiated transfer of the operational capacity of ELFSim MSE model and software to the QLD DAF.

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2. Methods

The project is divided into two components:

1. Collection and update of economic and commercial fishing data for parameters used in the simulation model through an economic survey.
2. Simulation and evaluation of monitoring, assessment, and decision procedures using the MSE software (ELFSim).

Component 1 addresses objective 2, and component 2 addresses objectives 1 and 3.

2.1 The Economic Survey

The survey approach was developed in close collaboration with active participants in the CRFFF, licence and quota holders, Fisheries Queensland, and the Great Barrier Reef Marine Park Authority (GBRMPA). A workshop was held in October 2011 to present and discuss the initial fleet profile developed by CSIRO and Fisheries Queensland, as well as the proposed approach to implementing the survey and the questionnaire (Figure 1). The workshop was attended by six industry members representing different areas and types of businesses (Appendix A).

Significant efforts were made to communicate the survey plans broadly to the industry to facilitate the establishment of contacts with potential respondents. A one-page flyer (**Project flyer**) was developed to present the project and the economic survey, and was circulated with the assistance of the Queensland Seafood Industry Association (QSIA) through the Queensland Fisherman magazine, as well as by the Reef Line Council through its regular email newsletter.

Fisheries Queensland also prepared annual data summaries of fishing effort and catch which were sent in November 2011 to all the holders of line fishing licenses which had been active in the CRFFF in 2010-11 to facilitate the interview process. The interviews were initiated during a time when many of the fishers would be in port due to a spawning closure period in November 2011.

Figure 1 Timeline of the economic survey timeline

2.1.1 Sampling strategy

The sampling strategy adopted has been successfully applied in a variety of contexts, including French (Daurès, Rochet et al. 2009; Van Iseghem, Quillérou et al. 2011) and English (Pascoe, Robinson et al. 1996) commercial fisheries. Sampling was based on producing an updated description of the industry and developing a fleet profile taking into account the size and nature of fishing operations. This fleet profile was used in combination with the spatial distribution of the fleet along the Queensland coast to structure stratified random sampling of fishing operations.

First contact of the interviewees was made by Fisheries Queensland (Figure 2). Second contact was made by the survey team with the interviewees who had agreed to participate and an interview time and location were arranged.

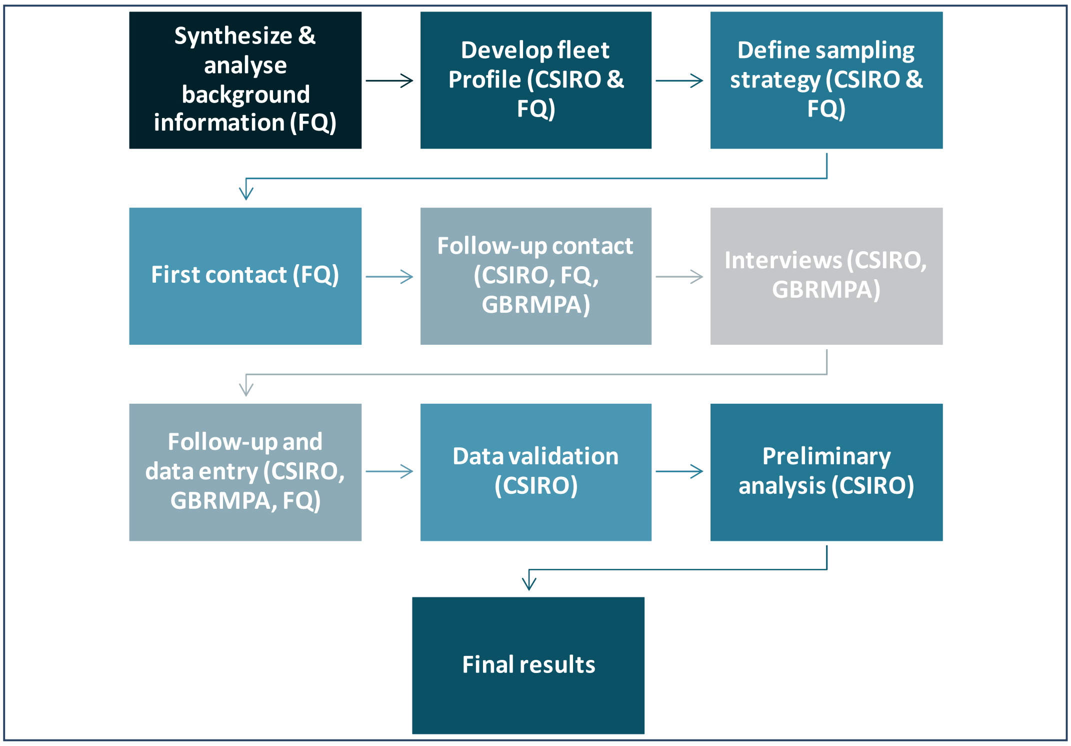


Figure 2 Survey process and participation from Fisheries Queensland (FQ), the Great Barrier Reef Marine Park Authority (GBRMPA) and CSIRO

Definition of a fleet profile

An initial description of the overall current status of the fishery was established based on data collected by Fisheries Queensland, including total catch and estimated gross sale value of Reef Quota (RQ) landings. Additional information was sought from alternative sources including expert knowledge from industry and management representatives and from other researchers with knowledge of the fishery, as well as from published data.

An initial confidential list of vessels identified by their boat marks was created by Fisheries Queensland based on the vessels that held an RQ symbol on their licence in 2010-11. This list contained 369 individual boat marks for which individual vessel technical characteristics, total fishing effort and its distribution across RQ and non-RQ fishing, annual landings information from logbooks, and total unloads of RQ species from the quota monitoring system were recorded. Approximately one third (115) of the boat marks selected through this initial process were inactive in the reference year (2010-11) and so were excluded from the population sampling frame. Another 41 vessels had no unloads of RQ species recorded for the reference year (i.e. had not fished the CRFFF in 2010-11), so also were excluded. This led to a remaining set of 213 vessels for which all technical, effort, and landings information was available and which had landed some RQ species in 2010-11.

Region	Main unloading port
Far North	Cape York
	Cooktown
Cairns	Cairns
	Innisfail
	Mission Beach
	Port Douglas
Townsville	Airlie Beach
	Ayr
	Bowen
	Lucinda
	Townsville
Mackay	Mackay
Capricorn	1770
	Gladstone
	Yeppoon
Sub-Tropical	Brisbane
	Bundaberg
	Gold coast
	Mooloolaba
	Noosa
	Tin Can Bay
	Urangan

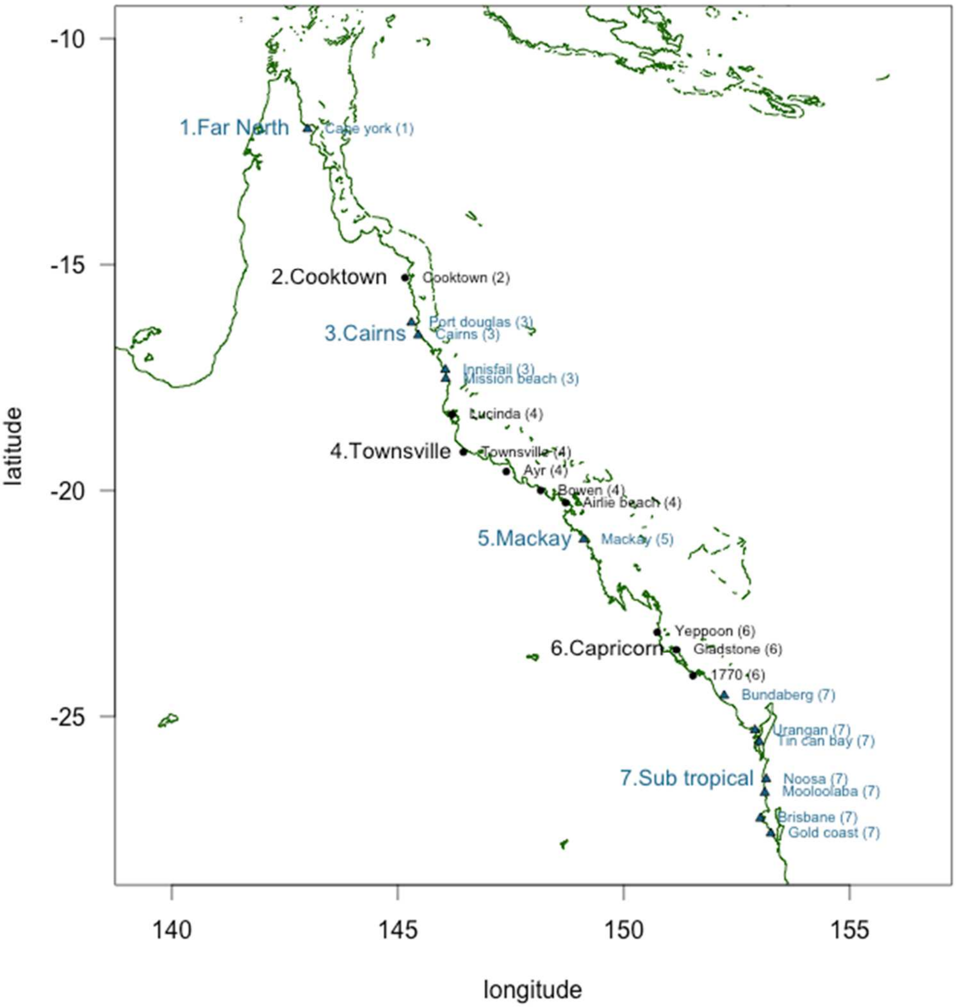


Figure 3 Coastal regions for the economic survey, and associated main landing sites within them.

Identification of groups of vessels with similar activity profiles was based on a cluster analysis using vessel characteristics (length, breadth, depth, engine power, number of tenders), landings by fishing method, proportion of coral trout (CT) landed live, and effort in days fished categorized into total effort, effort devoted to fishing in the CRFFF, and effort devoted to fishing in other fisheries. Symbol endorsements held, which determine the ability vessels have to access different fisheries and areas, were included as descriptive variables of the groups identified in the cluster analysis.

A hierarchical cluster analysis (*hclust* function in R; RDC Team, 2010) was used to identify groups of vessels displaying similar characteristics. hclust relies on the specification of a dissimilarity function between observations (Euclidean distance was chosen for the purpose of this analysis) and uses these distances to iteratively aggregate individuals into a hierarchical set of clusters (Teetor 2011). Visual evaluation of the resulting dendogram presents the hierarchy of clusters used to identify an appropriate number of groups in the fleet. A smaller number of clusters (3) was preferred given the objective of the analysis was to establish vessel types with homogeneous characteristics, with a need to further allocate vessel types geographically to ensure that the coastal regions were adequately represented in the sample.

The definition of the regions for the survey (Figure 3) was based on previous studies of the CRFFF, including the Effects of Line Fishing project (Mapstone et al. 2004), expert knowledge from the key stakeholders consulted while developing the approach, and existing information on the spatial distribution of landings by the fleet along the coast during 2010-11.

Identification of the survey sample

Each vessel was allocated to one of the three groups defined by the clustering algorithm and to a main landing port in 2010-11 (Figure 3) based on the information extracted from the quota monitoring system. A rank order was then used to select a sub-list of vessels which would initially be targeted for the survey. An initial sampling ratio of 30% in each group was applied evenly across all the regions to select this initial list of vessels. The following procedure was followed once the target vessels had been identified (Figure 2).

1. Fisheries Queensland staff involved in the project called each owner of the licences for the vessels that had been identified in the initial sampling list, gave a brief introduction to the economic survey, and asked if they were willing to participate and for Fisheries Queensland to pass on their contact details to the survey team.
2. The survey team, including CSIRO staff and one staff member from GBRMPA covering the region from Townsville to Airlie Beach, contacted respondents who answered positively, explained the survey process and the nature of the information collected through the interviews, answered any questions the respondents may have, and arranged an interview location and time, often requiring several calls.
3. The survey team then travelled to the location for the interview and carried out the survey. Some of the data were collected after the interview in some cases if the respondent did not have all the required information on the day of the interview. Examples included annual fishing activity and catches that a number of respondents were happy for the survey team to collect via the annual data summaries generated by Fisheries Queensland and profits and losses statements that respondents agreed the survey team could access after the interview.
4. In cases where potential respondents in the initial list declined participation in the survey Fisheries Queensland selected the next potential respondent in the lists following the random order created at the sampling stage. The entire sub-group was called in random order.

2.1.2 Questionnaire and other survey instruments

The questionnaire was developed initially taking into account background knowledge of the authors regarding the collection of economic data in a range of Australian and European fisheries (Table 1).

The questionnaire was designed to maintain anonymity of the information collected. It contained six main components on (i) the operators; (ii) vessel activity in the year under consideration; (iii) revenue; (iv) costs; (v) capital assets; and (vi) a set of questions regarding the history of the respondent’s involvement in the CRFFF, as well as the perceived key drivers of profitability and possible responses to changes.

Table 1 Previous economic surveys of commercial fisheries used to define the structure of the questionnaire applied to the CRFFF

Fishery surveyed	Country/Region	Organization	Years for which data was collected
Moreton Bay Otter Trawl	Moreton Bay, QLD, Australia	Qld DEEDI	2010
Marine Scalefish Fishery	South Australia	EconSearch Pty Ltd	2009-10
Eastern Tuna and Billfish Fishery & Southern and Eastern ScaleFish and Shark Fishery	Commonwealth, Australia	ABARE	2007-08 and 2008-09
Queensland commercial fisheries	Queensland, Australia	Department of Primary Industries and Fisheries	2007/08
Reef line fishery	Queensland, Australia	James Cook University	1994-99
French fishing fleet	France	Ifremer	2000-10
UK Fishing fleet	UK	SEAFISH	2001
English Channel fishing fleet	UK	University of Portsmouth	1995, 1997
North Sea beam trawlers	North Sea	University of Portsmouth	1990-2004

Several other documents in addition to the questionnaire were developed to assist with the interviews (Appendix A), including:

1. an interview tracking form, used to check the information available to the survey team regarding the respondent and the vessel for which information was being collected, stored separately from the data collected via the questionnaire to ensure anonymity of information,
2. an interviewer guide, providing guidance to interviewers about interpretation of certain sections of the questionnaire,
3. a map booklet containing the logbook maps to assist in coarse scale identification of the areas in which vessels had operated in 2010-11,
4. a participant information form, providing the respondents with background information on the survey as well as a clear indication of its voluntary character and of the anonymity of the information collected, and containing the contact details of the survey team,
5. a participant consent form, indicating consent from the respondent to take part in the survey, which was signed by each participant prior to the interviews,
6. an accounts data authority form, which participants signed if they agreed for the survey team to have access to annual profits and losses statements from their accountant, and
7. a data summary authority form, which participants signed if they agreed for the survey team to have access to the annual summaries of catch and effort produced by Fisheries Queensland.

The team also produced a short text introducing the survey that was used as a guide for the first contacts made with potential respondents. An agreement of confidentiality was signed by all members of the survey team.

2.1.3 Web survey tool

The information generated during the survey was managed to ensure consistency, anonymity, and confidentiality. A web survey tool was created to provide a central repository for interview-planning data, survey supporting documents, and the survey transcription form used to input data collected via paper questionnaires. These were accessible to all members of the survey team while the survey was being done, including those not employed by CSIRO. Non-CSIRO staff, however, only had access to the information relating to the interviews with which they were directly involved.

2.1.4 Other economic information collected and analysed

Price data

Short- and long-run changes in fish prices are a key driver of changes in the revenue of commercial fishing operations. The more prices vary the greater the uncertainty faced by operators in relation to their expected revenues. This uncertainty translates into increased risk, especially if the direction and strength of price movements are externally driven by changes affecting demand on international markets, which may include both fluctuations in demand preferences and factors affecting global trade, particularly exchange rates. This sensitivity to price fluctuations may be particularly high in a live-fish fishery because both increases in supply to take advantage of the higher prices and decreases in supply in periods of lower prices may be constrained by the capacity to store live-fish for significant periods of time.

Fish price data was collected for coral trout (CT), red-throat emperor (RTE) and other species (OS) from a variety of sources, including, but not exclusively, the survey itself in order to develop robust price scenarios for the ELFSim ITQ model. The sources of fish price data were:

1. Some interviewees provided average ex-vessel prices for CT, RTE, different species of OS and non-RQ species, in some cases distinguishing product presentation (live, whole fresh, filleted, frozen);
2. Two major processors of live fish provided the survey team with information on live CT prices, one providing daily price information for the period April 2005 to March 2011, with a break from January to June 2006, and the second providing monthly quantities and average ex-vessel prices of live CT from January 2004 to December 2011, with a break for quantities for January 2009 to December 2010;
3. Fisheries Queensland provided average quarterly beach prices from the Queensland Seafood Market Association for CT, RTE and Spanish Mackerel, distinguishing between live and dead fish, CT size (over or under 1.2kg), and product presentation (whole or filleted) for dead fish from the last quarter in 2006 to the last quarter in 2011;
4. Hong Kong import statistics provided data on monthly quantities and average import prices in Hong Kong dollars for coral trout, distinguishing between leopard and spotted trout, and between live and fresh presentation, by country of origin for the period January 2004 to December 2011.

Preliminary analysis of the time series data was done to identify patterns in fish prices and gain insights into potential drivers of changes in prices. This was based mainly on inspection of descriptive statistics and preliminary co-integration analysis (Johansen 1988; Johansen and Juselius 1990) of the data from Hong-Kong imports and the ex-vessel price time series obtained from processors. We tested for the existence of two long-run relationships between the price time series available. First, we examined the relationship at different points in the coral trout supply chain, involving investigation of the long run relationship between ex-vessel prices from the two processors who provided price information and the relation between these two price time series and the Hong Kong import prices for live coral trout. Second, we considered potential long-run relationships among the prices obtained by major exporters to the Hong Kong market from Australia, Malaysia, Indonesia and the Philippines.

Quota trading

It was also deemed important to gain a good background understanding of the current patterns of quota trading in the fishery and how these may change over time because ELFSim models the allocation of quota through the quota market and the interaction between quota allocation and fishing behaviour. Such an understanding is also required to assess the economic situation of operators in the fishery, depending on their status in the quota market. Social network analysis has been used to describe the patterns of trade in the quota market and how these patterns had evolved since the inception of the quota system and until the year considered in the survey (Innes et al. 2014).

The Queensland Department of Agriculture and Fisheries (DAF) holds data at the individual trade level for all quota types, along with the quantity of quota held and fished against separate quota account in each year. The project team was able to analyse an anonymised version of these data. The dataset covers the period since ITQs were first introduced on the 1st of July 2004 up to the end of the 2010-11 financial year (30th of June in Australia). Data relating to the years 2006-07 and 2007-08 were partially incomplete so are not included in the analysis. There is no requirement to report the $ value of quota transactions along with the quantity traded, as is common in many fisheries managed under ITQs, meaning that quota trade prices and how they have evolved over time were not available directly.

2.2 Management strategy evaluation modelling

The management strategy evaluation (MSE) used ELFSim (Appendix B). Briefly, ELFSim simulates the spatially explicit population dynamics on each of over 3000 individual reefs subject to fishing pressure. It operates at a monthly time step, with each simulation consisting of two parts. The first (‘initialization’) step operates historically, starting in 1965, by using information from visual surveys, and the physical characteristics of the reefs to determine the initial size of the population on each reef (CT or RTE) across all reefs. The model runs monthly through the historical period until the ‘present’ by subjecting the reefs to fishing pressure calculated from historical catch data, and subject to the condition that no reef has experienced an extinct population at any time during the historical period of the simulation. Whether a reef has an extinct population depends on the number of fish on it, which in turn depends on the value of the reef and species specific habitat scalar. This number sets the initial number of animals on each reef, and if it is too low for a reef, results in an extinct population given the historical amount of catch taken from that reef. ELFSim must go back to the start of the simulation if an extinction occurs at any time during initialisation, increase the initial density of fish on the reef, and then re-run the calculations for the historical period (see Mapstone et al. 2004). This is repeated until there are no extinct reefs in the historical period. This is called initialising the model.

After the model is initialised it projects the fishery into the future given the assumed fishing behaviour of the vessel dynamics model, and the implemented management conditions. The model is able to replicate the projection period many times, given the initial conditions from the initialisation process, with different results occurring from random processes in the model such as selecting where a vessel will fish.

Simulated historical and projected data collection in ELFSim

MSE modelling for this project involved simulated monitoring and data collection for use in a stock assessment model developed by DAF. The basis of this model was the CAB assessment model, which was originally integrated into the ELFSim operating model (Appendix C). The DAF assessment model used this template and customized it to deal with the spatial complexities inherent on the GBR (Appendix D). The DAF assessment model was thus used to estimate the underlying stock size in ELFSim.

Various sources of historically collected data are used in the assessment model. These data were collected from ELFSim during the historical period of the simulation, and used for input into the stock assessment model in the projection period. Through the projection period, the stock assessment estimated stock size annually, based on data collected during the historical period of the model, and during the projection period as the result of monitoring strategies.

Historical data collection from the operating model

1. *Historical Catch and Effort data*

Historical catch and effort data have been collected from the fishery since 1989, and are used to apply fishing pressure to reefs in the operating model prior to when the projection period starts. This catch and effort data thus is saved for stock assessment purposes in the projection period.

The data used by the assessment model to estimate stock size distinguish data collected from simulated monitoring programs in the projection period from data collected in the historical period, which conditioned the operating model. Data files that are read by the stock assessment model have a specific format where the source of the data is usually specified as a fleet or survey. (During the projection period of the model these data are written by ELFSim on an annual basis).

We distinguish index of abundance data from the historical period of the model from that collected during the projection period as a survey spanning the years from 1989 to the year prior to the start of the projection period (2011). Box 1 shows a portion of the *.dat file pertaining to abundance indices used by the assessment model that is generated dynamically by the ELFSim operating model. The data from fleet 4 ranging from year 24 (1989) to year 37 (2002), are the years for which we have catch and effort data from the fishery. In this example, year 37 (2002) was the last year of the historical period, and ELFSim projected from 2003.

Box 1. Part of .dat stock assessment data file compiled in projection year 2024 of the simulation showing different indices of abundance for **fleet 1**: Projected fleet catch and effort data; **fleet 4**: Historical fleet catch and effort data; **fleet 5**: Historical structured line survey; **fleet 6**: Projected structured line survey; **fleet 7**: Open reefs from the historical underwater visual survey; and **fleet 8**: closed reefs from the historical underwater visual survey.

```
#   Catch   rate   index   comm  Number  of  years,  Year (1based vector),
value,  CV
#   fleet 4 # years 14 (+1 from operating model because assessment is 1 based
array)
1 24 22.634623 0.100000
1 25 21.957666 0.100000
.
.
.
1 36 18.651846 0.100000
1 37 17.482363 0.100000
#   fleet 1 # years 22 (+1 from operating model because assessment is 1 based
array)
1 38 1.256730 0.100000
1 39 1.260670 0.100000
.
.
.
1 57 1.952210 0.100000
1 58 2.134190 0.100000
1 59 2.143410 0.100000
#   fleet 5 # years 6 (+1 from operating model because assessment is 1 based
array)
1 40 22.936407 2.160464
.
.
.
1 47 21.196476 2.390029
#   fleet 6 # years 21 (+1 from operating model because assessment is 1 based
array)
1 38 5.723072 0.878260
1 39 3.579365 0.801412
.
.
.
1 58 21.301085 0.822663
1 59 20.669737 2.055211
#   fleet 7 # years 5 (+1 from operating model because assessment is 1 based
array)
1 30 1751.077637 1.028522
1 31 1912.998779 1.858845
1 32 1894.417969 0.927153
1 33 2334.897949 0.875711
1 34 1780.871216 0.799354
#   fleet 8 # years 5 (+1 from operating model because assessment is 1 based
array)
1 30 659.024353 1.246123
1 31 658.849976 1.395975
1 32 700.295349 1.439138
1 33 894.872498 0.865454
1 34 498.370575 1.493311
```

2. Historical Structured Line Survey

A structured line survey was implemented in the CRFFF from 2005-9. In each year, six mid-shelf reefs in each of four regions (Cairns, Townsville, MacKay and The Swains) were selected for surveying between September and December each year (Department of Primary Industries and Fisheries 2005a; Fisheries Queensland 2012). This sampling survey was captured in the simulation model by selecting six reefs in the model from each of four regions (Cairns, Townsville Mackay and Swains) randomly in September of each year for the year 2005-2009, based on the amount of catch observed historically on each reef.

The CPUE in the historical period of ELFSim is based on actual fisheries data (outlined in the previous section above) that conditions the operating model in the historical period. The CPUE data for the 24 reefs in the *historical structured line survey* were taken from these data, and stored dynamically by ELFSim to the *dat file for use by the assessment. The CPUE index of abundance for this data source is shown in Box 1 as the average index across reefs (followed by the *cv*) for fleet 5, which in this example ranged from year 40 (2005) to year 47 (2009). The years in which the *historical structured line survey* operated are specified as model parameters in the input database.

The *historical structured line survey* also collected simulated length and age data, and so on the same 24 reefs 100 fish were randomly sampled from a selectivity-weighted age distribution on each reef. Because each age class in ELFSim also has an associated length, the length distribution on a reef is not smooth. Error was added to the length measurements in the form of a normal deviate $N(0,\sigma_l^2)$, where the variability in the length measurement σ_l was set to 6.17 cm (page 228, Little et al. 2007) because in reality length distributions are typically smooth. Both the number of fish sampled and the length error measurement in this sampling procedure can be specified in the elf_input.mdb database. The length data and age data are shown in Boxes 2 and 3 as the data from fleet 5 (the *historical structured line survey*). Note that these are raw data and not derived from an age-length-key.

Box 2. Part of .dat stock assessment data file compiled in projection year 2024 of the simulation that shows length distributions from different data collection sources. **fleet 5**: Historical structured line survey; **fleet 6**: Projected structured line survey; **fleet 7**: Open reefs from the historical underwater visual survey; and **fleet 8**: closed reefs from the historical underwater visual survey.

```
# Fleet 5
#(+1 from operating model because assessment is 1 based array)
1 30 0 0 0 0.000000 0.000417 0.012500 … 0.003333
1 31 0 0 0 0.000000 0.000833 0.012917 … 0.002500
1 32 0 0 0 0.000417 0.001250 0.011667 … 0.002083
1 33 0 0 0 0.000000 0.000000 0.007917 … 0.000833
1 34 0 0 0 0.000000 0.002083 0.014167 … 0.002083
1 37 0 0 0 0.000000 0.002083 0.012500 … 0.002083
# Fleet 6
#(+1 from operating model because assessment is 1 based array)
1 38 0 0 0 0.000000 0.001000 0.018333 … 0.002667
1 39 0 0 0 0.000000 0.000667 0.016000 … 0.002000
1 40 0 0 0 0.000333 0.002333 0.011000… 0.002333
1 41 0 0 0 0.000000 0.001333 0.019000 … 0.002000
.
.
.
1 59 0 0 0 0.000333 0.001000 0.016333 … 0.002333
# Fleet 7
#(+1 from operating model because assessment is 1 based array)
# Fleet 8
#(+1 from operating model because assessment is 1 based array)
```

Box 3. Part of CAB stock assessment data file compiled in projection year 2024 of the simulation that shows age distributions from different data collection sources. **fleet 5**: Historical structured line survey; **fleet 6**: Projected structured line survey.

```
# Fleet 5
#(+1 from operating model because assessment is 1 based array)
1 30 0 0 0 0.000000 0.000417 … 0.000417
1 31 0 0 0 0.000000 0.000417 … 0.000833
1 32 0 0 0 0.000000 0.000000 … 0.000000
1 33 0 0 0 0.000000 0.000000 … 0.000000
1 34 0 0 0 0.000000 0.000417 … 0.000417
1 37 0 0 0 0.000000 0.000417 … 0.000000
# Fleet 6
#(+1 from operating model because assessment is 1 based array)
1 38 0 0 0 0.000000 0.001000 … 0.001000
1 39 0 0 0 0.000000 0.001667 … 0.000000
.
.
.
1 59 0 0 0 0.000000 0.002000 … 0.000333
```

Historical Underwater Visual Survey
The final data generation that was developed for the historical period of ELFSim was the data collected from underwater visual survey from 1999-2004 (Samoilys and Lunow 2012). This survey focussed on 20 reefs from Cairns south to the central sections, and on blue (open) and green (closed) zones (Table 2).

Since ELFSim does not model the sub-reef level detail we did not consider transect placement in this simulated data collection. Instead, the number of fish ≥20 cm from each reef was determined with a log-normal sampling error $\exp\left(N(0,0.5^2)-\frac{0.5^2}{2}\right)$. This abundance estimate was scaled to the reef perimeter and the average index calculated across reefs. Box 1 shows the average index of abundance followed by the *cv* for the open (blue) reefs in the *Historical Underwater Visual Survey* as Fleet 7 and the green reefs as fleet 8. In this example, the historical UVS operated during the years 30 (1995) to 37 (2002), but the years can be specified as input parameters in the input database. The error variability (0.5) is also specified as a model parameter in the input database, and the set of reefs (Table 2) is specified as a table in the input database.

Table 2 Reefs (name, management status and code) used in the historical UVS data collection

Reef name	zone	URI
Lizard Is.	Green	14116A
	Blue	14116B
	Green	14116C
	Green	14116D
MacGillivrays	Green	14114S
Eyrie	Blue	14118S
Escape	Blue	15094S
St. Crispin	Blue	16019S
Norman	Green	16030S
Hastings	Green	16057S
Arlington	Blue	16064S
Channel	Blue	16075S
Wardle	Blue	17032S
Bramble	Blue	18029S
Dip	Green	18039S
Faraday	Green	18041S
Yankee	Green	18074S
John Brewer	Blue	18075S
Lodestone	Blue	18078S
Davies	Blue	18096S
Kangaroo	Green	19063A
	Green	19063B
Black	Blue	19127S
Hardy	Green	19135S

Data collection from the operating model in the projection period

Two indices of abundance were developed for the assessment models in the projection period.

Projected standardised CPUE
The first index was the fleet wide *standardised CPUE* that simply used the aggregate catch and effort data from the commercial fleet, standardised accordingly (Appendix C). Standardised CPUE from this data source are shown in Box 1 as the data from fleet 1 ranging from year 38 (2003) to year 59 (2024).

The second index of abundance comes from the first of four proposed monitoring strategies to be evaluated in this project: *the projected structured line survey*.

Monitoring strategies

Fishery independent projected structured line survey

The former discontinued fishery independent Long Term Monitoring Program (LTMP) involved one survey per year on 20 fixed reefs using a light and a heavy gear (6/0 and 9/0 hooks; Department of Primary Industries and Fisheries, 2005). We developed a simulated projected line survey for input into the DAF stock assessment model based on this survey.

This simulated structured line survey is based on a single survey vessel randomly chosen from the commercial vessels in the ELFSim vessel dynamics model in September each year. A sample of reefs is visited each year by the projected line survey. These reefs are selected at the start of the projection period, and sampled annually in each replicate projection. Seven reefs were selected randomly from each region, based on a probability that is proportional to the historical catch rate of the reef. Because most reefs in ELFSim have historical catch and effort attached to them, these reefs included both blue (open) and green (close) reefs. The projected line survey uses a single commercial vessel, randomly selected at the start of the replicate projection (and also sampled in each replicate projection). The selected survey vessel fishes the reefs on each day of the month in September of each projection year and collects CPUE across the reefs as an index of abundance.

Data collected at the daily time scale are used to calculate the survey index of abundance. The daily catch in the vessel dynamics model that is captured by the survey vessel is scaled to the corresponding monthly catch from the operating model for each survey reef $C^{r}_{y,m,s=CT}$. This gives the part of the monthly catch attributed to the survey vessel:

$$C^{v=SURVEY,r}_{y,m,s=CT} = C^{r}_{y,m,s=CT} \frac{q_{v,s} \sum_{d} E^{v,r}_{y,m,s=CT} \varepsilon_{q^{v}_{y,m,d,s=CT}}}{\sum_{v'} q_{v',s} \sum_{d} E^{v',r}_{y,m,s=CT} \varepsilon_{q^{v'}_{y,m,d,s=CT}}} \text{ (Little et al. 2007, page 92).}$$

The daily catch attributed to the reef therefore is:

$$C^{v=SURVEY,r}_{y,m,d,s=CT} = C^{v=SURVEY,r}_{y,m,s=CT} \frac{E^{v=SURVEY,r}_{y,m,d}}{\sum_{d'} E^{v=SURVEY,r}_{y,m,d'}} .$$

where $E^{v,r}_{y,m,d}$ is the perceived daily effort, $E^{v,r}_{y,m,d} \varepsilon_{q^{v}_{y,m,d,s=CT}} q_{v,s=CT}$ is the realised daily effort that includes $q_{v,s=CT}$ is the vessel specific catchability of coral trout, and the daily variation in catchability ($\varepsilon_{q^{v}_{y,m,d,s=CT}} = \exp(N(0,\sigma^2_{\xi}) - \sigma^2_{\xi}/2)$) for the survey vessel *v*, Little et al. 2007, page 91).

From these calculations the average daily CPUE for the survey vessel (and *cv*) is calculated and shown as an index of abundance in the *.dat file (Box 1) from fleet 6 ranging from year 38 (2003) to year 59 (2024).

The main data used in the stock assessment however that are provided by the *projected structured line survey* are age frequencies from the reefs it visits. This is achieved by sampling 100 fish from the selectivity weighted reef age distribution on each reef visited each day. As above, if length samples are required normal error is added (Little et al. 2007, page 228). Length data and age data for the *projected structured line survey* are shown in Boxes 2 and 3 as the data from fleet 6 ranging from year 38 (2003) to year 59 (2024).

Fishery dependent monitoring strategies

The remaining monitoring strategies examined in this project are based on fishery dependent data from the vessels in the vessel dynamics model that operate according to their behavioural rules (Little et al. 2007). The basis of these strategies is that biological samples of reef fish can be obtained from vessels, port or processors (Dept. Primary Industries and Fisheries 2005b).

- *On board observer data collection*

The second proposed monitoring strategy is an on-board (fishery dependent) observer sampling program which involves specifying a *number of observers* that would be on a number of associated vessels. A second variable, *observer coverage*, indicated the proportion or probability that the particular observer is on a trip taken by the vessel. The ages (and lengths) of the fish caught by the (simulated) vessel each day are collected for each reef, which is assigned to a specific "population" in the DAF assessment model (Appendix D). These data are then used in the assessment model.

- *Port sampling*

The third proposed monitoring strategy is a (fishery dependent) port sampling program which uses the same procedure as the *On board observer data collection* above, except data associated with "populations" in the DAF assessment model are aggregated to the "sub-regional" scale. Thus, "populations" in the DAF assessment model in the same "sub-region" would have identical age data. This was intended to give an impression of data aggregated at a larger "port" level.

- *Processor port sampling*

The fourth proposed monitoring strategy is a (fishery dependent) processor port sampling program implemented using the same procedure as the *On board observer data collection* above, except data associated with “populations” in the DAF assessment model are aggregated to the “regional” scale. Thus, “populations” in the DAF assessment model in the same “region” would have identical age data. This was intended to give an impression of data aggregated at a larger “processor port” level.

Model projections

We performed a single initialisation from 1965 to 2011 for coral trout in the current simulations under a habitat scalar that represented depletion levels for the start of the projection period so that the available biomass (the biomass that is selected by the gear, and if caught legally retained) of coral trout was approximately 55% of the pre-exploitation level. Twenty-five replicate projections from 2012 to 2035 were conducted to capture the long term effects of each management strategy allow consideration of the effect of variability (process and observation error) on the evaluation of the management strategy.

Management Strategies

There are three broad areas of interest in simulation results from this project. The first is a set of simulations intended to evaluate the effect of different monitoring strategies on the ability of a stock assessment model developed by the Queensland Department of Agriculture and Fisheries (DAF) to estimate accurately the size of the underlying population, with different amounts of information. These simulations did not evaluate any feedback control on the TAC but were designed strictly to evaluate the accuracy of the assessment under the different levels of data aggregation.

The second set of simulations was designed to evaluate the effect of a set of simple harvest control rules. These rules were based on three harvest control rules: the Queensland DAF stock assessment model, and two CPUE-based rules.

The third area of interest in the simulations in this project was to evaluate the state of the fishery under different conditions of two controllable variables believed to be an important influence on the fishery: the level of TAC, and the mobility of the fleet (i.e. the ability of the vessels in the fleet to move between regions).

2.2.1 Queensland DAF stock assessment evaluation

Data can be used in the Queensland DAF stock assessment at the population, sub-region and region levels (Appendix D). The data used in the assessment model include age and CPUE data. The purpose of the management strategy evaluations for the QLD stock assessment model, then, was to show the effect of different levels of data aggregation on estimation performance.

The three fishery dependent monitoring (management) strategies (On board, Port sampling and Processor port sampling) were further defined by the *number of observers*, and *observer coverage*. We examined a combination of these factors for each fishery dependent monitoring strategy: *number of observers* (10 and 50), and *observer coverage* (10% and 25%). This resulted in a total of 12 sets of 25 projections for the fishery dependent monitoring, and 1 set of 25 projections with the fishery independent monitoring from the *projected line survey*.

The objective of simulating these management strategies was to show the accuracy of the stock assessment model under the monitoring and data usage conditions. In addition, another set of 25 projections were conducted using monitoring data captured from the projected structured line survey. The results were presented to show the relation between the model-estimated quantities in each of the projection period, and the actual quantities in the underlying operating model.

2.2.2 Harvest control rule evaluation

Three harvest control rules were evaluated for the fishery. The first involved using the DAF stock assessment. The remaining two harvest control rules were based on standardised CPUE with the difference being the vessels from which the CPUE measured.

Queensland DAF stock assessment harvest control rule

Harvest control rules set a TAC based on a measure of the state of the stock (Smith et al. 2008). A harvest control rule was implemented that used the estimated relative spawning biomass from the DAF stock assessment model, and based on the on-board observer sampling strategy, as this sampling program seemed a likely trade-off between the expensive survey and the other aggregated sampling measures. The TAC in each simulation year was calculated as:

$$TAC = \max(0, C_{targ}\frac{X - X_{lim}}{X_{targ} - X_{lim}})$$

where X is the estimated spawning biomass relative to pre-exploitation levels in 1965, from the Queensland DAF stock assessment, X_{targ} is the target biomass (instead of an estimate of the biomass corresponding to MSY as X_{targ}, X_{targ} was set to the mean estimated biomass over years 2006 to 2008 because the catches and catch rates seemed to be at a desirable level during those years), C_{targ} is the average catch by the commercial fishery during 2006 to 2008, and X_{lim} is the limit reference point below which the fishery is closed ($TAC = 0$), set to 40% of X_{targ} based on Smith et al. (2008).

Four combinations of the monitoring strategy were tested: (*number of observers* at 10 and 50, were combined with *observer coverage* of 10% and 25%).

CPUE-based harvest control rules

CPUE-based harvest control rules based on Little et al. (2011) were also evaluated using the harvest control rule,

$$TAC = \max(0, C_{targ}\frac{CPUE - CPUE_{lim}}{CPUE_{targ} - CPUE_{lim}})$$

where $CPUE$ is the annual CPUE of the commercial fishing fleet from the previous year. $CPUE_{targ}$ is the standardised geometric mean CPUE from the fishery between 2006 and 2008 (16 kg/dory day), selected for consistency with how the target is set for the DAF stock assessment based HCR, and $CPUE_{lim}$ is the limit reference point below which the fishery is closed ($TAC = 0$), and calculated as 40% of $CPUE_{targ}$, again for consistency with how the HCR associated with DAF stock assessment is applied.

Two variations on this HCR were evaluated. The first calculated CPUE from the entire commercial fishing fleet. The second calculated the CPUE from a random, stratified subset of commercial vessels in the fleet by vessel length and port (Table 3). This subset was thought to reduce the variability in the indicator, and provide a better, more accurate representation of the stock.

Table 3 Number of randomly selected vessels each port used for the fleet subset CPUE-based harvest control rule

	Port:								
Vessel class:	**Cooktown**	**Port Douglas**	**Cairns**	**Innisfail**	**Townsville**	**Bowen**	**Mackay**	**Yeppoon**	**Gladstone**
>15m	0	1	2	0	0	1	1	0	1
<15m	2	2	3	3	1	2	1	1	1

2.2.3 Evaluating the effect of fleet mobility

The third set of simulations evaluated the state of the fishery under different conditions believed to be influencing the fishery: the level of TAC, and the mobility of the fleet. The vessel dynamics model in ELFSim currently constrains the vessels to operate in localised fishing areas associated with a fishing port (Little et al. 2007). The possible effect of this constraint (Figure 4) and the possible effect on the fishery if vessels could operate freely was explored by removing the condition constraining vessels to fish only in their port associated fishing areas and comparing the results from constrained and unconstrained simulations.

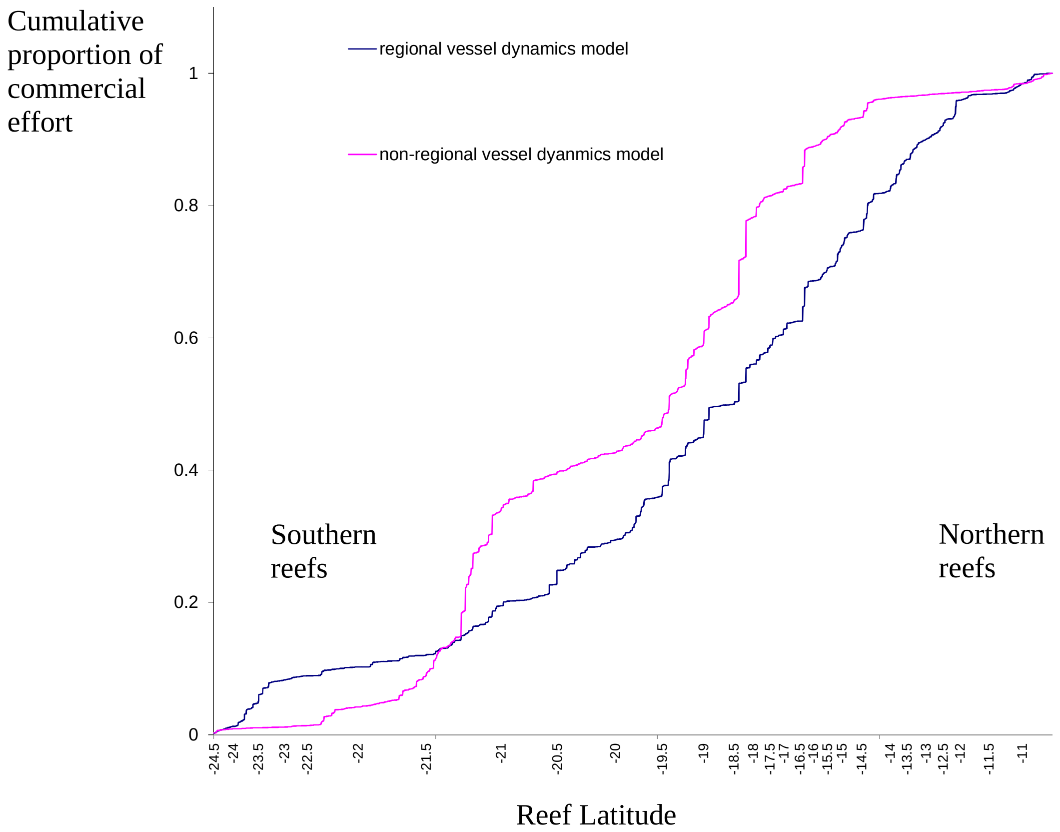


Figure 4 Cumulative distribution of effort across all reefs, ordered by latitude, during one projection year, when the vessels were constrained to fish in the their port associated fishing areas (regional vessel dynamics model) and when the constraint was lifted (non-regional vessel dynamics model) and effort could be allocated throughout the GBR

Three combinations of TAC (50%, 70% and 100% of the 1,288t TAC) were combined with both the regionally constrained and unconstrained (globally operating) fishing fleets. These scenarios were examined in terms of whether the fishery could achieve a set of management objectives set forth by stakeholders (Table 4).

Management Objectives

We sought input from a range of stakeholders in the CRFFF following the protocols used in Mapstone et al. (2004) to identify relevant management objectives and feasible management strategies by which those objectives may be attained. A stakeholder workshop was held in November 2012 to familiarise stakeholders with the modelling approach and identify and refine operational management objectives, performance indicators, and alternative management strategies for coral trout (**Extension and Adoption**). Our intention throughout this process was not to seek consensus among the different stakeholders but to capture the diversity of views (Mapstone et al. 2004), emphasising the benefits of an MSE approach which effectively examines the trade-offs amongst those views. Stakeholders included representatives with commercial, charter, and recreational interests, as well as conservation interests. The management strategies that were tested related to whether they could achieved the objectives set out by these respective groups.

The stakeholders were provided first with an opportunity to assess if the management objectives, performance indicators, and management strategies determined previously (see Mapstone et al. 2004, 2008; Little et al. 2009a), were still relevant. Objectives that were deemed to be still relevant were those concerning the spawning biomass in closed areas (objective 1, Table 4), and the available biomass in the areas open to fishing (objective 4, Table 4). A new objective for the available biomass on open reefs was added (objective 3, Table 4; Available Biomass on open reefs > 48% unfished levels 90% of the time, $P(AB/AB0 > 0.48) > 90\%$) to reflect the objective of achieving Maximum Economic Yield which was assumed to be at 48% of the unfished level. The objective relating to the spawning biomass on all reefs (objective 2, Table 4) was also updated from the desire to be above 90% of unfished levels to a more realistic 50% of unfished levels 80% of the time, reflecting the fact that approximately 50% of the reefs on the GBR are available to fishing pressure. Previous objectives relating to commercial fleet CPUE were dropped because it was believed that Profitability (objective 8, Table 4) better represented the objectives of the fleet. The recreational fisher objective (objective 7, Table 4) was also updated to represent the desire to catch 50% of the bag limit 50% of the time.

The objectives were specified in terms of quantifiable and measurable indicators that could be evaluated from ELFSim. A spatial division in the charter fleet CPUE applied to areas north or south of Townsville (Table 4). This division represented the different nature of charter trips in the different areas. For example, trips tend to cater to multi-day events south of Townville where the reefs are further offshore, whereas trips tend to cater mainly to single day outings north of Townsville.

The probability that an indicator achieved a management objective was determined by counting the number of replicates that met the objective in the final year of projections. Results were also presented by calculating the average value of key variables across replicates in the final year of the projection.

Table 4 Management objectives and performance indicators for coral trout derived from the stakeholder workshop

	Management Objective	In symbols	Performance Indicator
	Conservation		
1	Spawning Biomass on closed reefs > 90% unfished levels 80% of the time	$P(SB/SB_0 > 0.9) > 80\%$	SB/SB_0
2	Spawning Biomass on all reefs should be > 50% unfished levels 80% of the time (of the simulations)	$P(SB/SB_0 > 0.50) > 80\%$	SB/SB_0
	Stock		
3	Available Biomass on open reefs > 48% unfished levels 90% of the time	$P(AB/AB_0 > 0.48) > 90\%$	AB/AB_0
4	Available Biomass on open reefs > 40% unfished levels 90% of the time	$P(AB/AB_0 > 0.4) > 90\%$	AB/AB_0
	Economic		
5	Comm. CT CPUE > 80% 2006 CPUE > 90% of the time	$P(CPUE / CPUE_{2006} > 0.8) > 90\%$	
6	Charter CPUE south of Townsville - 50% of guests achieve the bag limit (2 daily bag limit / trip)(trip=4 days)	P(CPUE > 8 kg / day) > 50%	CPUE
7	Charter CPUE north of Townsville - 10% of the guests achieve the bag limit (bag limit / trip)(trip=1 days)	P(CPUE > 4 kg / day) > 10%	CPUE
8	Rec CPUE > 3.5 kg/dd 50% of the time (getting 50% bag limit 50% of time)	P(CPUE > 3.5) > 50%	CPUE
	Profitability		
9	Avg profit, π, should increase (be greater than the conditions in 2011) > 80% of the time	$P(\pi_{2035} / \pi_{2012} > 1) > 80\%$	π_{2035} / π_{2012}
	Harvest		
10	Total comm. CT catch > 80% TAC 90% of the time	P(C / TACC> 0.8) > 90%	C / TACC

3. Results

3.1 The Economic Survey

3.1.1 Summary

The commercial fishery consists of a wide diversity of operations, from single small vessels fishing inshore reefs with short (24 to 48 hour) trips, to larger operations using a mother vessel and a varying number of tender boats, undertaking trips of up to 2.5 weeks duration. In addition, fishing businesses display varying strategies regarding their effort and catch composition. Some focus solely on CRFFF species, in particular the landing of live CT, while others target a broader range of species, outside of the CRFFF, using hook and line as well as other fishing gears (e.g. nets, pots, trawl).

The commercial fishery is managed primarily via a range of both input and output controls detailed originally in the 2003 Coral Reef Fin-Fish Management plan (Queensland Government 2003) and updated in the Queensland Fisheries Regulation 2008. These controls include:

- technical regulations regarding maximum vessel length (20 meters), number of lines per fisher and number of hooks on lines (no more than 3 fishing lines per fisher at a time, and no more than six hooks or lures attached to the lines) and minimum and maximum sizes of fish;
- limited entry since 1984, through the issue of commercial fishing licences, which authorise the use of a primary boat (and identified tenders), to fish within the fisheries endorsed by fishery symbols on the licence. There are currently 369 licences authorised to operate in the CRFFF, of which approximately two thirds were recorded to be active in recent years (Fisheries Queensland 2011). Symbol endorsements on the licences may determine the regions in which a licence holder is entitled to fish, as well as the species which can be caught (the symbol “RQ” allowing catch of CRFFF species), the fishing techniques, and the maximum number of tenders which can be used in the fishing operation;
- commercial Total Allowable Catch (TAC) Limits. TAC limits were established in 2004 based on historical catch records. The available TACs are: coral trout (CT) ~ 1,288t, red-throat emperor (RTE) ~ 615t, and other species (OS) ~ 955t;
- allocation of the commercial TAC via individual transferable quota units (ITQs). The quotas were allocated as line units to individual licence holders in 2004 on the basis of 1 unit = 1kg (whole weight) of allowable landings of a particular species group. These entitlements are valid only if its owner also holds an RQ symbol that is in force for that particular year. A number of rules also apply to landings including designated landing points and prior notice of landing to maintain the integrity of the quota management system. Regulations also apply to the filleting of fish prior to landing;
- both input and output entitlements can be traded. Licences can be permanently sold or temporarily leased; fishery symbols can be transferred between licences; and individual line units can also be sold or leased between RQ symbols; and
- seasonal closures to protect spawning aggregations (currently two 5-day closures in October and November of each year).

In addition, the fleet predominantly operates in the area covered by *Great Barrier Reef Marine Park (GBRMP) Zoning Plan 2003* (GBRMPA 2004).

In 2010-11, total landings by the fishery amounted to approximately 1,600 tons and estimated total gross returns of approximately $44 million. This was composed of 763 tons of live CT (49% of total RQ landings) and 115 tons of dead CT. Live CT generated the greatest share (81%) of total gross returns from the fishery ($36 million, Figure 5) due to the much higher first sale price of this product category ($47/kg on average). With lower average sale prices (around $10/kg for RTE and $7/kg for OS), landings of RTE and OS represented approximately 43% of total landings and an estimated gross return of approximately $5.6 million, (less than 13% of the total returns from the fishery; Figure 5).

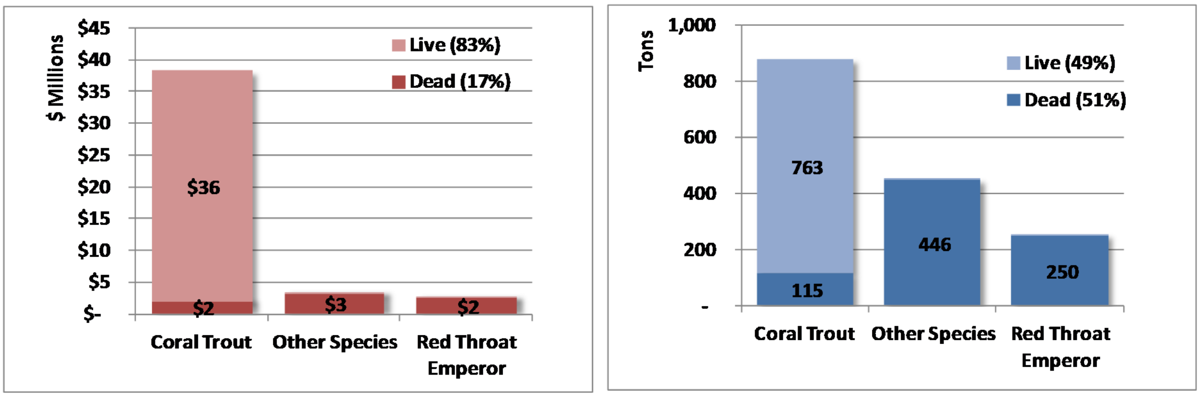


Figure 5 Estimated 2010-11 gross turnover (AU$ Million) of the CRFFF (Left) and total landings (Tons) in 201-11 (right). Source: own calculations based on Fisheries Queensland landings data and estimated average prices per species group

The fishery has undergone significant changes since the introduction of a commercial TAC and its associated management, and the *Great Barrier Reef Marine Park Zoning Plan 2003* (Zoning Plan). Some CT, RTE and OS quota and associated RQ symbols were bought out in a structural adjustment package associated with the introduction of the Zoning Plan. After these changes, there was an initial increase in catch rates and landings of CT up to a peak in 2008-09 where the entire TAC for these species was nearly landed. This was followed by a drop in catch rates, that was attributed to the ecological impacts of Cyclones Hamish (March 2009) and Yasi (February 2010), which led to a significant drop in fishing effort and catches in recent years (Figure 6).

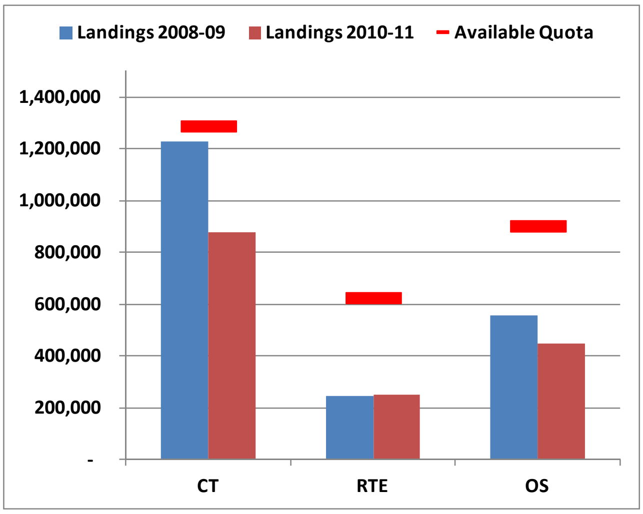


Figure 6 Landings in 2008-09 and 2010-11, and Total Allowable Landing limits. Source: Fisheries Queensland

This recent trend in the fishery has been reflected in the value of CRFFF access rights, in particular for quota units. Figure 7 reports the advertised nominal prices for CT quota sales and leases as observed in a specialized commercial fishing magazine (Queensland Fisherman) between January 2006 and December 2007, after the TACs were introduced (i.e. in the booming period of the CT fishery), and in the same magazine and quota broker web sites for months August 2011 to February 2012. While the lowest prices observed in the booming period were reportedly around $45/unit to $50/unit for sales and $3 to $4 for leases.

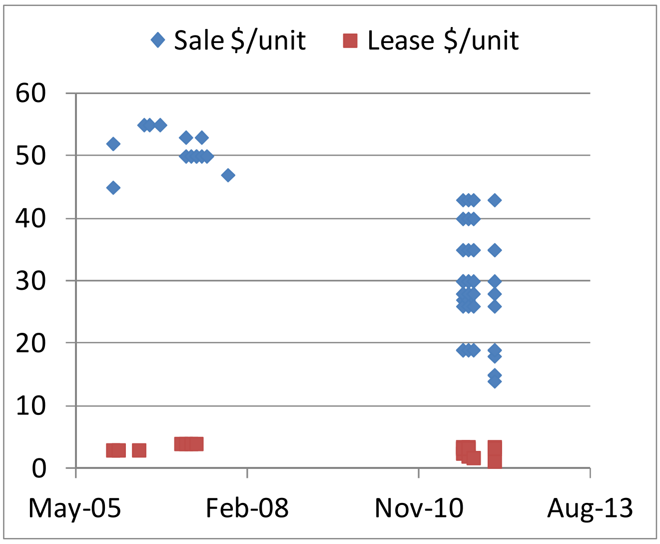


Figure 7 Changes in monthly advertised CT nominal quota lease and sale prices ($/unit), January 2006 to December 2007 and August 2011 to February 2012

Cluster analysis on the fleet profile led to the identification of three distinct groups of vessels (Table 5) with differing levels and types of fishing activity. These groups were used as a basis to define a stratified random sample of vessels (owners/operators) to interview, taking into account the regional distribution of vessel types.

Table 5 Technical characteristics of vessels in the three groups

Group	Number of vessels	Average Length (m) ± SD	Average Engine Power (kw) ± SD	Average Number of Tenders per Vessel ± SD
1 Generalist Line Fishers	133	8.6 ± 2.4	143.5 ± 83.9	1.3 ± 1.1
2 Dedicated live CT fishers	56	14.5 ± 2.7	175.5 ± 88.3	4.5 ± 1.3
3 Diversified fishers	24	9.9 ± 2.7	164.9 ± 93.2	1.3 ± 1.4
Grand Total	213	10.3 ± 3.6	154.1 ± 87.3	2.1 ± 1.9

Overall, the fleet profile led to the clear differentiation of (i) a large group of small ***Generalist line fishers***, many of whom were only very partially active in 2010-11, relatively focused on line fishing but only partially focused on CRFFF catch; (ii) a group of ***Dedicated live CT fishers*** with relatively large vessels focused on live CT, contributed to three quarters of the total harvest from the CRFFF, and (iii) a group of medium-sized ***Diversified fishers*** that operate across a range of fisheries including the CRFFF, which provide a small share of their total harvest, and whose RQ harvest only represents a small proportion of the total RQ harvest.

The first group (***Generalist line fishers***) represented the largest number of vessels (133). Vessels in this group were of smaller average size, and expended lower levels of fishing activity in 2010-11, mainly landing line-caught species, both from the CRFFF and from other fisheries, although they also landed some net-caught fish. The greatest share of CT landing by this group was composed of dead fish. Altogether, while representing a large number of vessels, this group only contributed to 20% of the total unloads of RQ species.

The second group (***Dedicated live CT fishers***) involved a relatively smaller number of vessels (56), of larger average size and a larger number of tenders. These vessels had much higher levels of average annual fishing effort, were exclusively focused on line fishing and targeted mainly CT. Vessels from this group landed mostly live CT (90% of all CT harvest). Altogether, this group contributed to 75% of total landings of RQ species in 2010-11.

The third group (***Diversified fishers***) involved a small (24) group of medium-sized vessels, operating in a wide range of fisheries, of which the CRFFF only constituted a small component in terms of both fishing effort and landings, but that had levels of activity in terms of fishing days, comparable to those observed for group 2 in 2010-11. This group represented a small share of the total landings of RQ species, which constituted on average less than a quarter of their annual harvest, while crab and net landings represented the largest share. CT landings by these vessels were mainly dead fish (80% of all CT harvest).

The costs of catching fish was highest in the ***Dedicated live CT fishers***, (Table 6). The costs of operations by the ***Generalist line fishers*** was about 60% of the ***Dedicated live CT fishers***, while the ***Diversified fisher*** costs represented about 15% of the ***Dedicated live CT fishers*** (Table 6). Fuel and oil costs included all diesel and petrol as well as oil costs at the annual level, and are presented before the fuel rebate in the tables and figures below (Table 6). This provides an indication of the magnitude of the fuel and oil costs which must be borne by operators upfront. A complete depiction of the vessel groups and the survey is given in Thébaud et al. (2014).

Table 6 Annual total catching costs ($) for each vessel group

Fishers		**n**	**mean**	**sd**	**median**	**s.e.m.**
Diversified fishers	**Total:**	**28**	**33,387**	**39,881**	**15,657**	**7,537**
	Fuel & Oil* ($)	28	19,672	19,631	11,212	3,710
	Bait & Tackle ($)	28	5,971	6,957	2,446	1,315
	Quota Lease ($)	28	899	1,439	-	272
	Food ($)	28	2,818	4,527	1,270	856
	Ice ($)	28	2,809	3,654	729	690
	Boxes & Bags ($)	28	1,019	3,141	-	594
	Other Catching Costs ($)	28	199	532	-	100
Generalists line fishers	**Total:**	19	**130,193**	**108,685**	**102,979**	**24,934**
	Fuel & Oil* ($)	19	58,157	41,457	54,639	9,511
	Bait & Tackle ($)	19	32,865	20,845	26,654	4,782
	Quota Lease ($)	19	23,725	28,696	10,823	6,583
	Food ($)	19	9,260	7,750	8,091	1,778
	Ice ($)	19	4,477	5,402	2,772	1,239
	Boxes & Bags ($)	19	845	2,449	-	562
	Other Catching Costs ($)	19	864	2,086	-	479
Dedicated live fishers	**Total:**	14	**219,422**	**136,575**	**197,774**	**36,502**
	Fuel & Oil* ($)	14	112,529	61,339	110,554	16,394
	Bait & Tackle ($)	14	48,929	21,493	45,665	5,744
	Quota Lease ($)	14	33,663	31,557	24,407	8,434
	Food ($)	14	22,346	18,592	16,964	4,969
	Ice ($)	14	950	1,878	-	502
	Boxes & Bags ($)	14	599	868	184	232
	Other Catching Costs ($)	14	406	848	-	227

3.1.2 Defining vessel characteristics for ELFSim

Allocation of vessels to vessel groups and regions

Data

In collaboration with Fisheries Queensland, an initial list of vessels identified by their boat marks was created, based on the vessels that held an RQ symbol on their licence in 2010-11. This list contained 369 individual boat marks, for which individual vessel technical characteristics, total fishing effort and its distribution across RQ and non-RQ fishing, annual landings information from logbooks and total unloads of RQ species from the quota monitoring system were recorded. Approximately a third (115) of the boat marks selected through this initial process were inactive in the reference year (2010-11). Another 41 vessels had no unloads of RQ species recorded for the reference year (i.e. had not fished the CRFFF in 2010-11). This led to a remaining list of 213 vessels for which all technical, effort and landings information was available, and which had landed some RQ species in the reference year.

The results of the economic survey indicated that 15m vessel length defined the *Dedicated live fishers* from the *Generalist line fishers* and *Diversified line fishers*. In addition, the survey results showed that on average, the value of the live fish catch landed by Diversified fishing operations represented only 12% of the total landed value by these operations at the annual level. These criteria were applied to the 213 vessels for which annual catch data was available, to allocate the vessels to one of the three groups:

1. Diversified,
2. Generalist: Live CT – Small, and
3. Dedicated: Live CT – Large.

In addition, the main unloading port used by these vessels in 2010-11 was also available in the data used for the fleet profile. The list of unloading ports was harmonized with the list of ports in the ELFSim database, to establish a description of the vessel distributions across groups and unloading ports. From the survey and fleet description vessel types differed regionally by port (Table 7).

Table 7 Distribution of vessels across groups and unloading ports (based on the 213 vessels identified as having been active in the CRFFF in 2010-11)

Port	Diversified		Dedicated: Live CT Large		Generalist: Live CT small		Grand Total
	n	%	n	%	n	%	n
1 Cooktown	3	21	2	15	9	64	14
2 Port Douglas	8	47	1	6	8	47	17
3 Cairns	5	83		0	1	17	6
4 Innisfail	16	70		0	7	30	23
5 Townsville	17	89		0	2	11	19
6 Bowen	2	12	2	12	13	76	17
7 Mackay	2	12	5	29	10	59	17
8 Yeppoon	10	100		0		0	10
9 Gladstone	23	68	7	21	4	12	34
10 Bundaberg	28	97	1	3		0	29
11 Brisbane	27						27
Grand Total	**141**		**18**		**54**		**213**

This depiction of the reef line fishery fleet has been integrated into the ELFSim database, which consists of 369 vessels assigned one of 10 homeports used in ELFSim based on the port closest to the registered homeport. Vessels were distributed across the ELFSim homeports as in Table 8.

Table 8 Distribution across ports of the updated vessel list operating in the reef line fishery. (adjusted frequency redistributes vessels from Brisbane) Arrows indicate whether the number of vessels associated with the port has gone up ↑ or down ↓ since Little et al. (2007). Also, for comparison the change in proportion of commercial effort fished on reefs of the different regions is shown for the interval 1989-2000, on which Little et al. (2007) was based, and a more recent interval, 2001-20011

ELFSim Port	Frequency	Proportion	Proportion (excl. Brisbane)	Little et al. (2007)	Region	Proportion effort (1989-2000)	Proportion effort (2001-2011)
Cooktown	7	0.02	0.03	0.03	Far North	0.09	0.09
Port Douglas	22	0.06	0.10 ↑	0.04			
Cairns	45	0.12	0.20 ↑	0.09	Cairns	0.13	0.14 ↑
Innisfail	32	0.09	0.14 ↓	0.15			
Townsville	21	0.06	0.09 ↑	0.06	Townsville	0.35	0.39 ↑
Bowen	31	0.08	0.14 ↓	0.19			
Mackay	26	0.07	0.11 ↓	0.22	Mackay	0.24	0.22 ↓
Yeppoon	10	0.03	0.04 ↓	0.09			
Gladstone	23	0.06	0.10 ↑	0.07	Swains	0.11	0.12 ↑
Bundaberg	44	0.12	0.05 ↓	0.06	Cap-bunkers	0.08	0.03 ↓
Brisbane	108	0.29					

More than 40% of the homeports were in the south in the Bundaberg and Brisbane area. The Brisbane vessels however represented mailing addresses of registered vessels, and so it was deemed unrealistic that vessels actually fished from Brisbane. We therefore, re-distributed these vessels according to the proportions in the other ports, with the assumption that Bundaberg contained 5% of the fleet (this values was used in Little et al.; 2007). This resulted in a distribution (Table 8) roughly comparable to that used by Little et al. (2007). In the current version of the model, Port Douglas and Cairns have more, almost twice the vessels assigned previously, while Mackay and Yeppoon have fewer associated vessels. The shift in vessel distribution to the north, notably to Townsville, Cairns and Port Douglas came at the expense of Bowen, Mackay and Yeppon. This northward shift in vessels roughly matched the shift in effort (Table 8). As Little et al. (2007) showed however, several of the ports fish overlap in the latitudes at which they fish.

Trip numbers and trip lengths

The economic survey also collected information on the number of fishing days and the average trip length. The average number of trips per year used by the simulation model was calculated from the ratio of the total Annual Fishing days and the Average Number of Days per trip (Table 9).

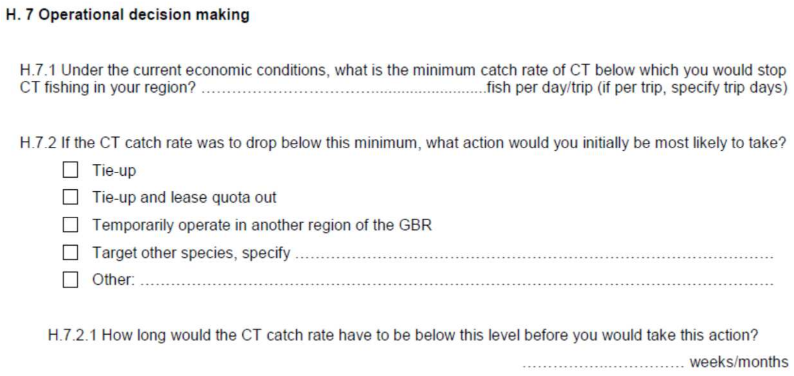
Table 9 Annual number of fishing days and average trip lengths per vessel type (source: economic survey)

	Diversified vessels	Generalist: Live CT – small vessels	Dedicated: Live CT large vessels
Average trip length	2.82	7.2	12.64
SD trip length	1.33	2.63	2.44
Average annual fishing days	78.39	131.20	171.07
SD annual fishing days	70.7	50.44	39.56

Vessel mobility

Data

The last section of the economic survey included a question on decision-making by the operator if confronted with low catch rates in their fishing area during a set period of time. The question specified the CPUE conditions, and the length of time required before an action would be taken by the respondent. The actions included stopping fishing altogether, selling or leasing out quota, target a different species of moving on to another area, as follows:



H. 7 Operational decision making

H.7.1 Under the current economic conditions, what is the minimum catch rate of CT below which you would stop CT fishing in your region? ……………………………………………………fish per day/trip (if per trip, specify trip days)

H.7.2 If the CT catch rate was to drop below this minimum, what action would you initially be most likely to take?

- ☐ Tie-up
- ☐ Tie-up and lease quota out
- ☐ Temporarily operate in another region of the GBR
- ☐ Target other species, specify ……………………………………………………………………………
- ☐ Other: ……………………………………………………………………………………………………

H.7.2.1 How long would the CT catch rate have to be below this level before you would take this action?

…………………………… weeks/months

The responses to these questions are presented in Figure 8 and indicate that for vessels that target live CT moving to another area was the most likely response to undesirable catch rates. This provided the basis for exploring the effect of a globally unconstrained fleet (see Section **3.2.3 Evaluating the effects of fleet mobility**). ‘Other’ actions mentioned by respondents (Figure 8) consisted of the following: “Go fishing no matter what” and ”Attempt to target trout in a different way e.g. cut expenses by using other bait other than pilchards, etc.”.

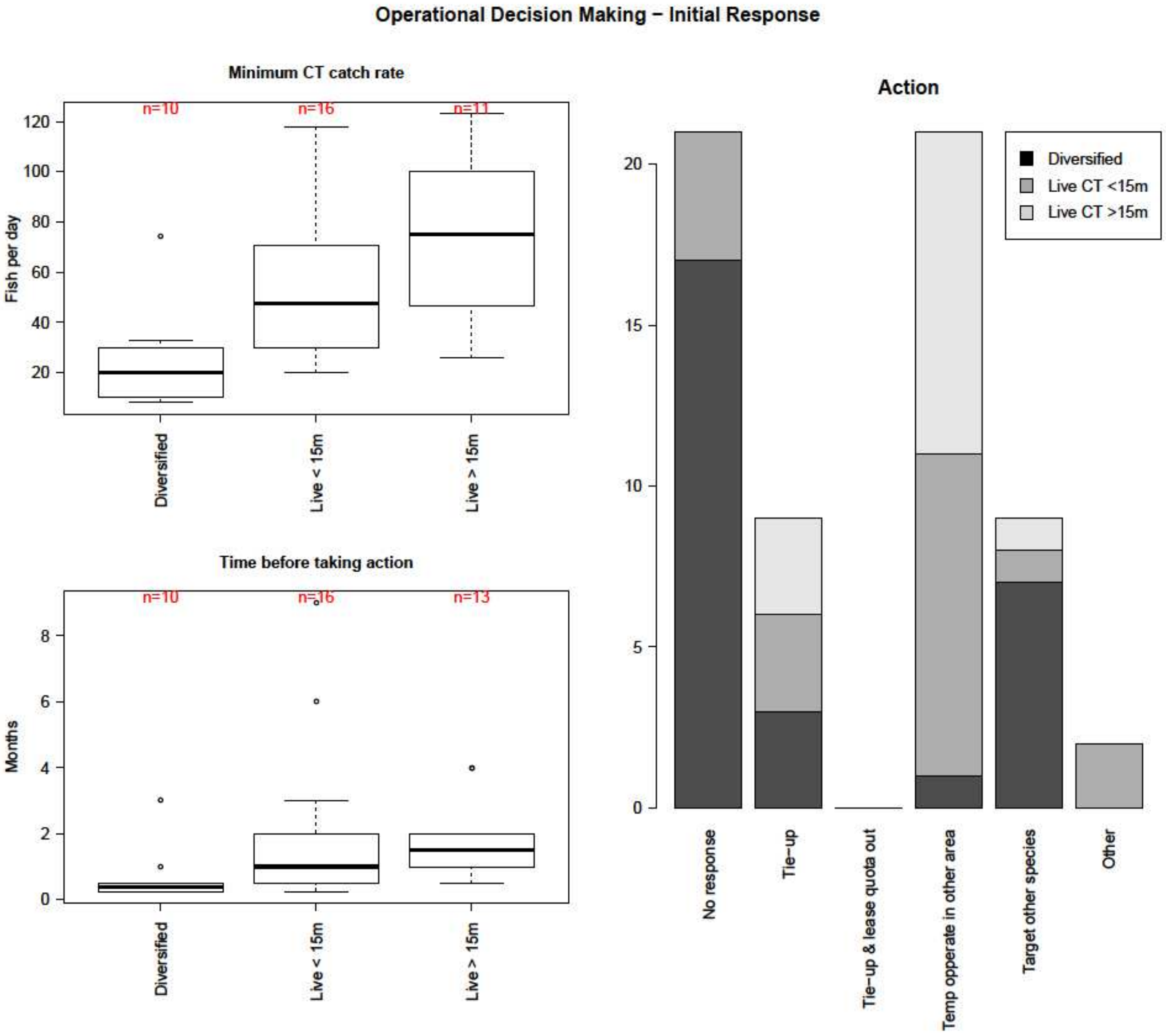


Figure 8 Operational decision-making: short-term responses

3.1.3 Parameterization of vessel mobility in ELFSim

In the non-regional, global vessel dynamics model, vessels may decide to move to another spatial location in the fishery. This depends on the vessel type. Based on the data collected (Figure 8), a proportion of operators indicated that they would likely operate their vessel from a different region of the GBR. These results were summarized in Table 10.

Table 10 Proportions of vessels likely to temporarily operate in another region of the GBR

Vessel Length	Action	Proportion in sample (n=62) M_l
<15m (Diversified and Small vessels)	Temporarily operate elsewhere in the GBR	23%
	Other	77%
>15m	Temporarily operate elsewhere in the GBR	71%
	Other	29%

We used the proportions in Table 10 to indicate willingness for operators to relocate their fishing operation temporarily in a region different from their main (home) port. These proportions are used to define the probability a vessel will choose to fish outside of the region that is associated with their homeport. No effort was made to include costs or constrain the movement of vessels, so the scenario may be unrealistic. However, it is used as an initial comparison, and may highlight the effect of regionally constrained fishing.

3.1.4 Defining economic parameters for use by ELFSim

Operating costs

Table 11 presents the operating costs per fishing unit (dory) for the line fishing technique only, based on the results of the economic survey. Fuel costs indicated here include diesel and petrol for both primary vessels and tenders. These are before the fuel rebate is paid back to operators. Based on the information collected during the survey, it appears that the fuel rebate amounts to approximately 28% of the total fuel cost.

Table 11 Operating costs per fishing unit (dory), for line fishing only (Source: economic survey)

Vessel group:	Diversified		Generalist: Live CT small vessels		Dedicated: Live CT large vessels	
Cost category	Average	sd	Average	sd	Average	sd
Bait & Tackle	71.3	79.7	54.2	26.9	45.2	13.9
Boxes &Bags	16.4	49.4	1.1	3.1	0.6	0.9
Food	30.3	34.2	15.0	10.2	21.1	13.2
Fuel & Oil	183.1	150.6	88.3	32.4	108.4	54.1
Ice	31.0	41.8	8.5	11.8	1.0	1.9
Other Catching Costs	3.9	12.1	1.6	3.3	0.4	0.8
Quota Leasing	13.4	22.8	36.6	39.2	34.5	35.0

Table 12 presents the operating costs per fishing unit across all fishing activity of vessels including line and other gears. The differences between line-fishing related costs and costs relating to other types of fishing are small. ELFSim used the total catching costs in the model parameterization given that the crew costs are only available at the overall scale of the operation (Table 12).

Table 12 Total operating costs per fishing unit (dory). (Source: economic survey)

Vessel group:	Diversified		Generalist: Live CT small vessels		Dedicated: Live CT large vessels	
Cost category	**Average**	**sd**	**Average**	**sd**	**Average**	**sd**
Bait & Tackle	71.3	79.7	54.2	26.9	45.2	13.9
Boxes &Bags	16.4	49.4	1.1	3.1	0.6	0.9
Food	30.3	34.2	15.0	10.2	21.1	13.2
Fuel & Oil	183.1	150.6	88.3	32.4	108.4	54.1
Ice	31.0	41.8	8.5	11.8	1.0	1.9
Other Catching Costs	3.9	12.1	1.6	3.3	0.4	0.8
Quota Leasing	13.4	22.8	36.6	39.2	34.5	35.0

Fish prices

Fisheries Queensland provided the survey team with average quarterly beach prices from the Queensland Seafood Marketers Association for CT, RTE and Spanish Mackerel, distinguishing between live and dead fish, CT size (over or under 1.2kg) and product presentation (whole or filleted) for dead fish, from the last quarter in 2006 to the last quarter in 2011. Two major processors of live fish provided information on live CT prices. The first processor provided price information for the period from April 2005 to March 2011, with a break in the data set from January to June 2006. The second processor provided quantities and average ex-vessel prices of live CT from January 2004 to December 2011, with a break for quantities for January 2009 to December 2010. The fish prices used in the model (Table 13) included prices for different CT product, live and dead, as well as RTE and obtained from a time series analysis. Prices for dead CT used were from Little et al. (2007).

Table 13 Fish prices by product used in ELFSim (AUD/kg)

Month	Live CT	Dead CT	RTE
Jan.	54.90	12.84	9.82
Feb.	43.60	13.09	9.63
March	42.80	13.63	9.68
April	36.70	14.18	9.93
May	33.80	13.9	9.56
June	34.80	13.77	9.54
July	46.10	13.58	9.72
August	43.00	13.13	9.45
Sept.	49.20	13.08	9.8
Oct.	49.70	13.47	9.72
Nov.	45.20	13.43	9.8
Dec.	44.70	12.88	9.8

Fish prices by vessel type

Since each vessel type caught different proportions of CT product, the prices were weighted by the proportion of live and dead CT product each vessel type caught (Table 14). These data were obtained from the economic survey.

Table 14 The proportion of live coral trout in the catch for each vessel type derived from the economic survey

Vessel type	Proportion of live fish caught
Diversified vessels	0.06
Generalist	0.90
Dedicated	0.89

3.2 Management strategy evaluation modelling

Management strategy evaluations were conducted using the DAF stock assessment under different monitoring strategies, to compare potential harvest control rules, and to evaluate the effects of fleet mobility on achieving stakeholder objectives.

3.2.1 Queensland DAF stock assessment evaluation

Evaluation of the DAF stock assessment model used different monitoring strategies including from a simulated projected line survey, and at three levels of length data aggregation: on board observer data collection, port observer data collection, and processor port sampling. Using data from the projected line survey, mainly in the form of age composition, the DAF stock assessment model typically over-estimated the underlying operating model available biomass by about 10% (Figures 9, 10). Most estimates ranged around 70% B_0 (Figure 10). Throughout the projection period fewer than 10 estimation attempts resulted in estimates greater than 80% B_0, while a similar amount underestimated the underlying operating model biomass, which fluctuated about 60% B_0 (Figure 10).

The assessment model estimated biomass more precisely when it relied on data from on-board observers (Figure 11) because the data were less contradictory as they were sourced from only blue (fished) reefs. Across the entire projection period, starting in 2012, when very little observer data is used in the assessment model, through to the end of the projection period, the estimated biomass had a broader range of estimates, some as low as 20% B_0 (Figure 12). The effect of increased sampling on the accuracy of the assessment model is seen in Figure 12 where the scenario with the highest number of observers (50), and highest observer coverage (25%) had the most precise estimates (lowest variability among replicates) and the estimate closest to the actual underlying biomass.

Compared to the on-board age class data collection at the vessel scale (Figure 11, 12), there is almost no change when aggregating the observer data to the port scale (Figure 13, 14). The reason for this is that the on-board monitoring strategy assigns age data to “populations” in the assessment model, and the port-sampling monitoring strategy assigns data to “sub-regions” in the assessment model (Appendix D: Figure 110). Originally, each “sub-region” in the assessment model was intended to consist of four “populations”, which contain reefs, and the associated fisheries data, with different management histories. Namely,

Population 1: Reefs **open** in pre-RAP, and **open** in RAP
Population 2: Reefs **open** in pre-RAP, but **closed** in RAP
Population 3: Reefs **closed** in pre-RAP, but **open** in RAP
Population 4: Reefs **closed** in pre-RAP, and **closed** in RAP

However, there is little distinction in the ELFSim historical catch and effort data between historically opened and closed reefs as almost all reefs in the ELFSim historical catch and effort database have catch and effort data, even if they were nominally identified as being closed historically. The reason for this is that the algorithm that allocates data collected at the 6’ grid cell to the reef level does not accurately account for the historically closed reefs. As a result of the disaggregation algorithm, only a 2-population scheme makes sense: reefs open pre-RAP and open post-RAP, and reefs open pre-RAP and closed post-RAP, and thus populations and sub-regions are identical with respect to the on-board age data collection process.

The effect of the “regional” scale monitoring strategy, i.e. processor-port sampling strategy, also showed little difference from the “population” scale on-board monitoring strategy. The assessment model was relatively accurate in the final year of the projection (Figure 15), and across the entire projection period, the estimated biomass had ranged as low as 20% B_0 (Figure 16). Compared to the “population” level on-board monitoring strategy, the “regional” scale processor-port monitoring varied very little (Figure 16). The reason for this is that the age data in the processor-port strategy, was aggregated mainly across the sub-regions north of Townsville (Appendix D), which probably had little effect on the assessment model, when most of the fishery operations, in terms of effort and catch, are south of Townsville. Nevertheless, small difference were seen between the use of on-board sampling, and aggregated processor port sampling but with more intensive sampling, either by increasing the number of observers, or the coverage of observers (Figure 17).

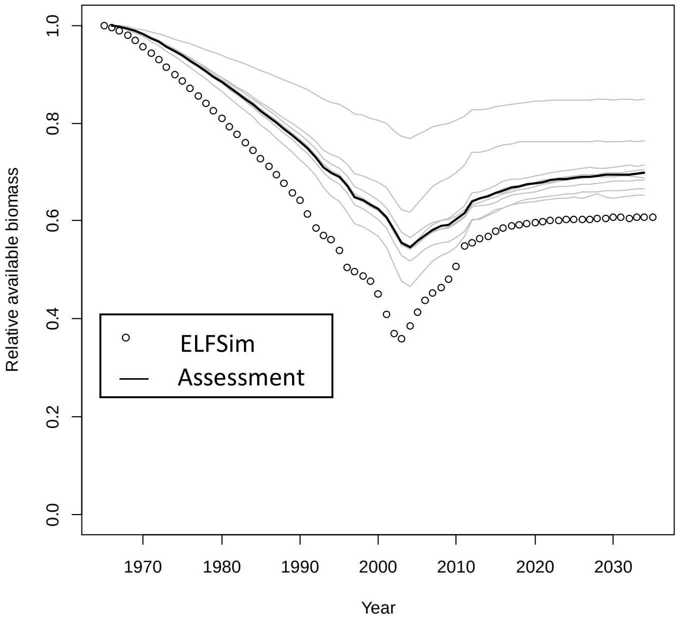


Figure 9 Mean (over replicate projections) relative available biomass trajectory from the ELFSim operating model (circles), and the mean estimated relative biomass trajectory (dark line) from the assessment model, using data from the projected line survey monitoring strategy, for assessments conducted in the final year (2035) of the simulation. Grey lines represent individual replicate biomass estimates in the final year of the simulation

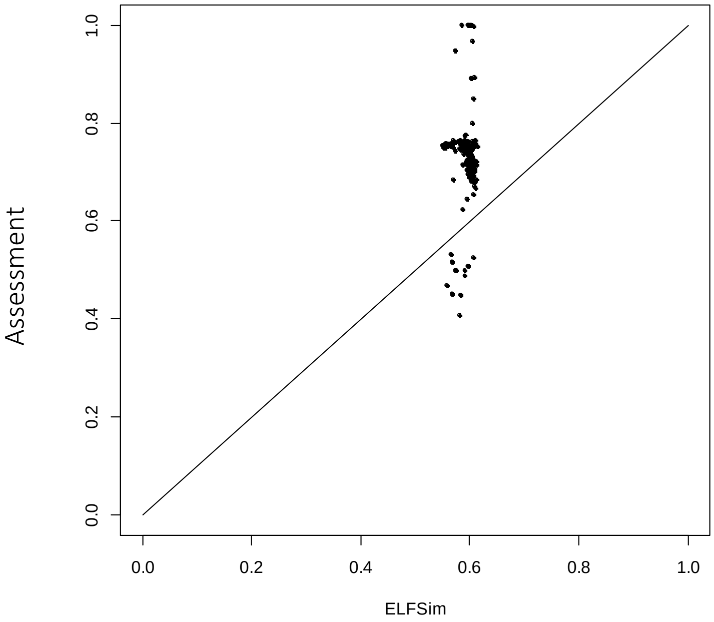


Figure 10 The estimated relative available biomass from the assessment model using data from the projected line survey monitoring strategy, in each year and replicated simulation, plotted against the corresponding actual relative biomass in the ELFSim operating model

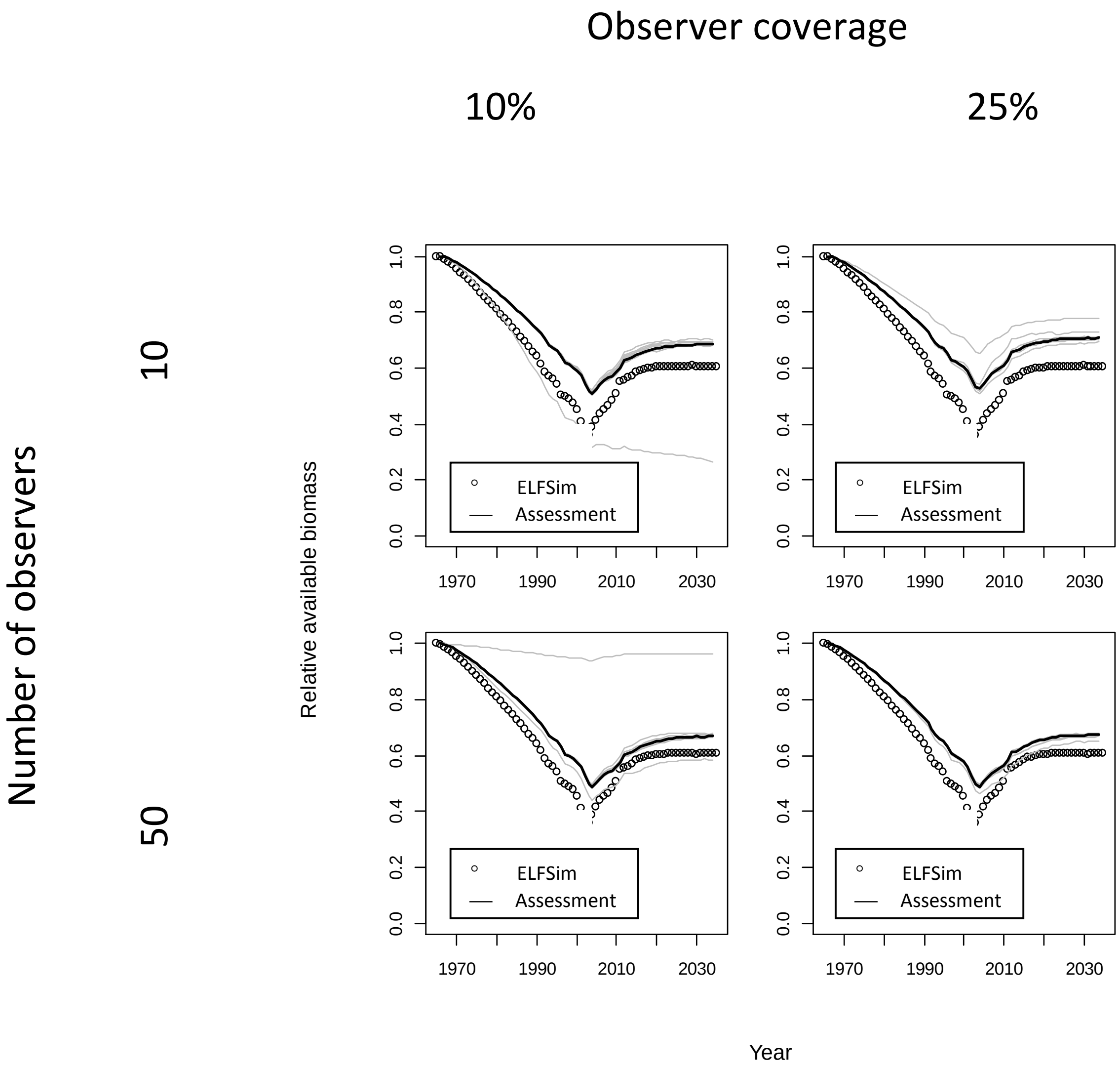


Figure 11 Mean (over replicate projections) relative available biomass trajectory from the ELFSim operating model (circles), and the mean estimated relative biomass trajectory (dark line) from the assessment model, using data from the on-board observer monitoring strategy for 2 levels of observers (10, 50), and 2 levels of coverage (10%, 25%), in the final year (2035) of the simulation. Grey lines represent individual replicate biomass estimates in the final year of the simulation

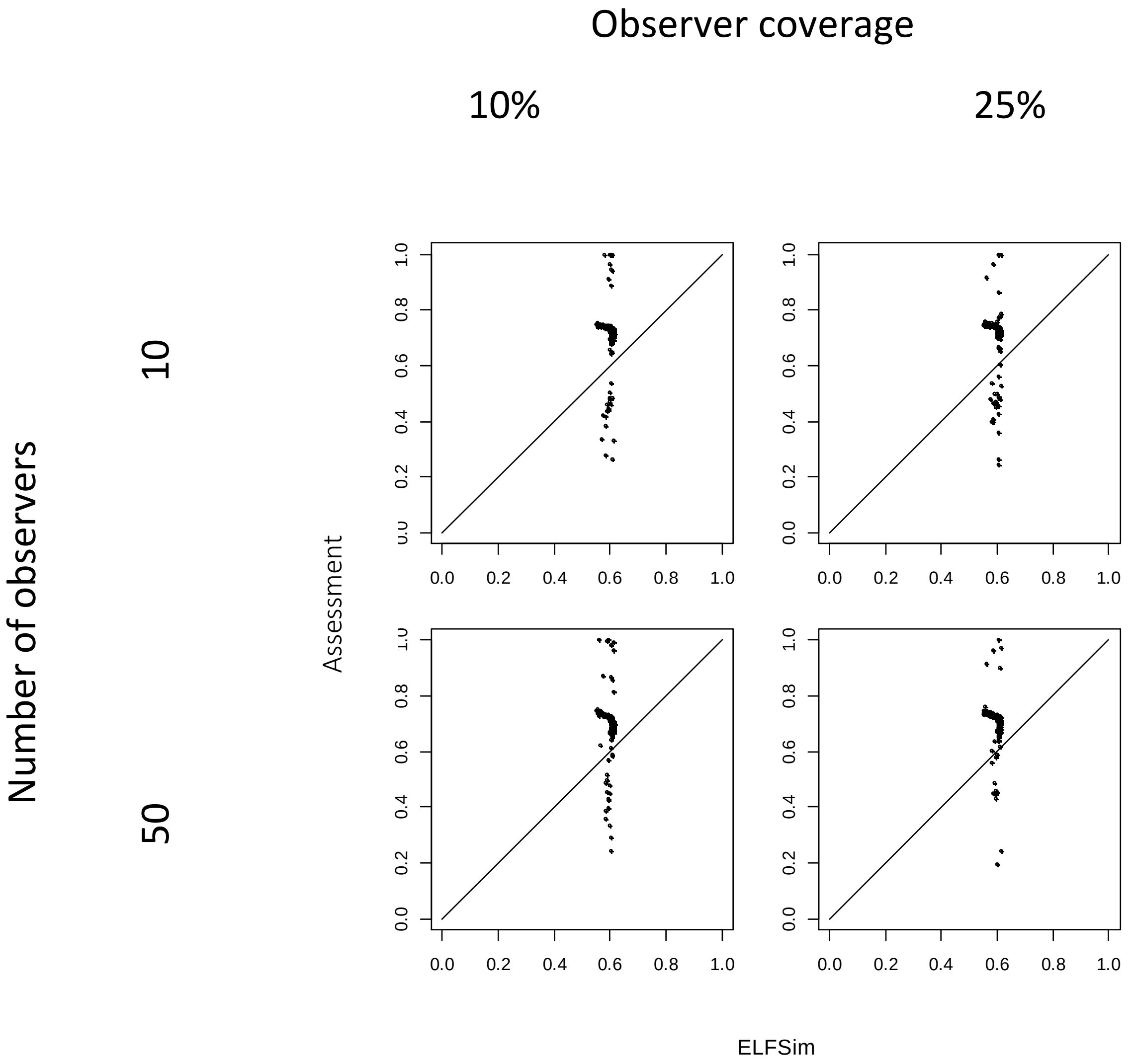


Figure 12 The estimated relative available biomass from the assessment model using data from the on-board observer monitoring strategy for 2 levels of observers (10, 50), and 2 levels of coverage (10%, 25%), in each year and replicated simulation, plotted against the corresponding actual relative biomass in the ELFSim operating model

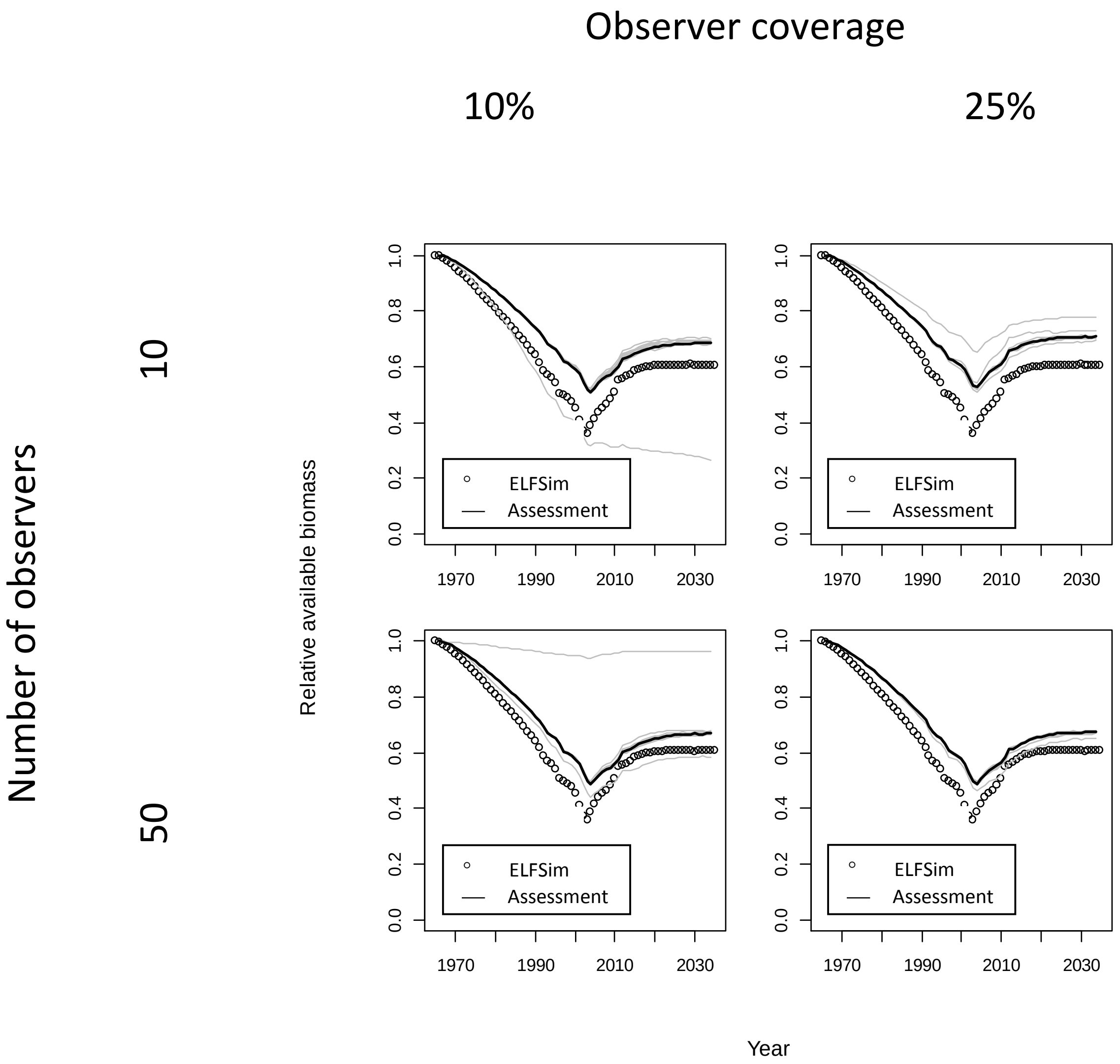


Figure 13 **Mean (over replicate projections) relative available biomass trajectory from the ELFSim operating model (circles), and the mean estimated relative biomass trajectory (dark line) from the assessment model, using data from the aggregated observer port-sampling monitoring strategy, for 2 levels of observers (10, 50), and 2 levels of coverage (10%, 25%), in the final year (2035) of the simulation. Grey lines represent individual replicate biomass estimates in the final year of the simulation**

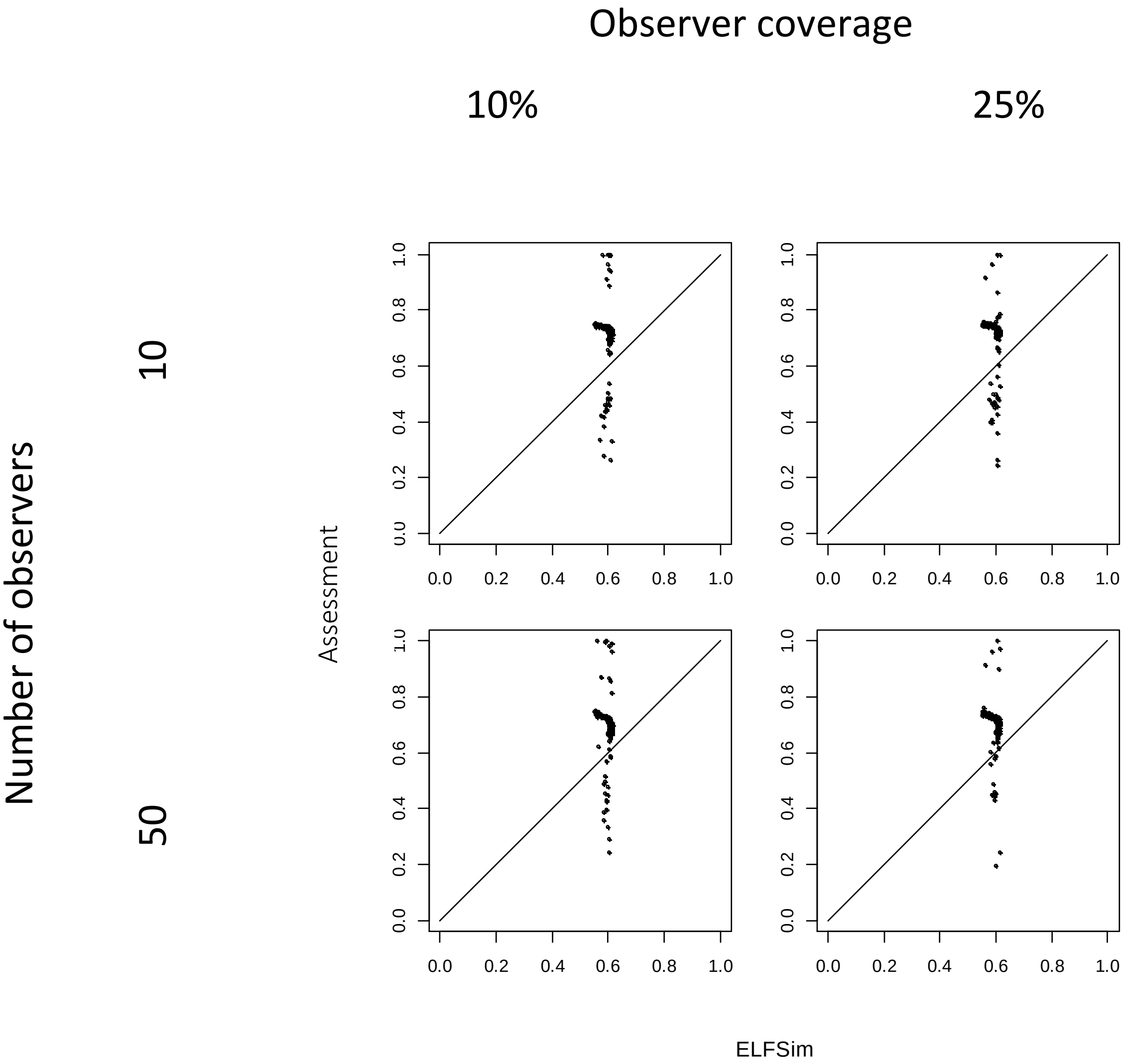


Figure 14 The estimated relative available biomass from the assessment model using data from the aggregated observer port-sampling monitoring strategy for 2 levels of observers (10, 50), and 2 levels of coverage (10%, 25%), in each year and replicated simulation, plotted against the corresponding actual relative biomass in the ELFSim operating model

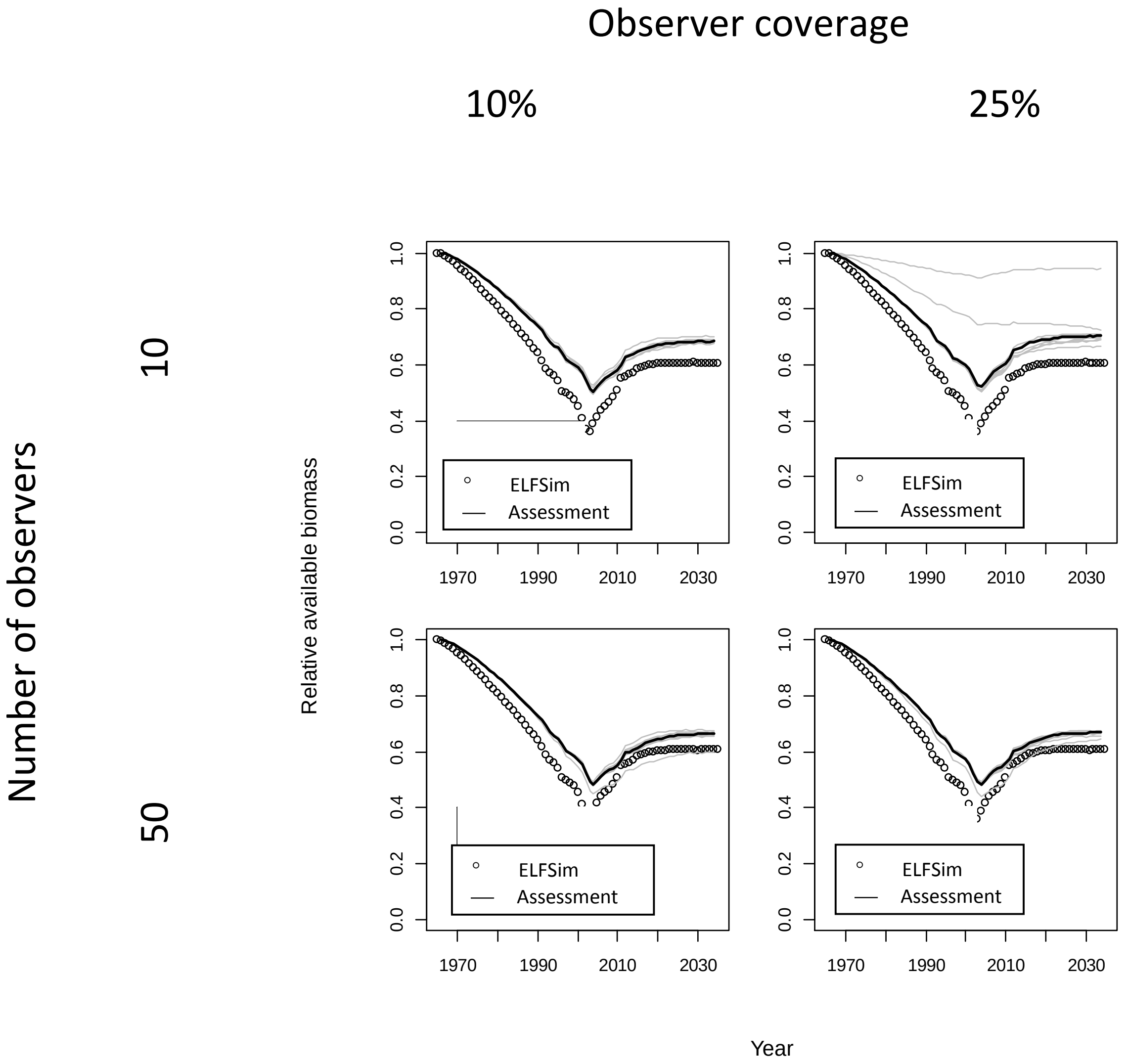


Figure 15 Mean (over replicate projections) relative available biomass trajectory from the ELFSim operating model (circles), and the mean estimated relative biomass trajectory (dark line) from the assessment model, using data from the aggregated observer processor port-sampling monitoring strategy, for 2 levels of observers (10, 50), and 2 levels of coverage (10%, 25%), in the final year (2035) of the simulation. Grey lines represent individual replicate biomass estimates in the final year of the simulation

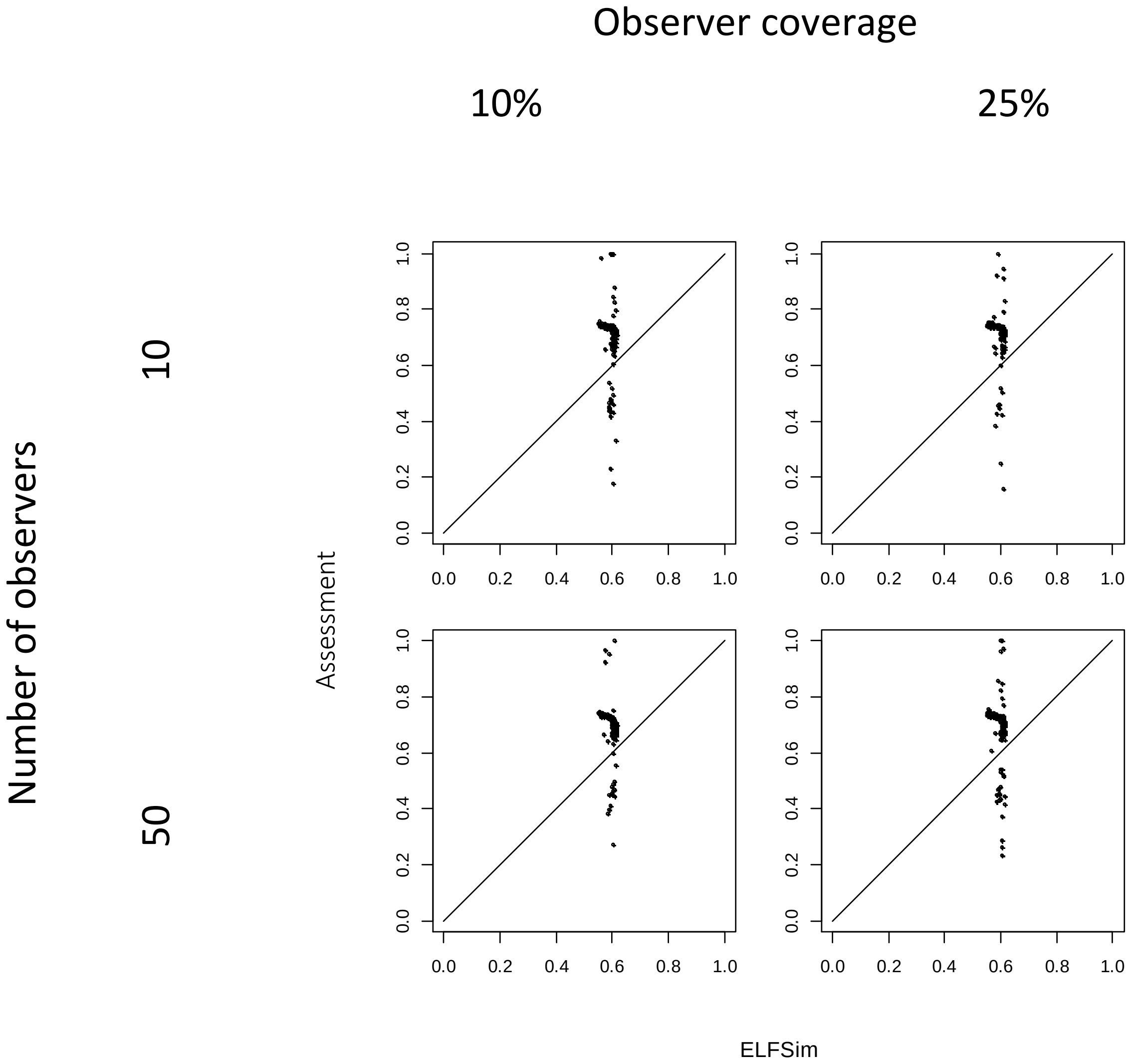


Figure 16 The estimated relative available biomass from the assessment model using data from the aggregated observer processor port-sampling monitoring strategy for 2 levels of observers (10, 50), and 2 levels of coverage (10%, 25%), in each year and replicated simulation, plotted against the corresponding actual relative biomass in the ELFSim operating model

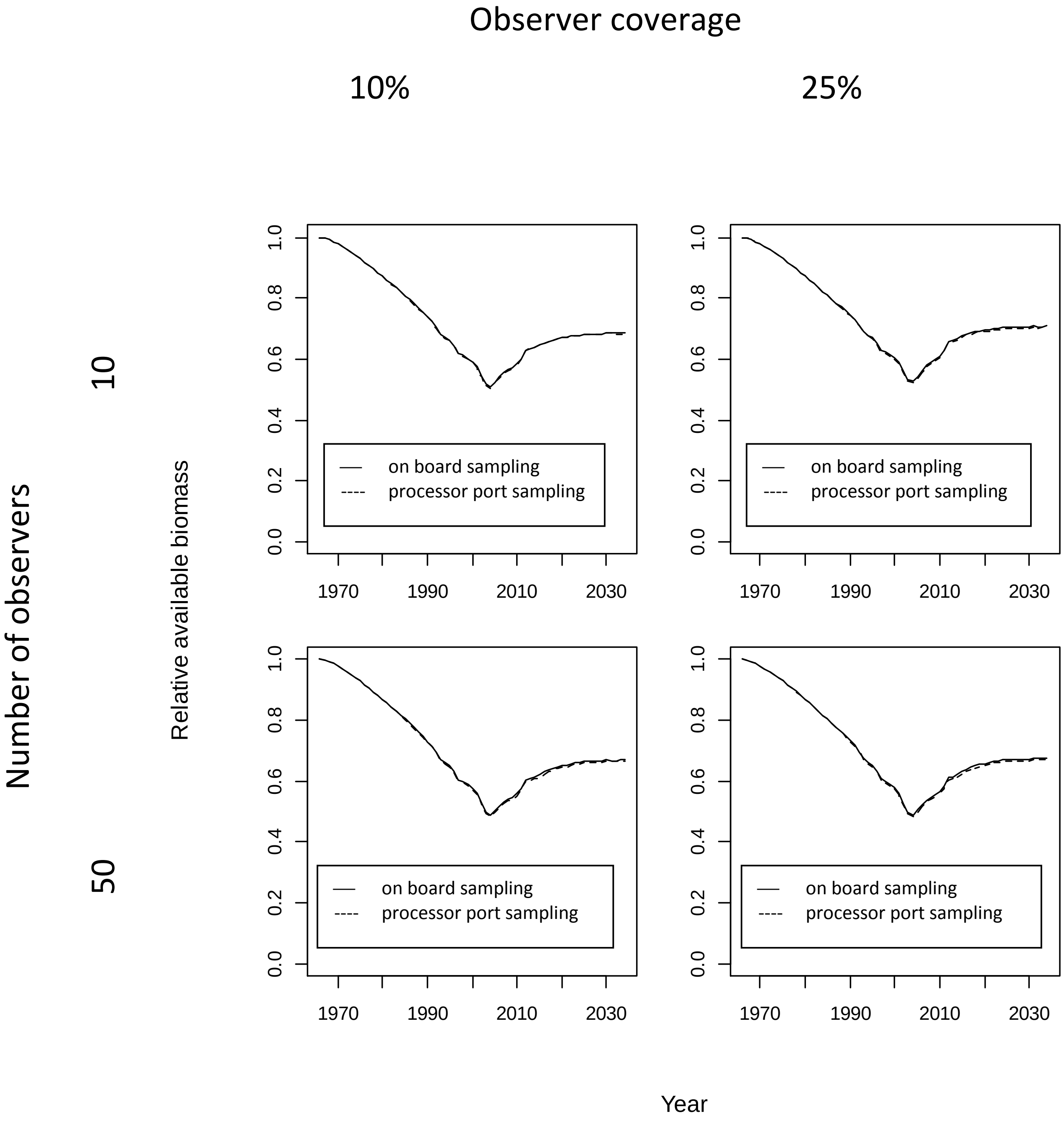


Figure 17 Comparison between estimated relative available biomass by the Queensland DAF assessment model strategy data using on-board sampling, and processor port sampling, for two levels of observers (10, 50), and two levels of coverage (10%, 25%) in the final year (2035) of the simulation

3.2.2 Comparison of proposed harvest control rules

Three harvest control rules were evaluated based on the:

1. DAF stock assessment
2. CPUE of the entire commercial fleet
3. CPUE of a subset of the commercial fleet

The feedback HCR based on the DAF stock assessment led to catches that were higher than under the current TAC with no harvest control rule (Figure 18). These catches however, were more variable (Figure 18), with the TAC sometimes declining several hundred tonnes in a single year, only to return to previous levels in the next year. This is the result of random experimental error in the biomass estimates by the assessment model, which would probably be explored in more detail if the assessment were done in reality. In these simulations, however, these results were kept and presented for demonstrative purposes. The effect of the HCR is to reduce the biomass slightly as a result of the increased catches (Figure 19).

It should be noted that the results are predicated on a 2011 available biomass level of about 55% of pre-exploitation biomass (see “Model projections” in section 2.2 above). In reality it is unknown whether the level of 55% at the start of the projection period is accurate, and so the most appropriate sustainable catch could be numerically different from indicated here. The results presented here however are intended to indicate the ability of the proposed harvest strategy to achieve the implied fishery objective of estimating and maintaining the fishery in the historical conditions experience in 2006-08.

The CPUE-based HCR that used the full commercial fleet standardised CPUE to inform the HCR reduced the TAC at the start of the projection period from 1,300t to about 11t (Figure 20 top). The catch and the CPUE in the historical period both declined in the years prior to the projection period (shaded grey areas, Figure 20, 21) with the corresponding biomass increasing a result of the declining catches (Figure 22). This indicates that the relation between biomass from the model and the historical aggregated across the whole GBR are not proportional, possibly as a result of spatial changes in the distribution of effort that were experienced in the fishery.

In the projection period, the TAC was maintained in the first year of the projection period before there was a CPUE value to use in the HCR. It increased afterwards because CPUE and biomass increased (Figure 21, 22). The model eventually settles in the final years of the projection period, on relatively high biomasses, and lower catches than specified by the catch target catch, C_{targ} (defined as the average catch over the same period indicated by the grey area of Figure 20). The reason for such high biomass and low catch is that the targeted fishery state ($CPUE_{targ}, C_{targ}$) likely does not lie on the equilibrium curve (Figure 23) and attempts to achieve $CPUE_{targ}$ require lower catches (Figure 23).

The feedback HCR that used the CPUE from a subset of the fleet resulted in similar result of low TACs, but led to much greater variability among simulations in both the TAC (Figure 20 bottom), and CPUE (Figure 21 red). The reason for increased variability is the smaller number of sample vessels selected based on port stratification (Table 3), used to calculate the CPUE index for the HCR, and hence great variability. Biomass levels are higher with the low TAC trajectories from the CPUE-based HCRs, than with a constant TAC, and no HCR (Figure 22). The CPUE-based HCR that used data for the whole fleet led to an available biomass that stabilized at about 70% of B_0 (Figure 22 top), while the HCR that used a subset of the fleet to calculate the CPUE index led to biomass of about 80% B_0 (Figure 22 bottom).

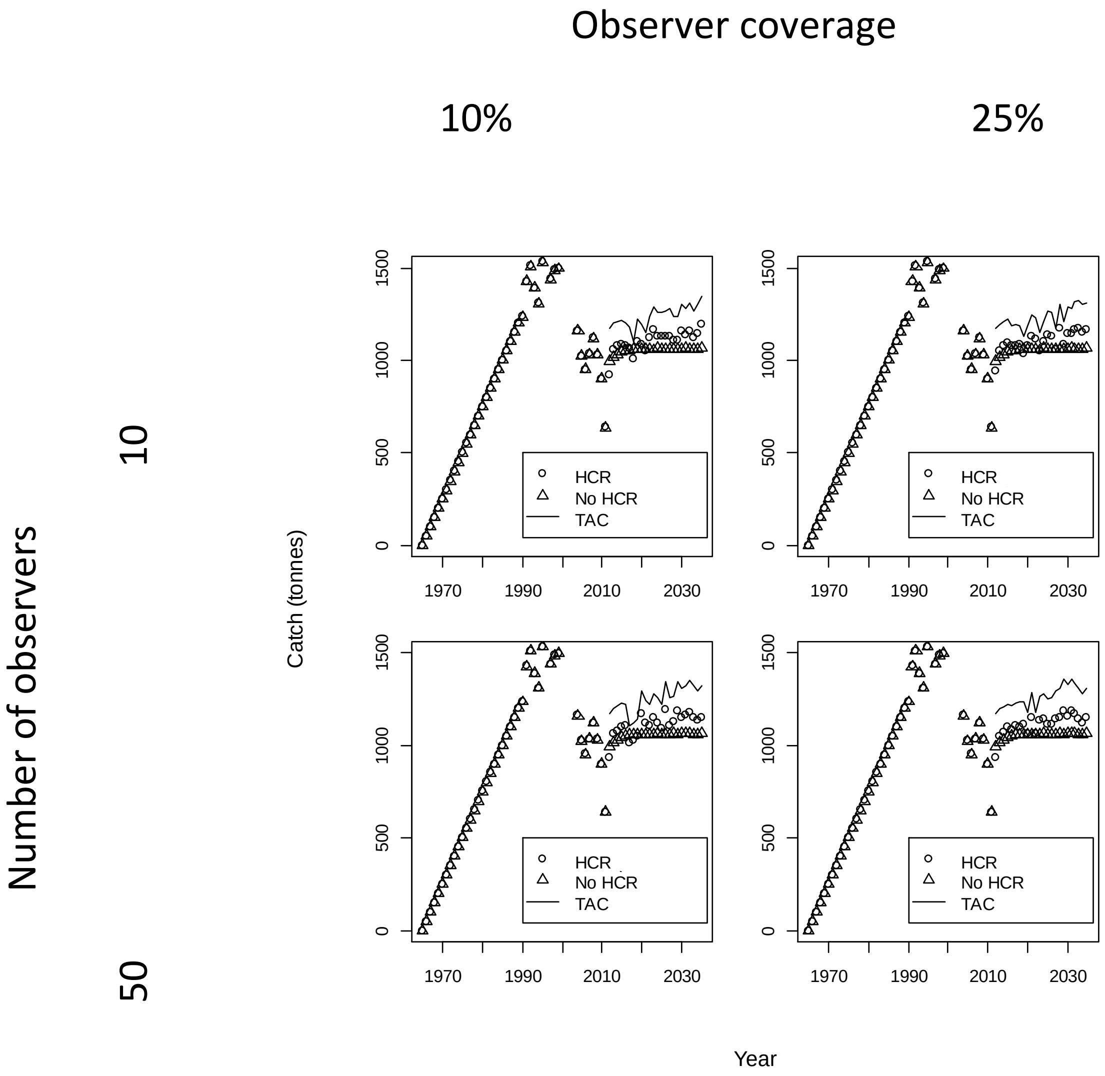


Figure 18 Average commercial catch by year across simulated replicates, based on an HCR derived TAC that was determined from the Queensland stock assessment model using on-board sampling monitoring strategy for two levels of observers (10, 50), and two levels of coverage (10%, 25%), (circles). The TAC set by the HCR is shown as the solid line. Also shown are the catches from the projections in which the TAC is held constant at 1,200 t (triangles)

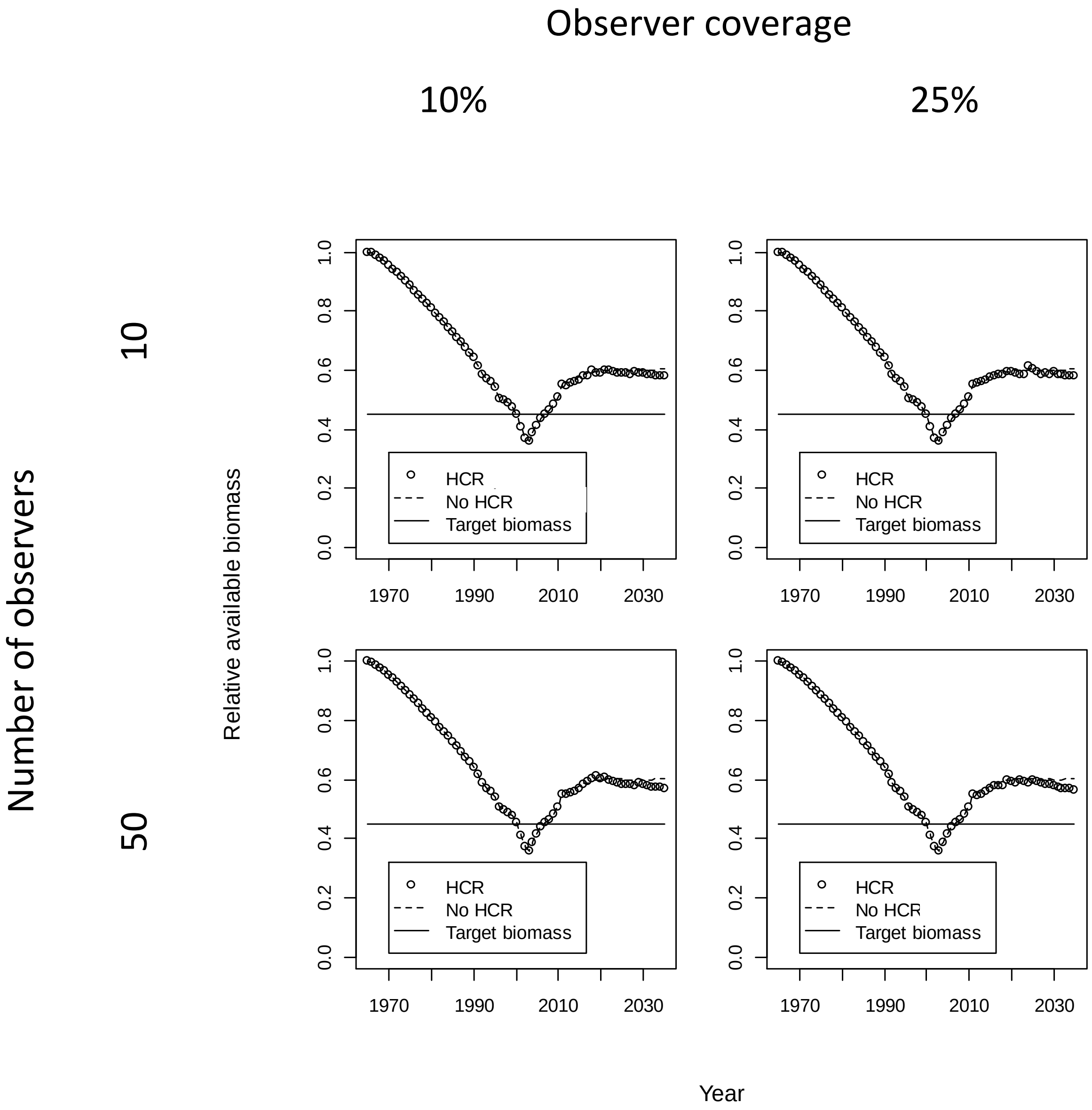


Figure 19 Average relative available biomass by year across simulated replicates that resulted from an HCR-derived TAC that was determined from the DAF stock assessment model using the on-board sampling monitoring strategy for two levels of observers (10, 50), and two levels of coverage (10%, 25%), (circles). For comparison purposes the corresponding biomass is shown from projections in which the TAC is held constant at 1,200 t (dashed line). The line representing the target biomass as average biomass from 2006-08 is shown as the solid line

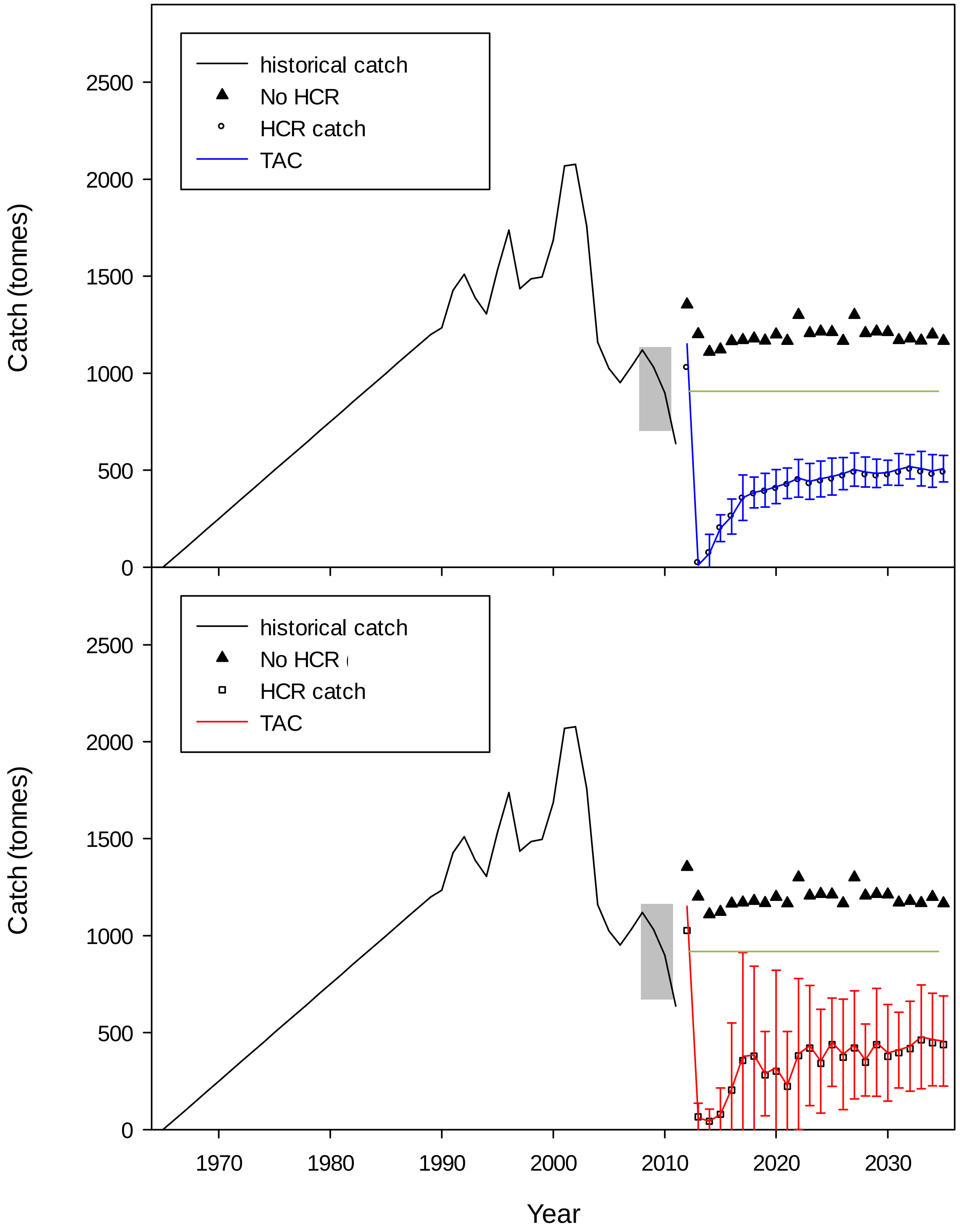


Figure 20 Average commercial catch and associated TAC (± SD) by year across simulated replicates, based on an HCR derived TAC that was determined by the CPUE (upper panel) and from the CPUE of a subset of the commerical fleet (lower panel). Also shown are the catches from the projections in which the TAC is held constant at 1,200 t (triangles). Green line indicate the target catch (C_{targ}) which was determine as the average value in the period 2008-10 (grey box)

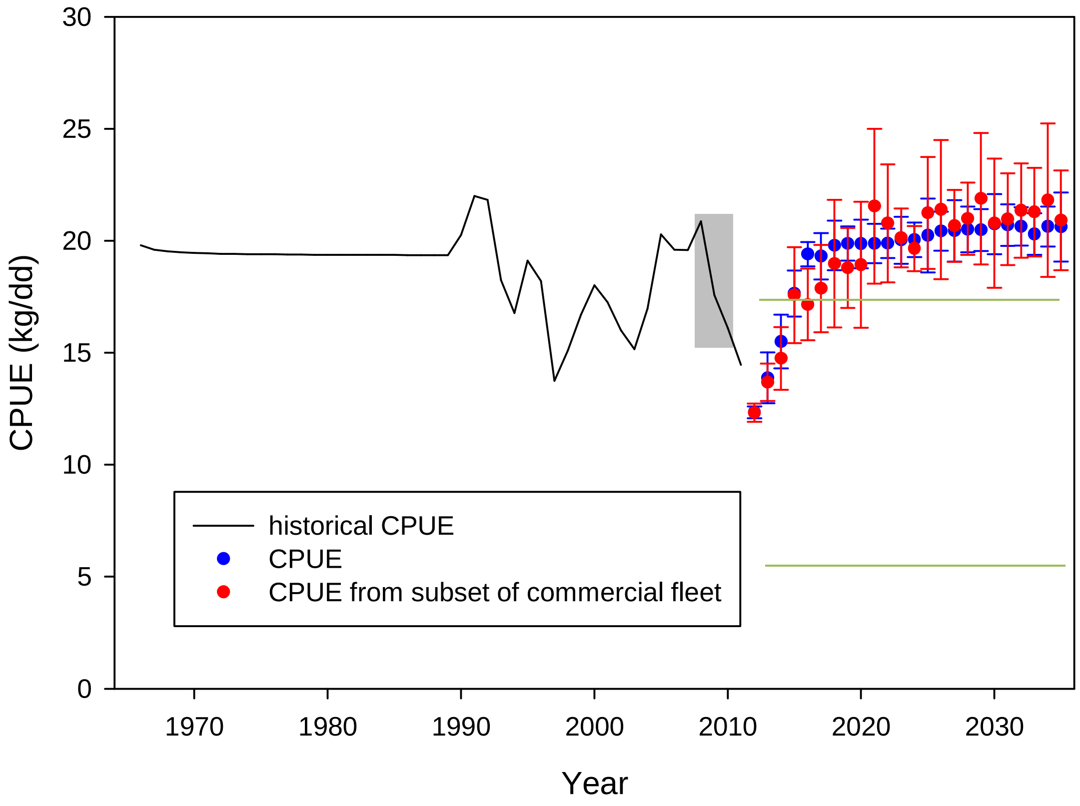
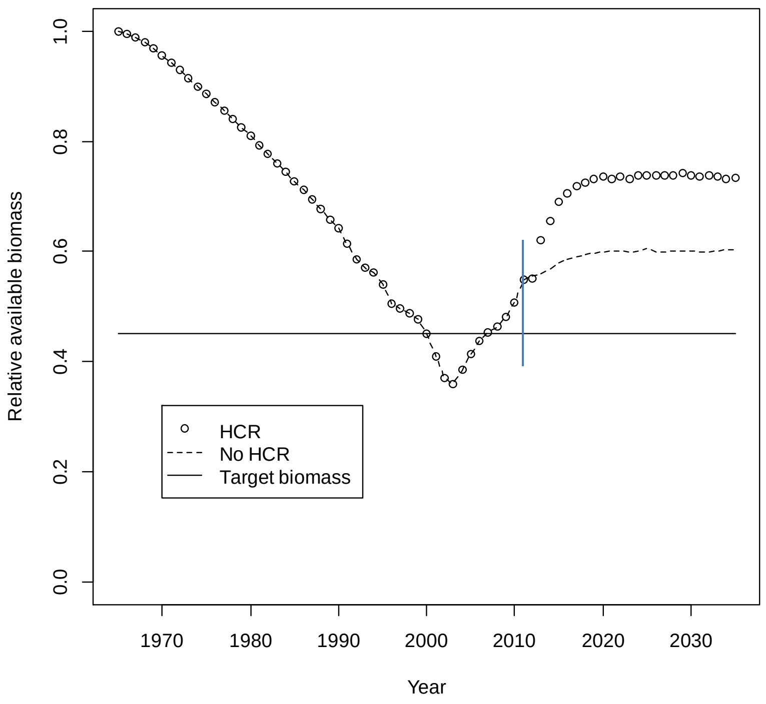


Figure 21 Average commercial CPUE (± SD) by year across simulated replicates, based on an HCR-derived TAC that was determined by the CPUE of the entire commercial fleet (blue) and from a subset of the commerical fleet (red). Also shown are the average historical CPUE experience in the fishery (black), and the reference years in which the CPUE$_{targ}$ was derived (grey box). Upper green line indicates the target CPUE ($CPUE_{targ}$) the lower green line indicates the limit CPUE ($CPUE_{lim}$) which was determine as the average value in the period 2008-10 (grey box)



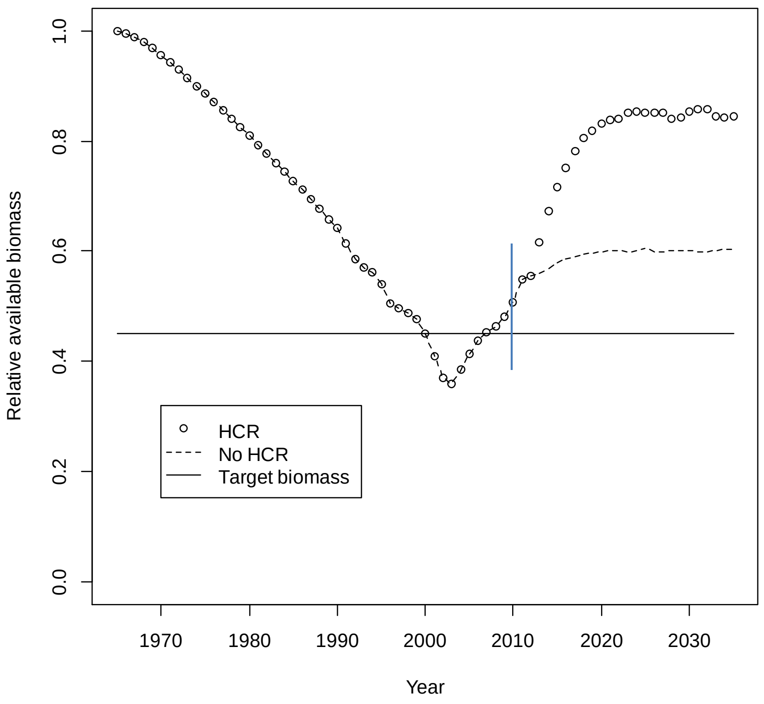


Figure 22 Average relative available biomass by year across simulated replicates that resulted from an HCR-derived TAC that was determined by the CPUE (upper panel, circles) and determined by the CPUE from a subset of the commercial fleet (lower panel, circles). For comparison purposes the corresponding biomass is shown from projections in which the TAC is held constant at 1,200 t (dashed line). The line representing the average biomass from 2008-10 is shown as the solid line

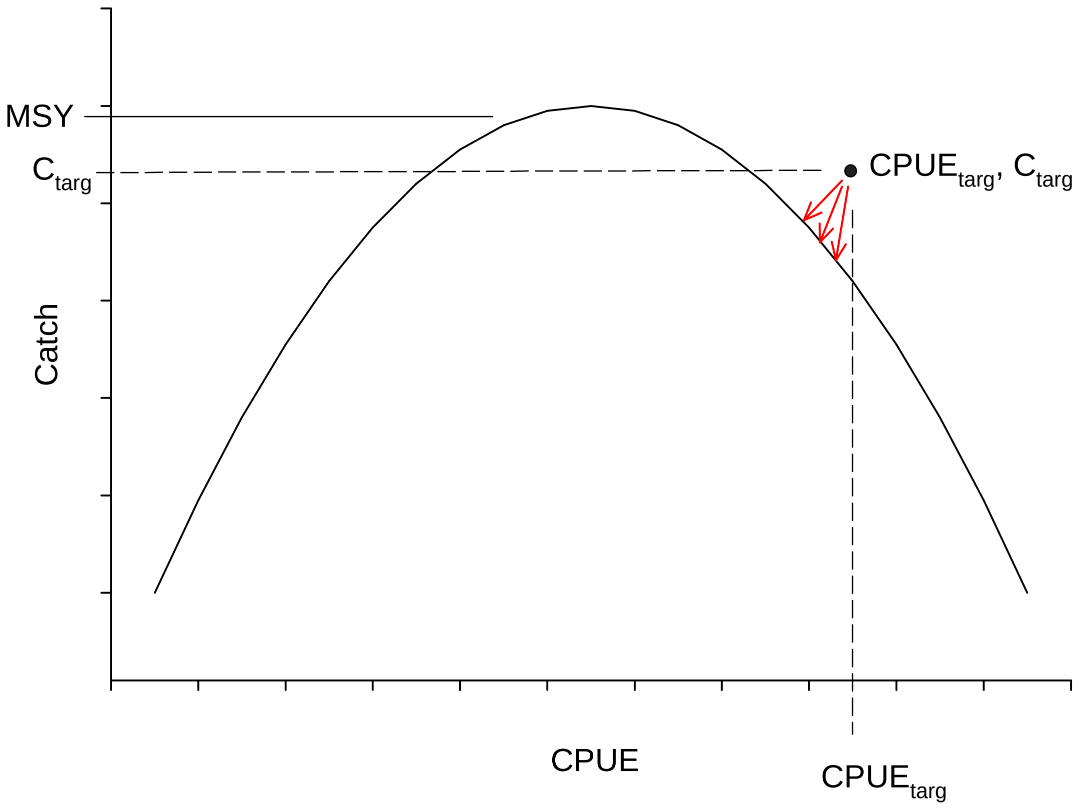


Figure 23 Stylised representation of a fishery equilibrium relationship between CPUE and Catch. The consequences of the target fishery state ($CPUE_{targ}$, C_{targ}) being above the equilibrium curve would be to move the fishery to a state on the equilibrium curve

3.2.3 Evaluating the effect of fleet mobility

Lastly, simulations were performed to explore the implications of increased fleet mobility across ports, and the level of (constant) TAC on stakeholder-derived fishery management objectives. The biomass trajectories across the six combinations of TAC and fleet mobility (Figure 24) showed a greater difference in biomass resulting from the level of TAC than from changes in fleet mobility. Specifically, the biomass decreased as the TAC increased. It would be expected however, that fleet mobility would affect more the regional distribution of indicators such as effort, catch and biomass, than the overall total amounts across the GBR. Available biomass was much more sensitive to the fishing depletion than spawning biomass (Figure 24) mainly because spawning biomass is defined as the biomass of mature females, which includes a significant proportion of the population that is below the minimum legal size, and unaffected by the fishery. The pattern that shows a greater effect of the TAC level than fleet mobility is reflected in the trajectories of commercial catches taken under the different levels of TAC, with little difference in landings between the fleet mobility scenarios (Figure 25).

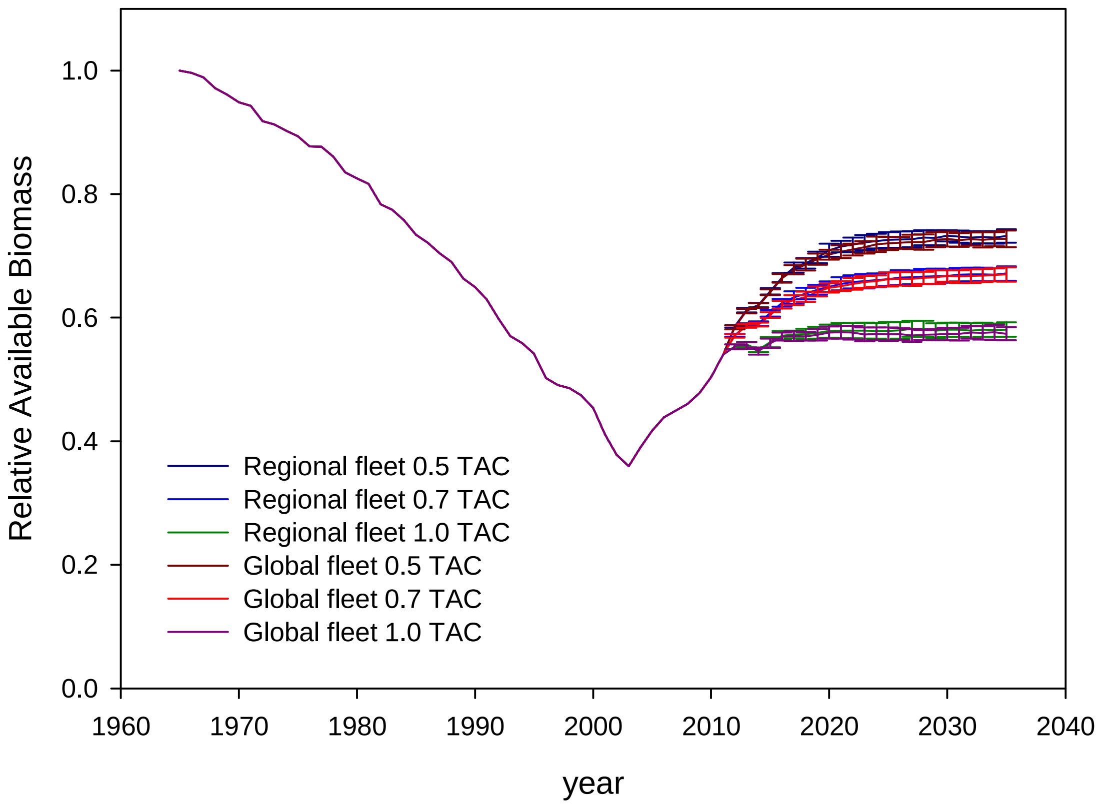
Commercial CPUE shown in Figure 26 (top) is representative of the biomass trajectories in the projection period. The constant ratio between catch and effort that is assumed to have occurred before 1989 is also apparent in Figure 26 (top). There was much less variability among scenarios in recreational CPUE (Figure 26, bottom) mainly because the model that allocates recreational effort is static and simply distributes recreational effort proportionally according to historical patterns. As a result, the allocation of effort does not change according CPUE as it does in the commercial fishing vessel dynamics model.

The CPUE for the charter fleet was divided between the reefs north of Townsville, and the reefs south of Townsville (Figure 27). The catch rates in the reefs north of Townsville declined below historical values, while the CPUE on reefs south of Townsville increased above historical levels (Figure 27). Although the model that allocates charter effort is unlike the model that allocates recreational effort in that the effort distribution is dynamic and responsive to CPUE, the charter effort allocation model is not agent-based like the commercial effort allocation model, and not constrained to the port regions. Charter effort is allocated by ranking reefs in a region by CPUE, and allocating effort sequentially from the highest ranked reef, an amount of effort equal to that experienced on the reef historically. The procedure allows less stringent adherence of effort to the regions compared to the commercial effort. The decline in charter CPUE in the north, and corresponding increase of it in the south, is the result of a shift in the commercial effort to reefs north of Townsville (Figure 28). The results show little difference in the fleet mobility scenario on the charter CPUE in both the north and south of Townsville. The effect of the TAC level is seen mainly in the reefs south of Townsville.

The distribution of commercial effort to the regions (Figure 29) shifted from regions 2 (Far North), 3 (Cooktown) and 6 (Capricorn-Bunkers) to regions to regions 4 (Cairns), 5 (Mackay) and 6 (Swains) under the increased mobility of the commercial fleet (global fleet scenario). This shift in effort resulted in a higher CPUE resulting for the mobile global fleet (Figure 26 top), which meant that profitability increased (Figure 30). The higher profitability however, does not consider the cost of moving among regions, through delivery and steaming costs from the home port.

Figure 30 shows that under the current TAC, the regional fleet would result in the lowest long-term profitability of all the scenarios. The other scenarios fare better, and increase in the long term, as a result of reduced catches, or more flexible effort distribution. The profitability of the global fleet under the current TAC, in particular, declines initially like the regional fleet, but increases quickly after four years, as a result of more flexibility in the effort distribution.

Decreasing the TAC results in increasing profits (Figure 30). Although this pattern has been seen in other model results of the fishery (Little et al. 2010), in a previous report, Little et al. 2009a showed that decreasing the TAC resulted in reduced profits. It is important to note that, unlike Little et al. 2009a, these figures do not include revenue from other species like RTE, or fixed costs. The report also uses new economic data resulting from the survey to condition the vessel dynamics model. A more detailed examination of the data would provide greater insight into the reason for this pattern.



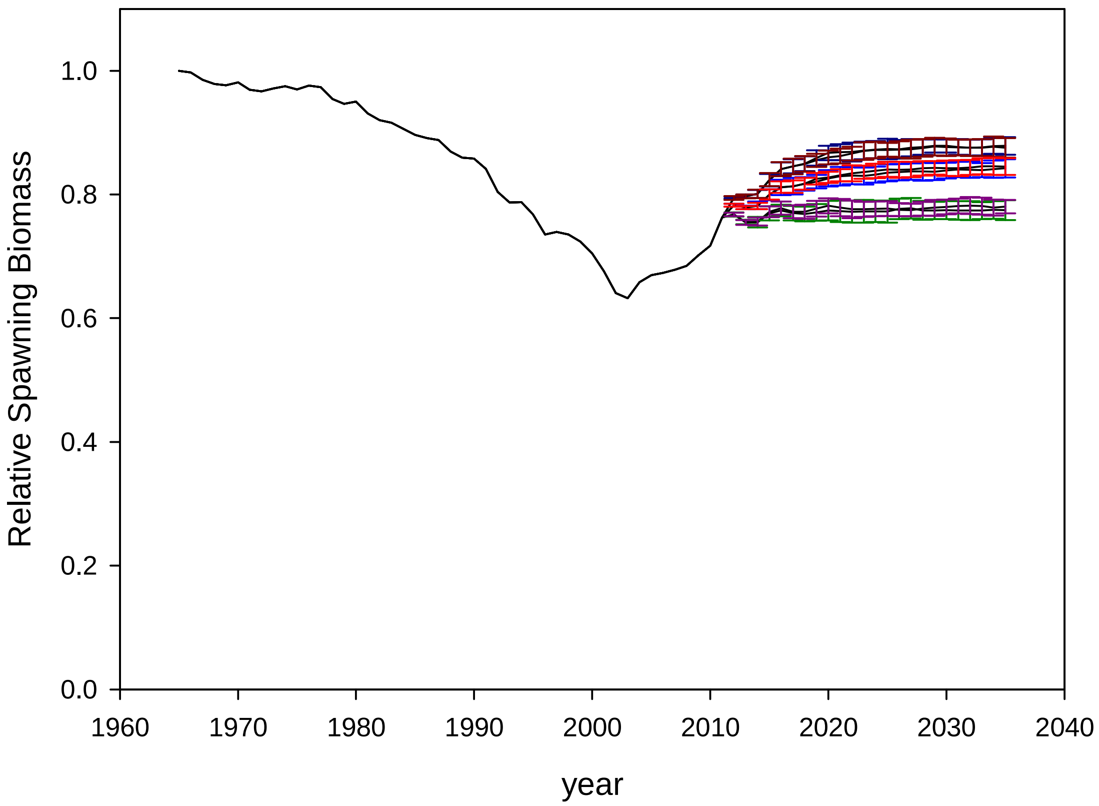


Figure 24 Mean (±SE) available biomass (top) and spawning biomass (bottom) relative to pre-exploitation levels of coral trout on all reefs during the historical (1965-2011) and projection (2012-35) period under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility

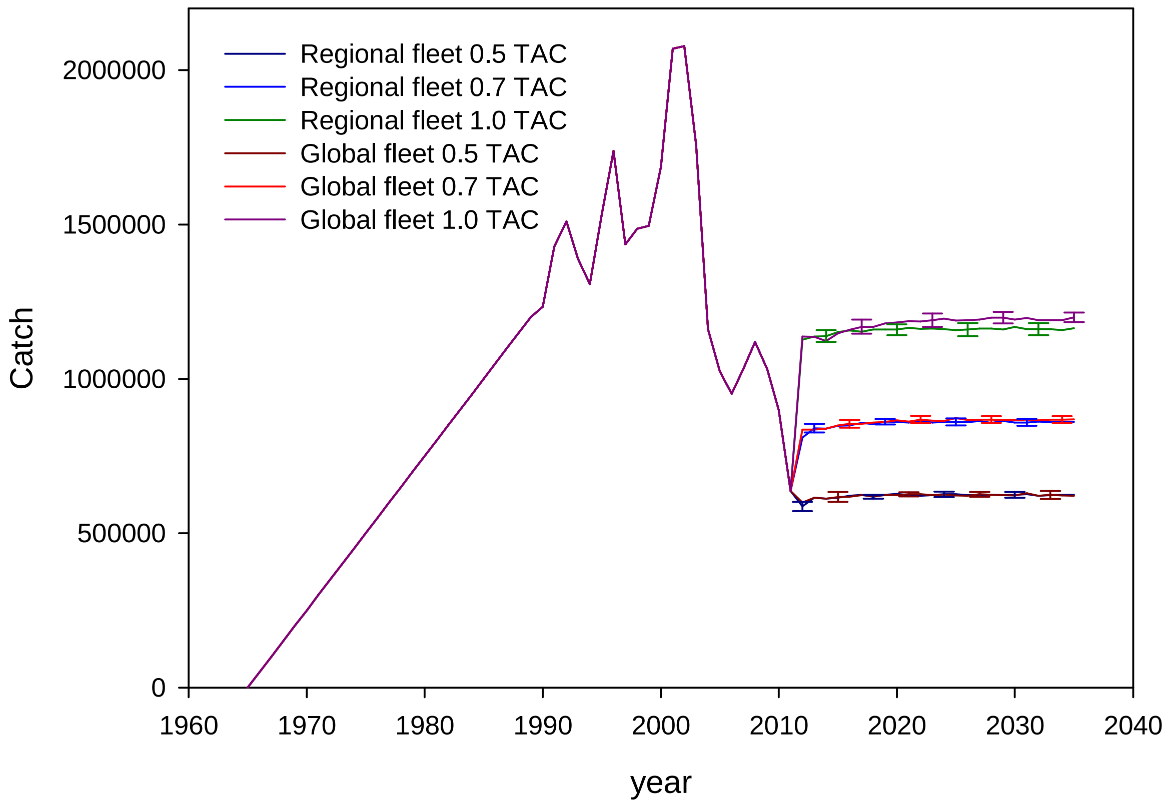
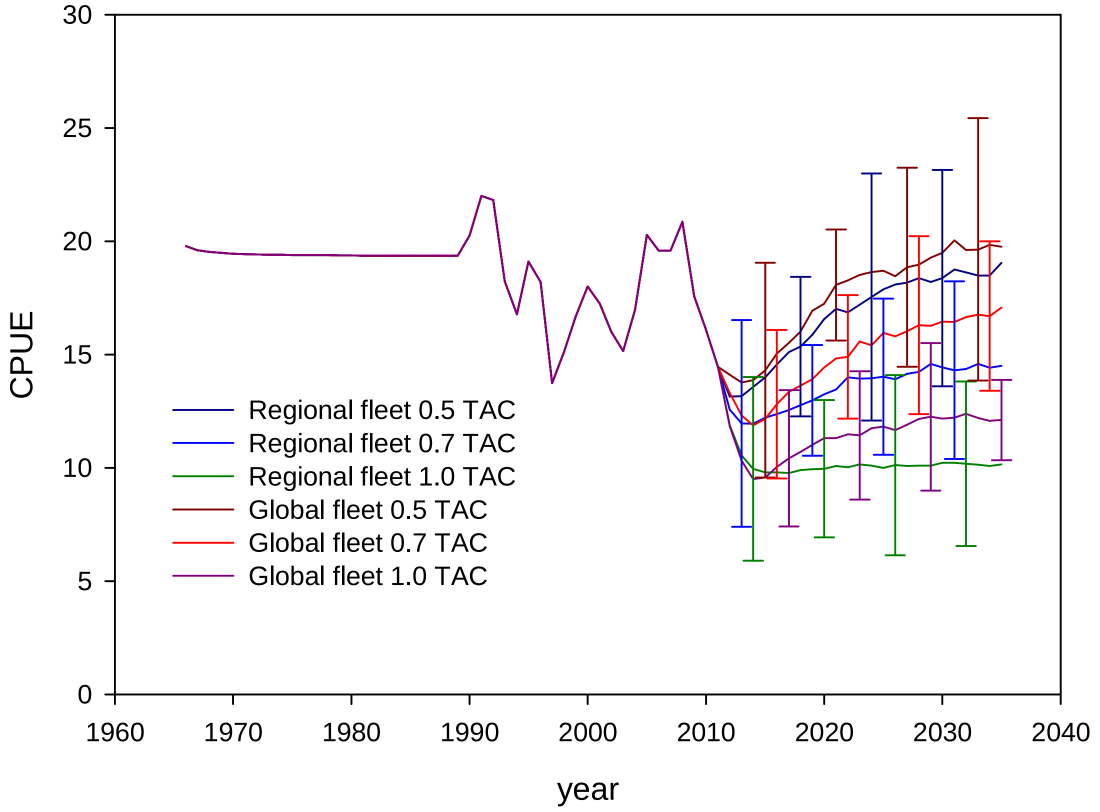


Figure 25 Mean (±SE) commercial landings of coral trout during the historical (1965-2011) and projection (2012-35) period under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility



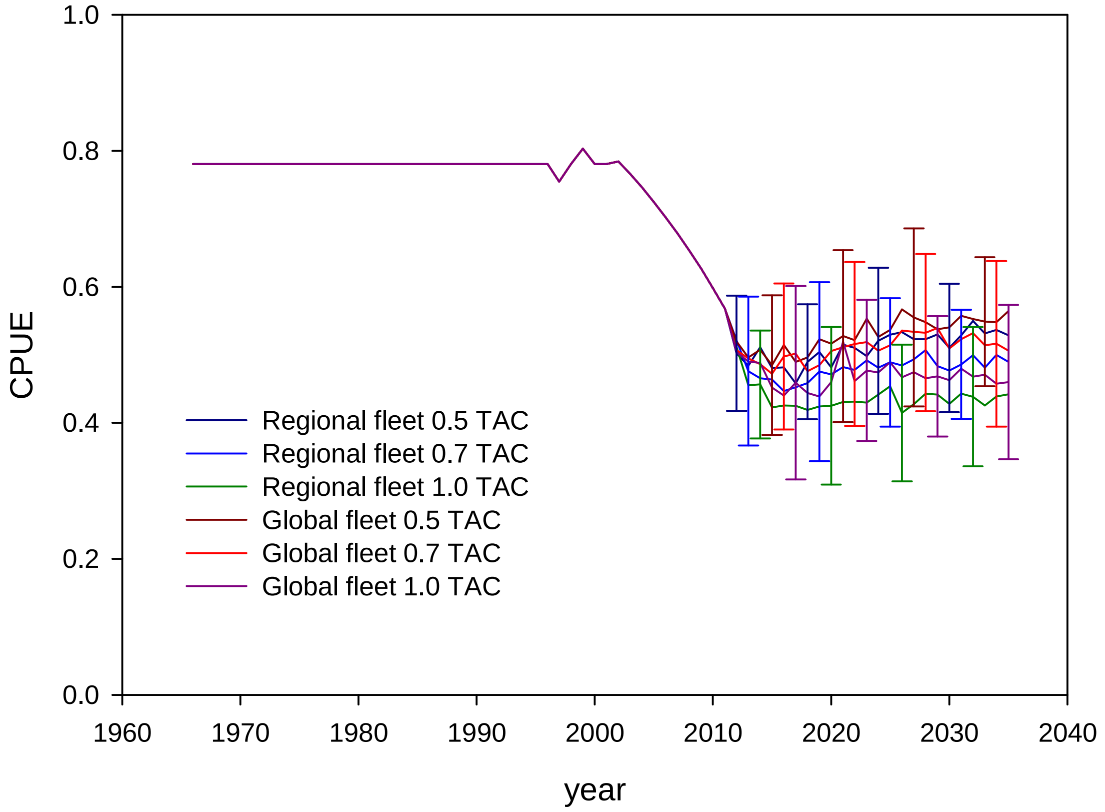
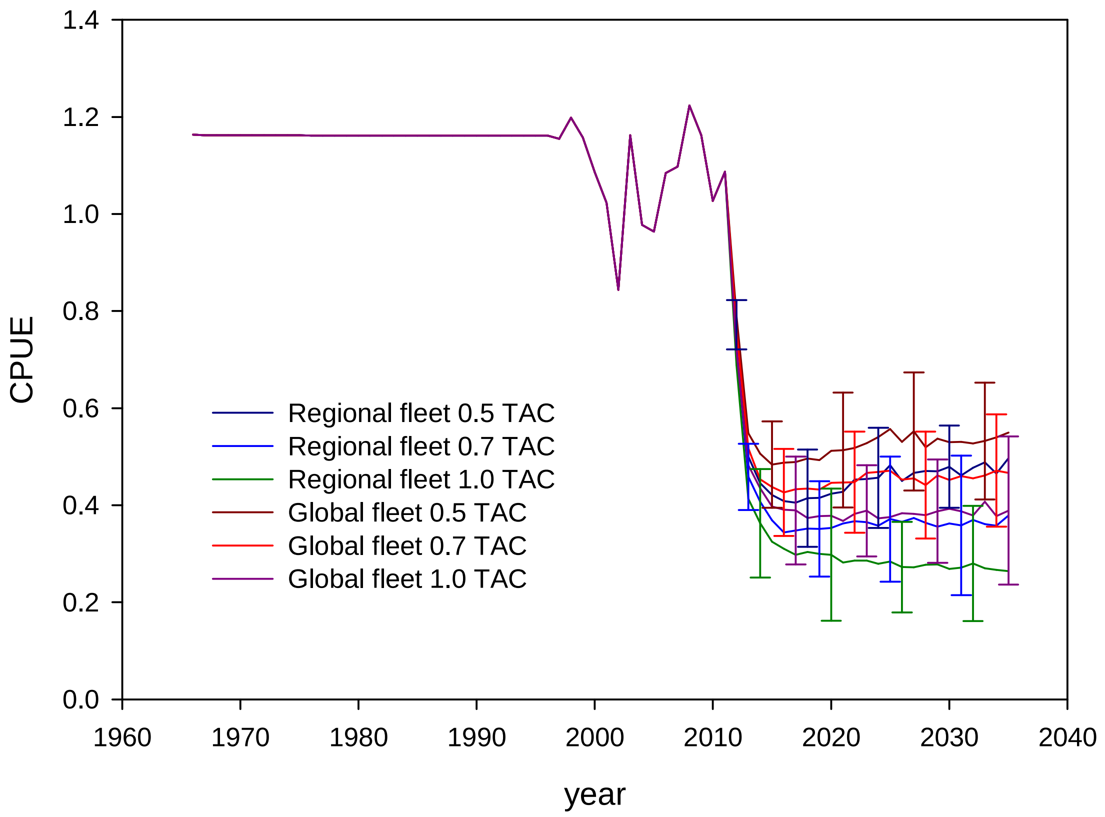


Figure 26 Mean (±SE) CPUE from the commercial sector (top) and recreational sector (bottom) during the historical (1965-2011) and projection (2012-35) periods under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility



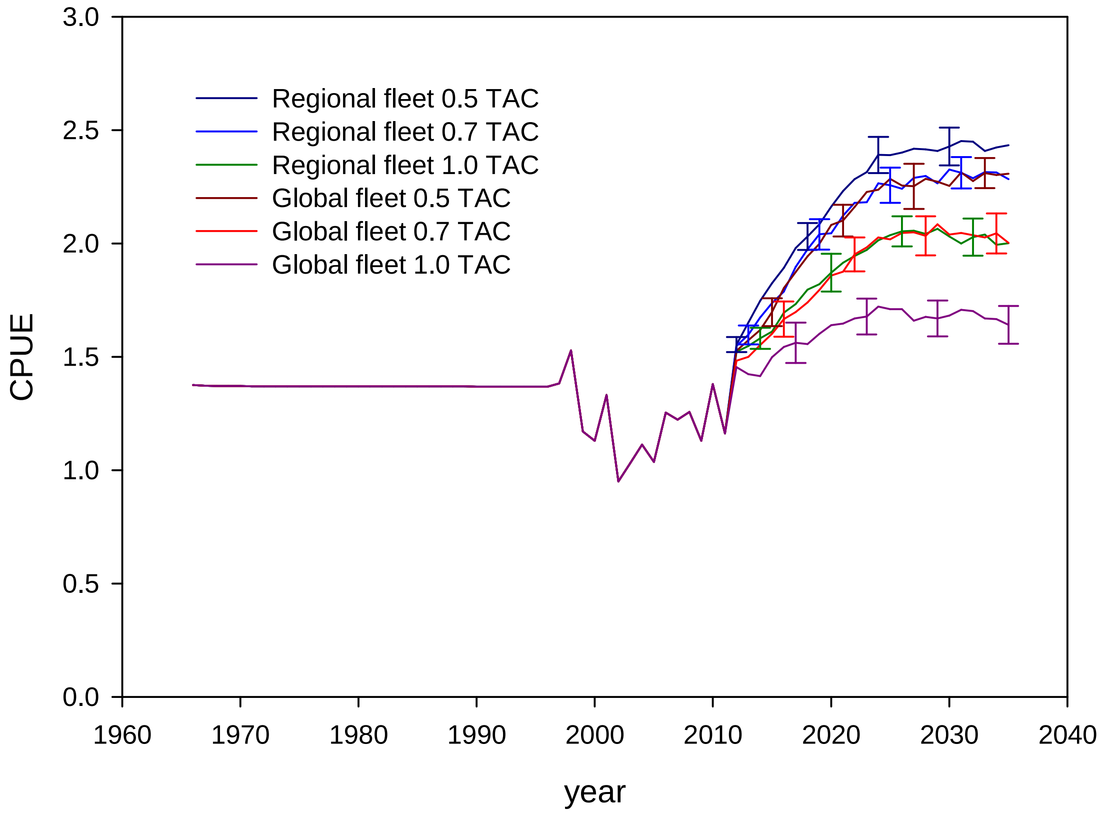


Figure 27 Mean (±SE) CPUE from the charter sector from reefs north of Townsville (top) and south of Townsville (bottom) during the historical (1965-2011) and projection (2012-35) periods under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility

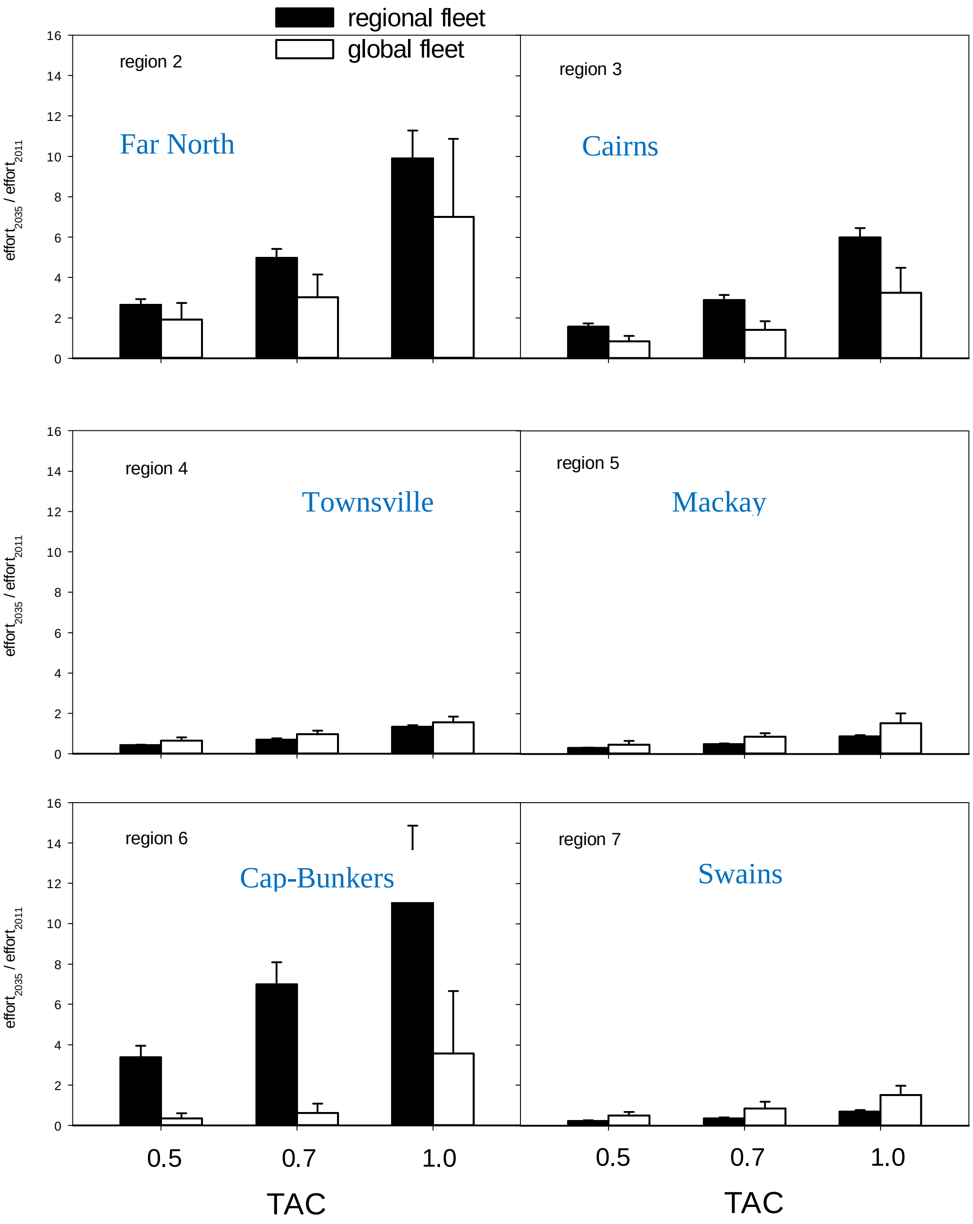


Figure 28 Mean (±SE) commercial effort relative to effort in 2011, across the regions at the end of the simulation (2035), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

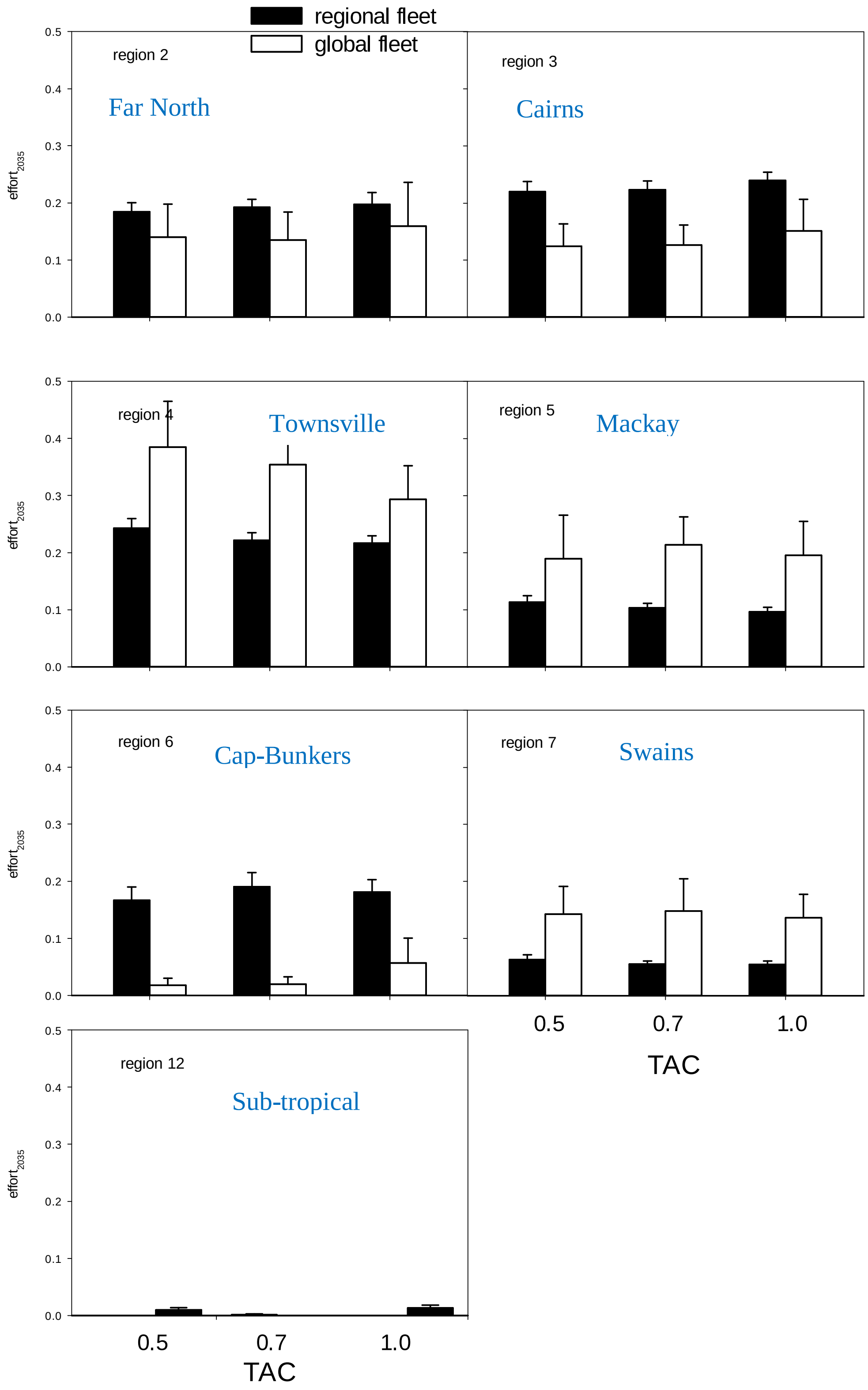


Figure 29 Mean (±SE) proportion of commercial effort distributed across the regions at the end of the simulation (2035), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

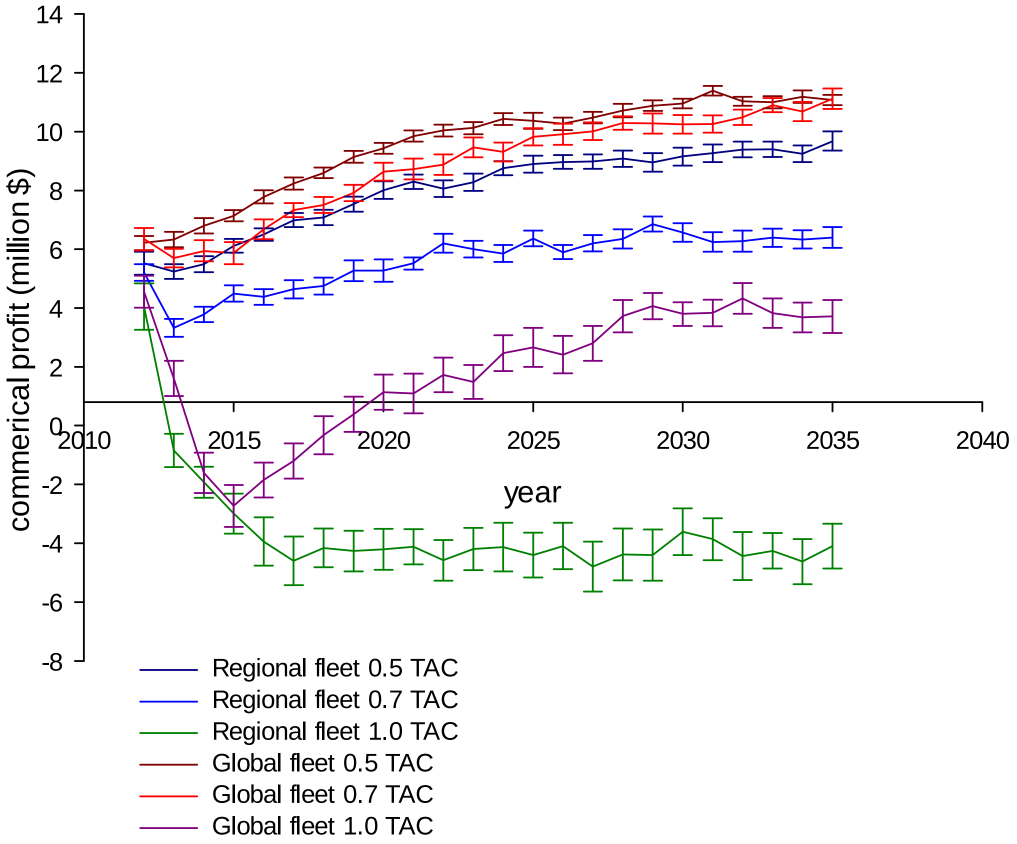


Figure 30 Mean (±SE) commercial profit during the projection (2012-35) period under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility

Although the management objectives originally derived from the stakeholder workshop, generally referred to the entire fishery across the GBR, we show how they are met in each of the regions. The first objective required spawning biomass on reefs closed to fishing to be greater than 90% of pre-exploitation levels, at least 80% of the time (Table 4). The ability to achieve this objective across the TAC and fleet mobility scenarios was mixed (Figure 31). No scenario achieved this objective in the northern regions (Far North, Cooktown). The mid-latitude regions (Townsville, Mackay, Swains) achieved the objective at the lower TAC levels (0.5 and 0.7). Across the whole GBR, the global fleet mobility scenario led to higher chances of achieving the objective, especially as the TAC increased. The relative spawning biomass in the closed areas ranged between 70% and 95%, across scenarios (Figure 32), and corresponded to the results seen relating to the management objective (Figure 31). The lack of data in the Sub-tropical region (Figures 31 and 32) indicated the lack of reefs closed to fishing in the region. The effect of the fleet mobility is seen resulting in higher closed area spawning biomasses in the northern regions (Figure 32). While the fishing activities that resulted from the different fleet mobility scenarios would not directly affect the biomass in the areas closed to fishing, larval subsidy of the areas open to fishing by the closed areas in the model (Little et al. 2007) has an effect of reducing the settlement of recruits in the closed areas.

Management objective 2, which required the spawning biomass on all reefs across the GBR to be greater than 60% of pre-exploitation levels at least 80% of the time, was achieved under almost all scenarios (Figure 33). The exception was region 12 (Sub-tropical) where no scenario was able to achieve the objective. The reason for these results are shown in Figure 34, which shows that the spawning biomass in the Sub-tropical region to be low and variable as a result of having only 1 (virtual) reef.

Management objective 3, which required the available biomass on reefs open to fishing to be greater than 48% of pre-exploitation levels at least 80% of the time, was achieved under all scenarios for the Townsville, Mackay and Capricorn-Bunkers regions (Figure 35). This objective was not achieved for the Swains regions under 1.0 TAC and the global fleet mobility scenario. This objective was most likely to be achieved in the northern regions (Far North and Cairns) under the lowest TAC (0.5) and global fleet mobility. In the far southern region (Sub-tropical) no scenario was able to achieve the objective.

Management objective 4, was related to management objective 3, but easier to attain as the threshold of achieving the objective was 40% of pre-exploitation levels instead of 48% (Figure 36). In general and not surprisingly, more of the scenarios achieved the objective, mainly in the northern regions (Far North and Cairns), and under the global fleet mobility scenario. The results are reflected in the actual available biomass in each region (Figure 37). In general the available biomass in the northern regions (Far North, Cairns), and the southern regions (Capricorn-Bunkers and Subtropical) increased as a result of the fleet mobility scenario (Figure 37), and the shift of effort away from these regions (Figure 28), while correspondingly the available biomass in the central regions (Townsville, Mackay, Swains) declined under the global fleet scenario. The movement of effort to these central regions (Figure 28, 29) and the increased depletion (Figure 37) however did not greatly reduce the chances of achieving the management objectives for available biomass (Figure 35, 36).

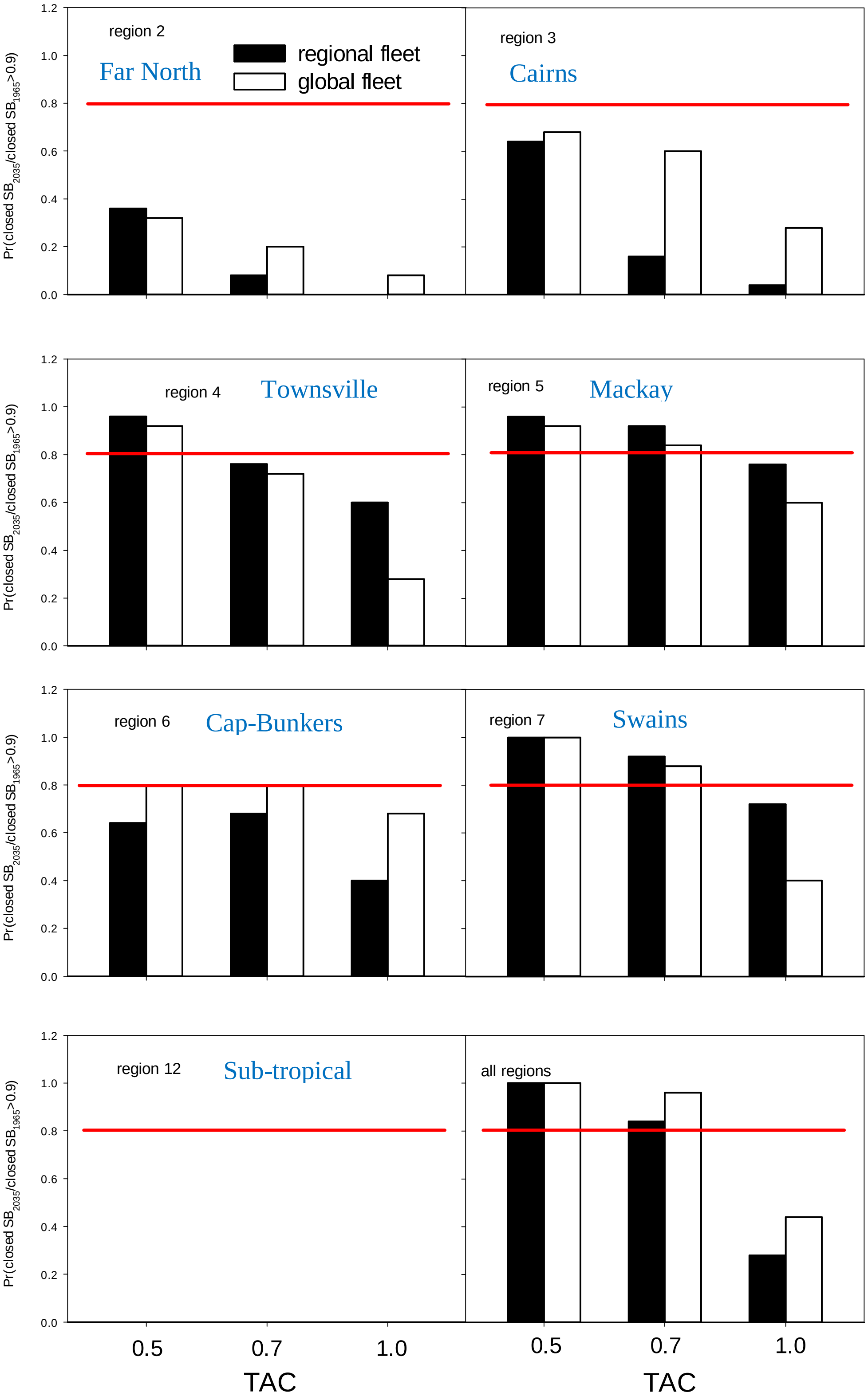


Figure 31 Proportion of simulations in which the spawning biomass (SB) in the different regions at the end of the simulation (2035) on reefs closed to fishing is above 90% of their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

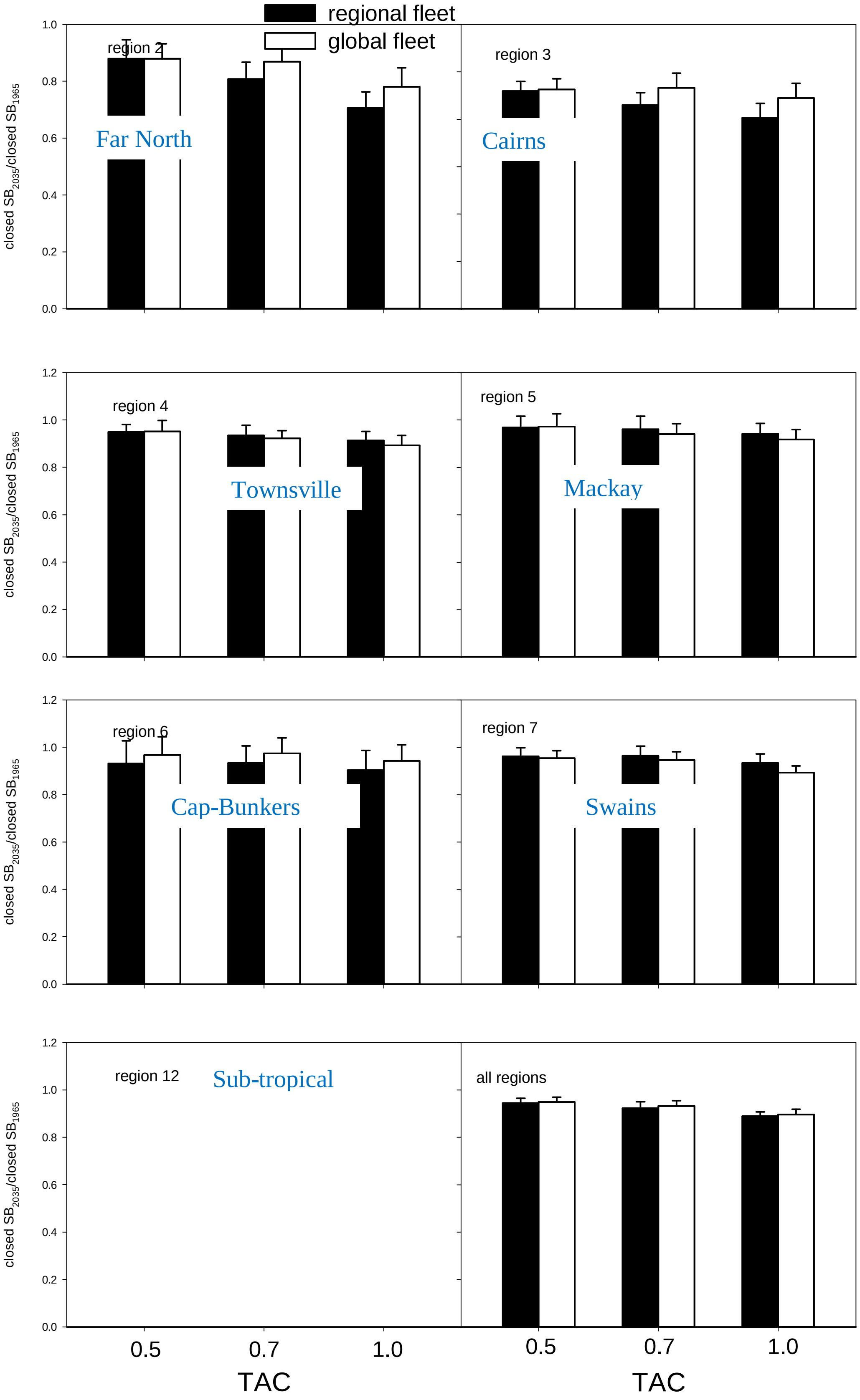


Figure 32 Mean (±SE) spawning biomass (SB) in the different regions at the end of the simulation (2035) on reefs closed to fishing relative to their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

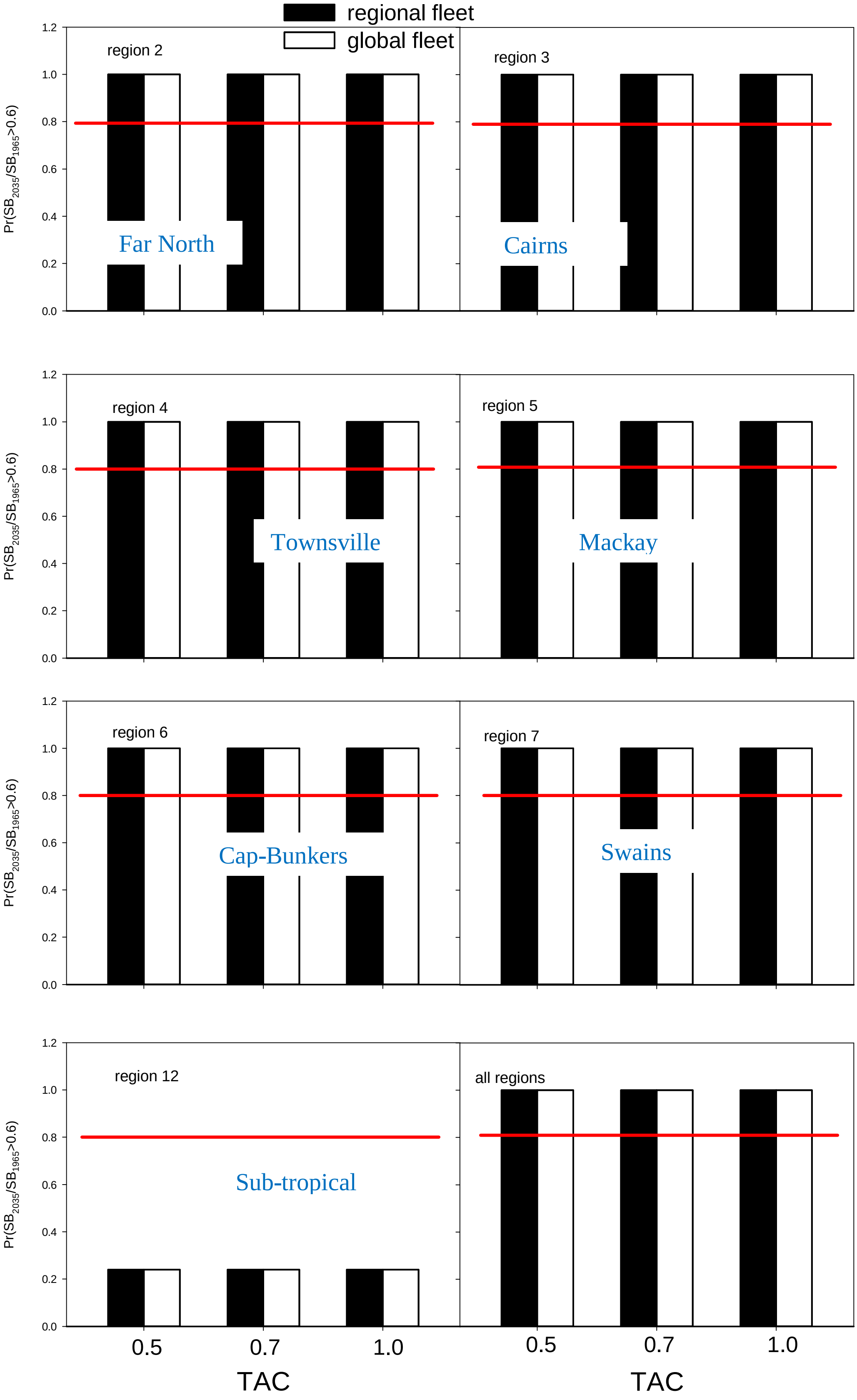


Figure 33 Proportion of simulations in which the spawning biomass (SB) in the different regions at the end of the simulation (2035) on all reefs across the GBR is above 60% of their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

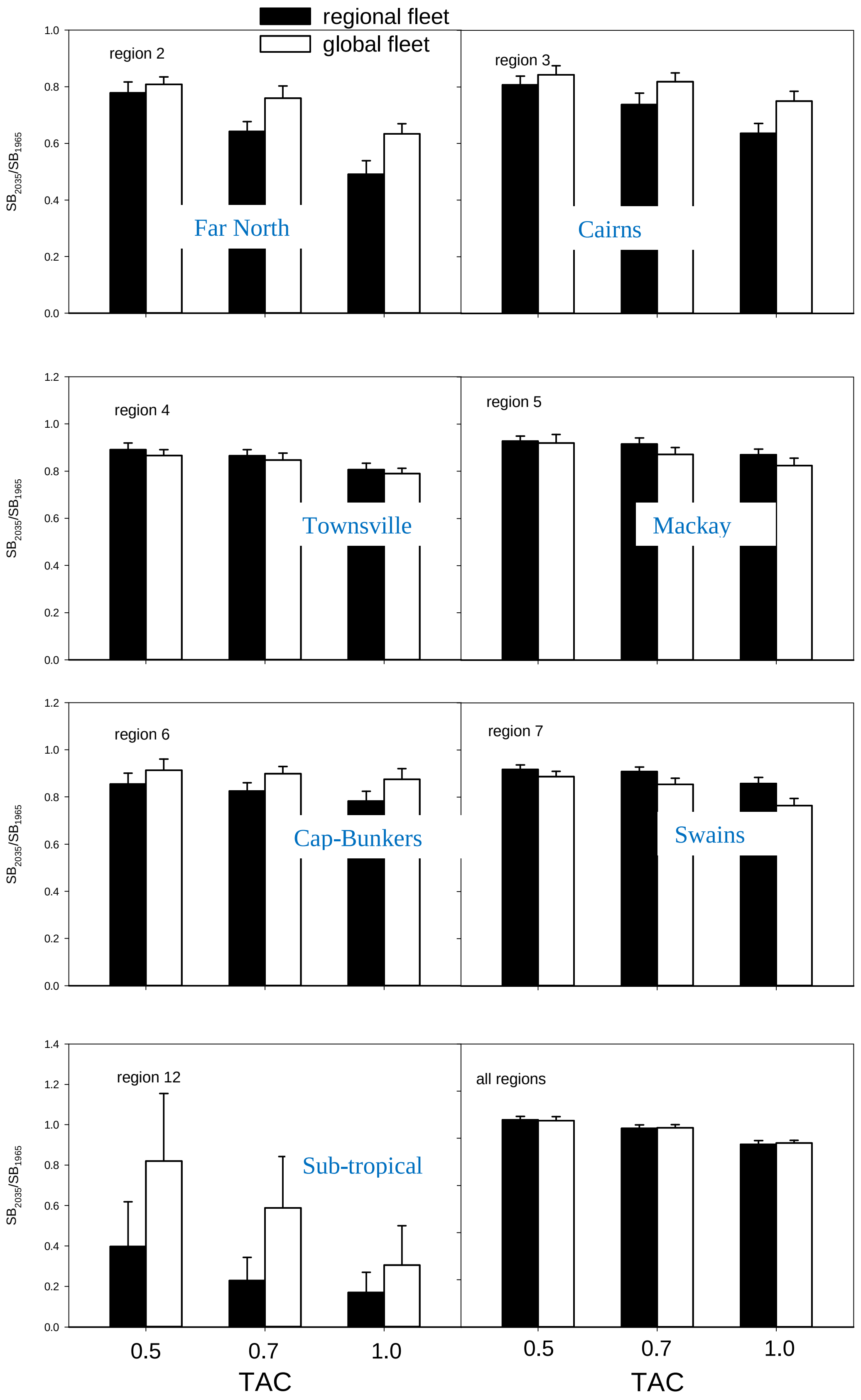


Figure 34 Mean (±SE) spawning biomass (SB) in the different regions at the end of the simulation (2035) on all reefs across the GBR relative to their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

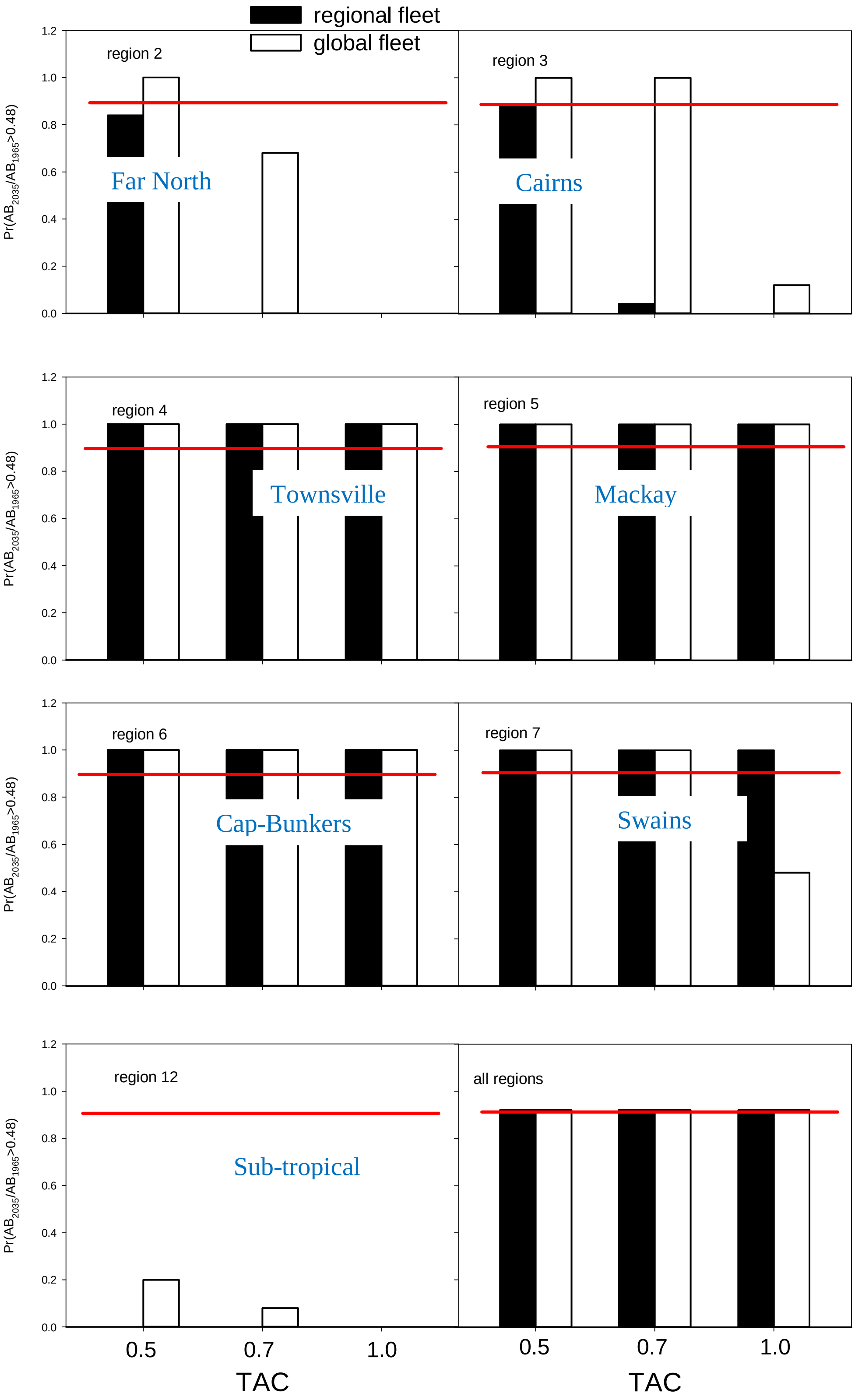


Figure 35 Proportion of simulations in which the available biomass (AB) in the different regions at the end of the simulation (2035) on reefs open to fishing is above 48% of their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

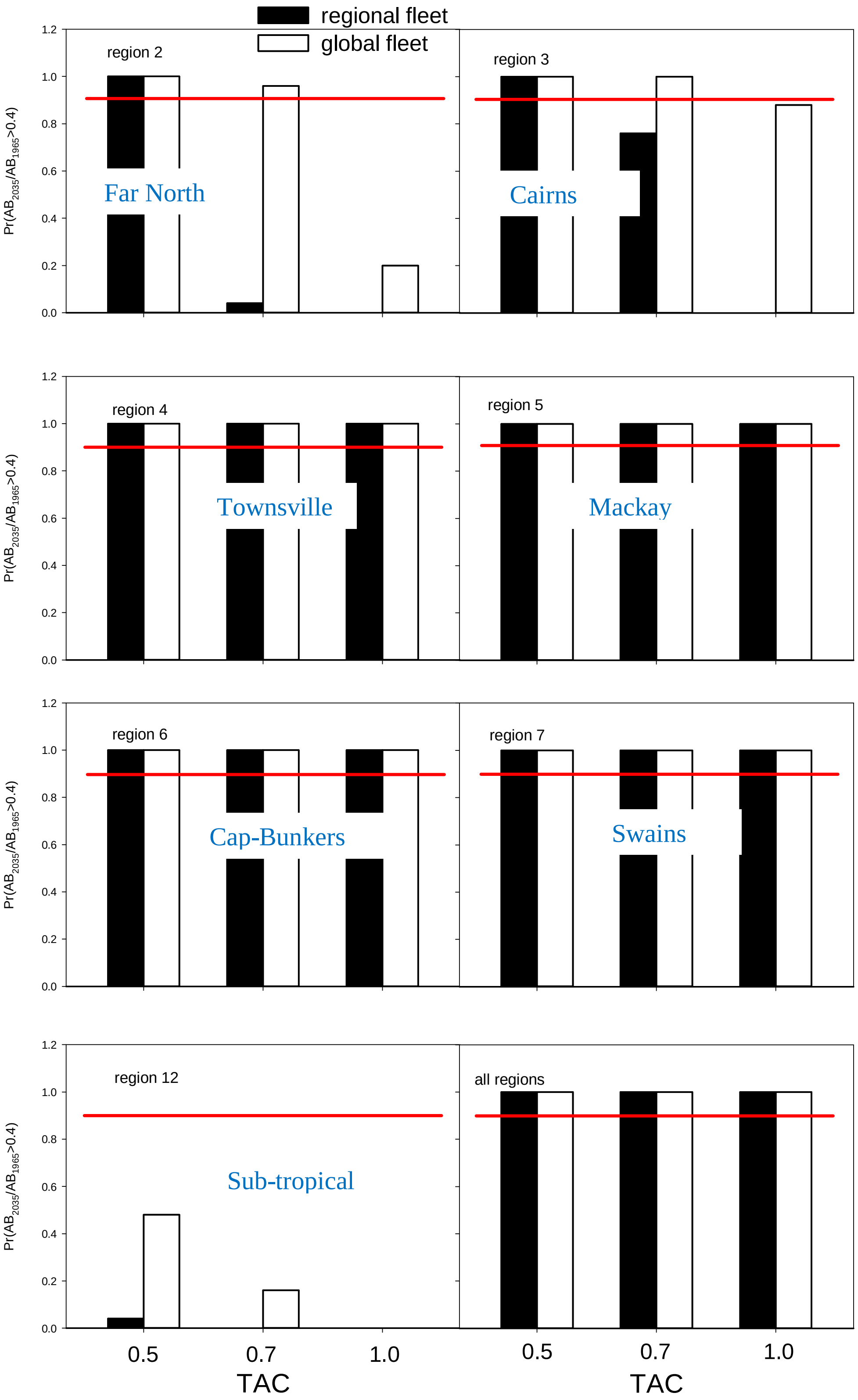


Figure 36 Proportion of simulations in which the available biomass (AB) in the different regions at the end of the simulation (2035) on reefs open to fishing is above 40% of their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

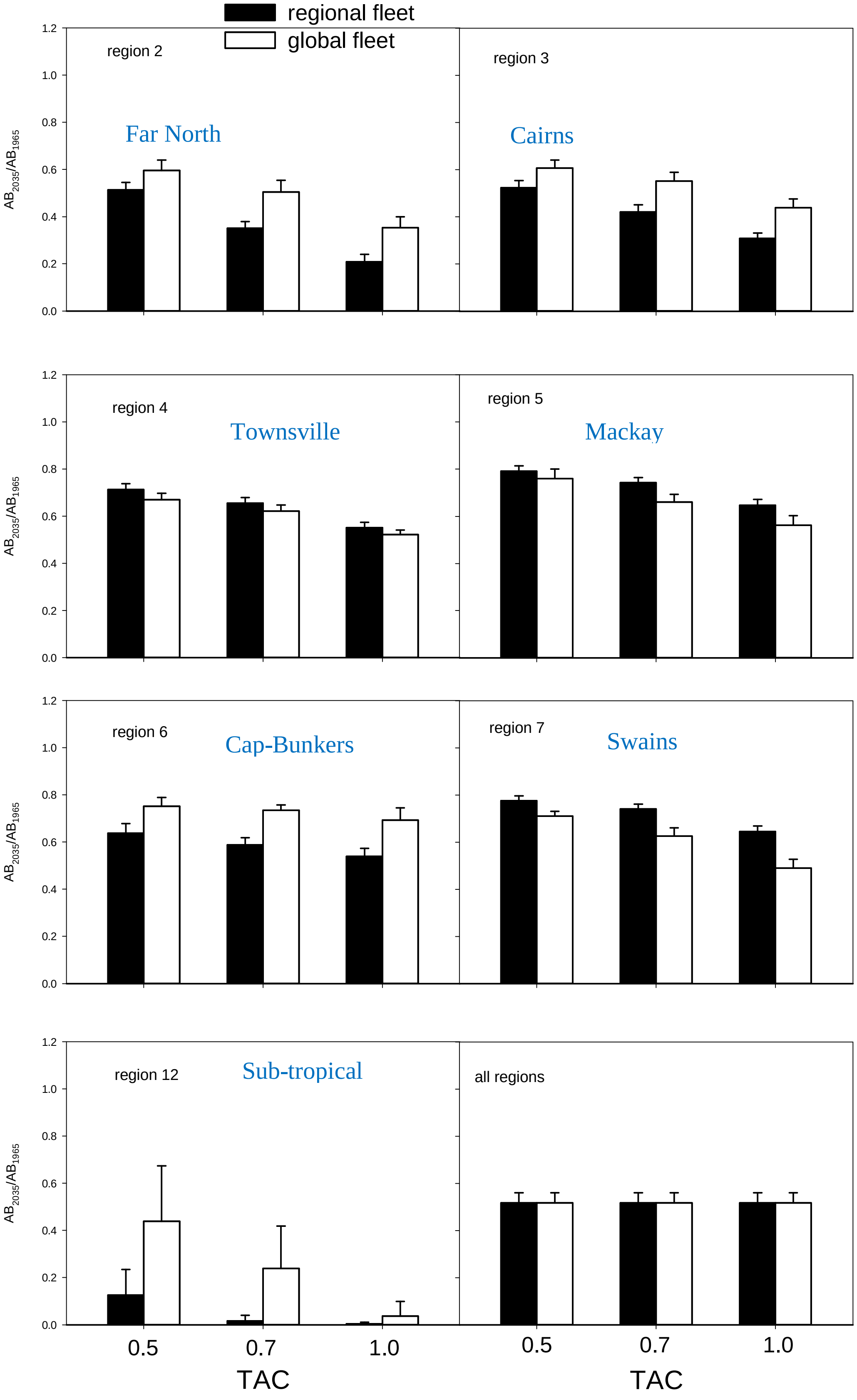


Figure 37 Mean (±SE) available biomass (AB) in the different regions at the end of the simulation (2035) on reefs open to fishing relative to their pre-exploitation values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

Management objective 5, which required commercial CPUE to be greater than 80% of what it was in 2006 at least 90% of the time, mimicked the results for available biomass. The objective was achieved in the middle regions (Townsville, Mackay, Swains) under the regional fleet scenario irrespective of TAC (Figure 38). Under the global fleet mobility scenario, the chances of achieving the objective declined with increasing TAC as the biomass declined. In the northern regions (Far North, Cairns) and the southern (Sub-tropical), the objective was not achieved under any scenario. The regional CPUE for each scenario indicated that CPUE would decline in Townsville, Mackay and Swains regions under the global fleet mobility scenario (Figure 39). However, commercial CPUE is predicted to increase in the southern Cap-Bunkers and northern Far North and Cairns regions.

Management objective 6 that required 80% of the TAC to be landed was achieved in all scenarios (Figure 40) as the TAC was generally caught in the simulations throughout the projection period (Figure 25).

Management objective 7 that required vessel profitability to increase in the future was more likely to be achieved under the global fleet mobility scenario, and decreasingly as the TAC increased (Figure 41). Figure 42 recapitulates Figure 30, in that the fishery operated at a loss at the end of the projection period under the regional fleet scenario and 1.0 TAC, although profit is highly variable. The regional fleet scenario was also much more sensitive to changes in TAC than the global fleet mobility. It is important to note that these figures do not include revenue from other species like RTE or OS product categories, nor fixed costs.

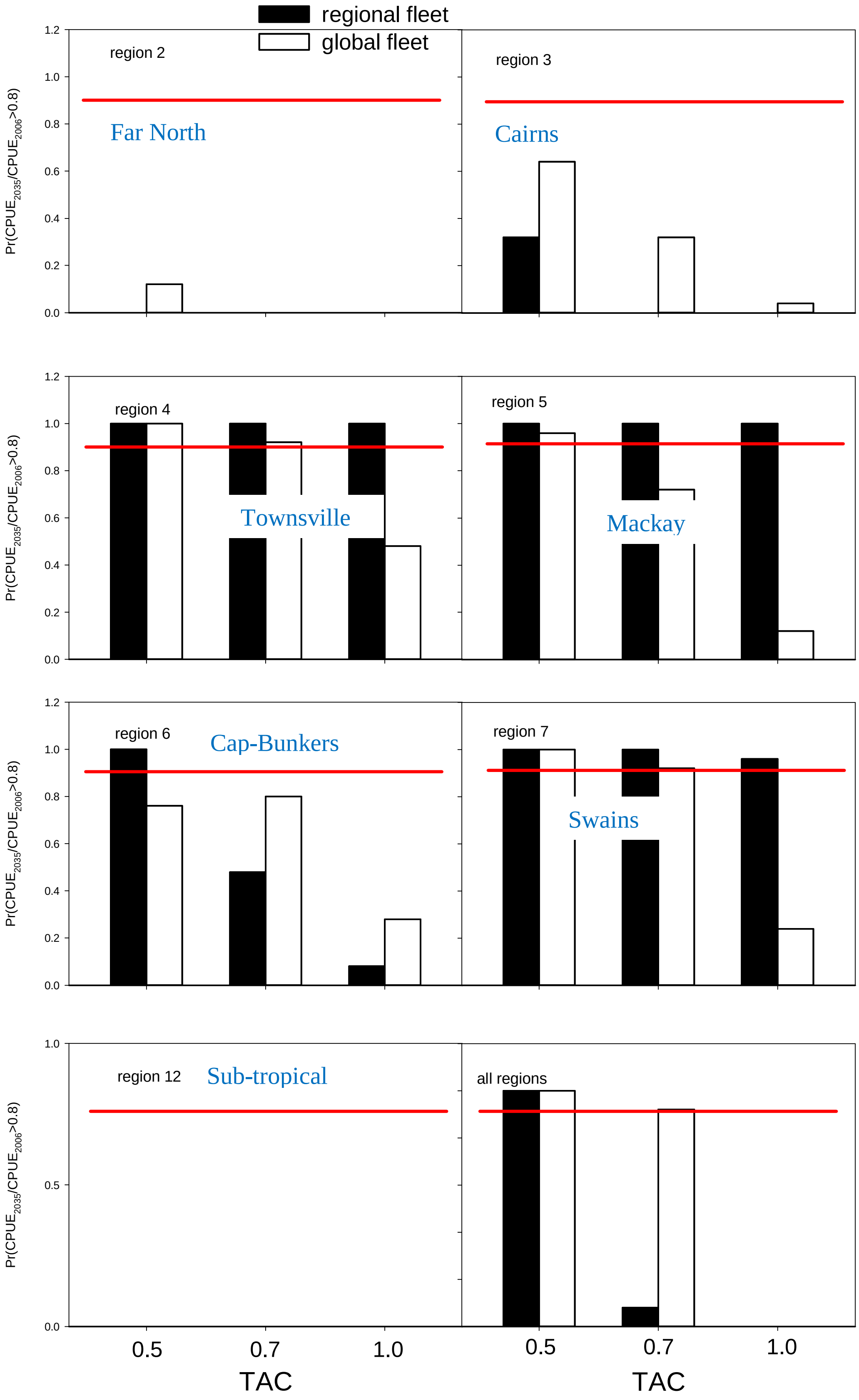


Figure 38 Proportion of simulations in which the commercial catch per unit effort (CPUE) in the different regions at the end of the simulation (2035) is above 80% of the 2006 values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

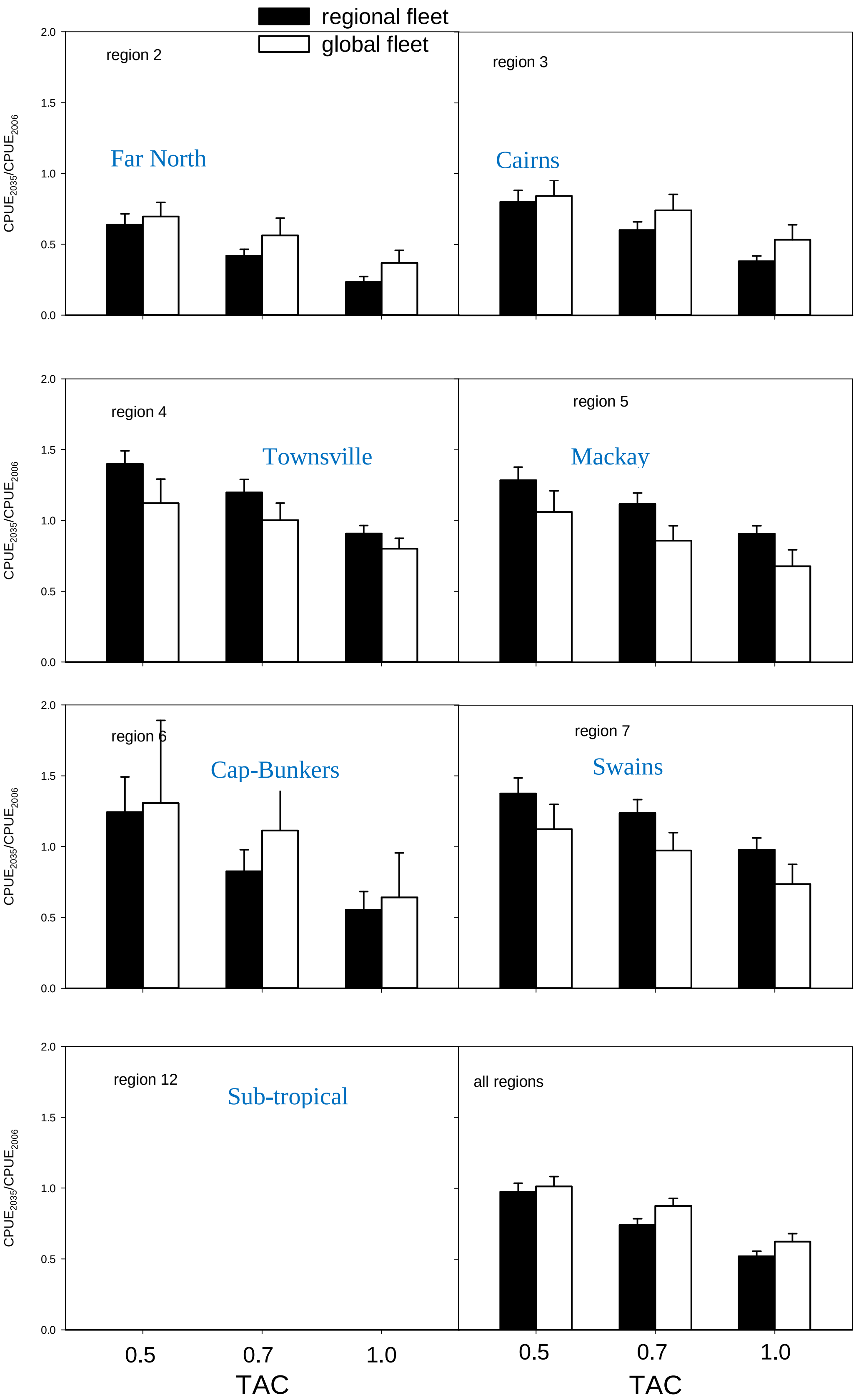


Figure 39 Mean (±SE) commercial catch per unit effort (CPUE) in the different regions at the end of the simulation (2035) relative to the 2006 values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

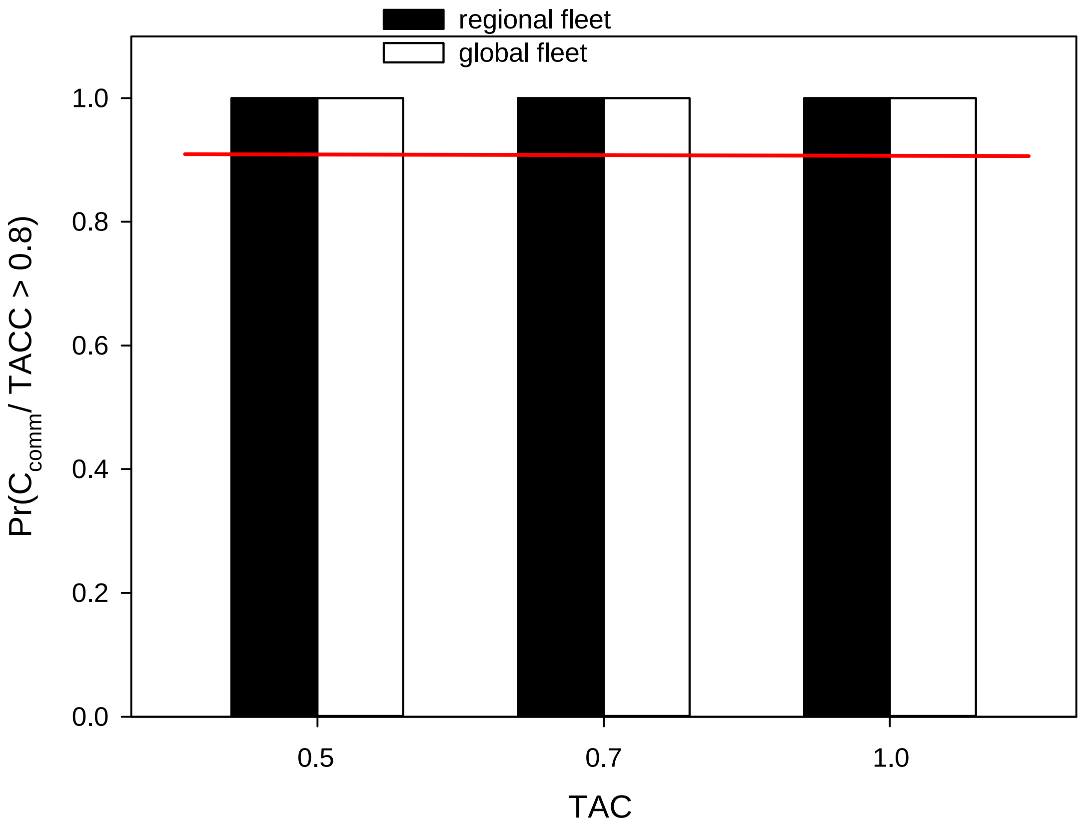


Figure 40 Proportion of simulations in which the commercial landings at the end of the simulation (2035) is above 80% the TAC, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4)

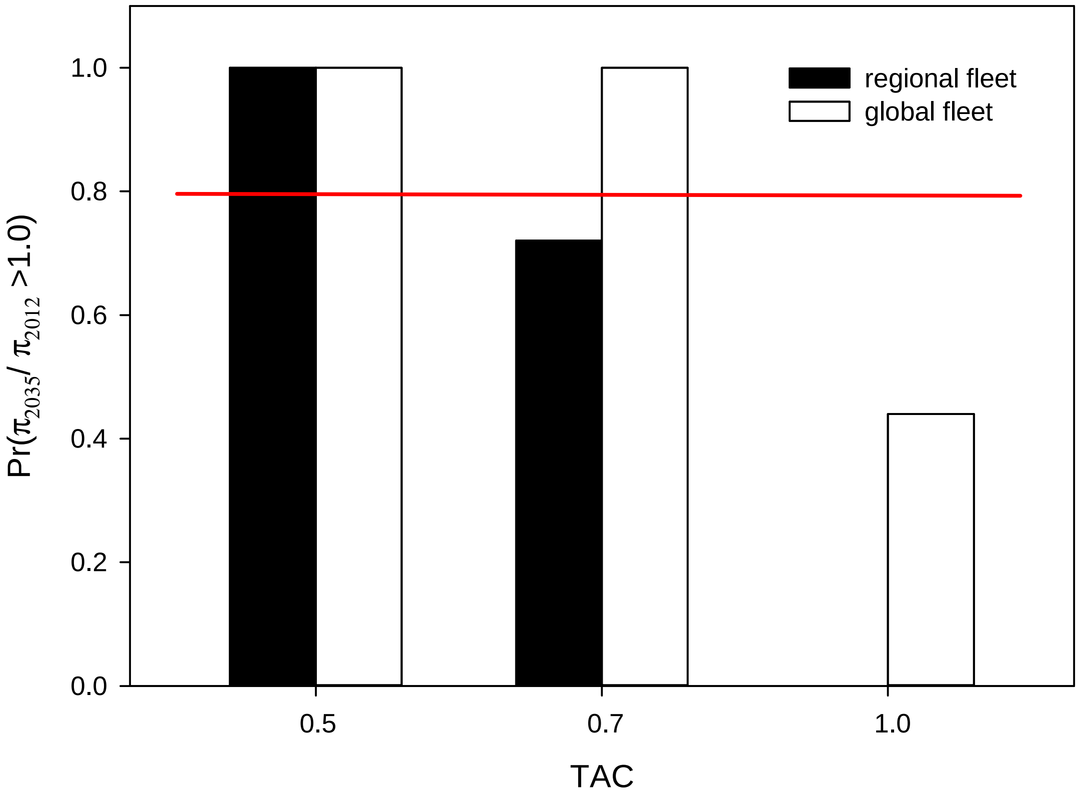


Figure 41 Proportion of simulations in which the commercial profitability at the end of the simulation (2035) is above the profitability at the start of the projections (2012), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4)

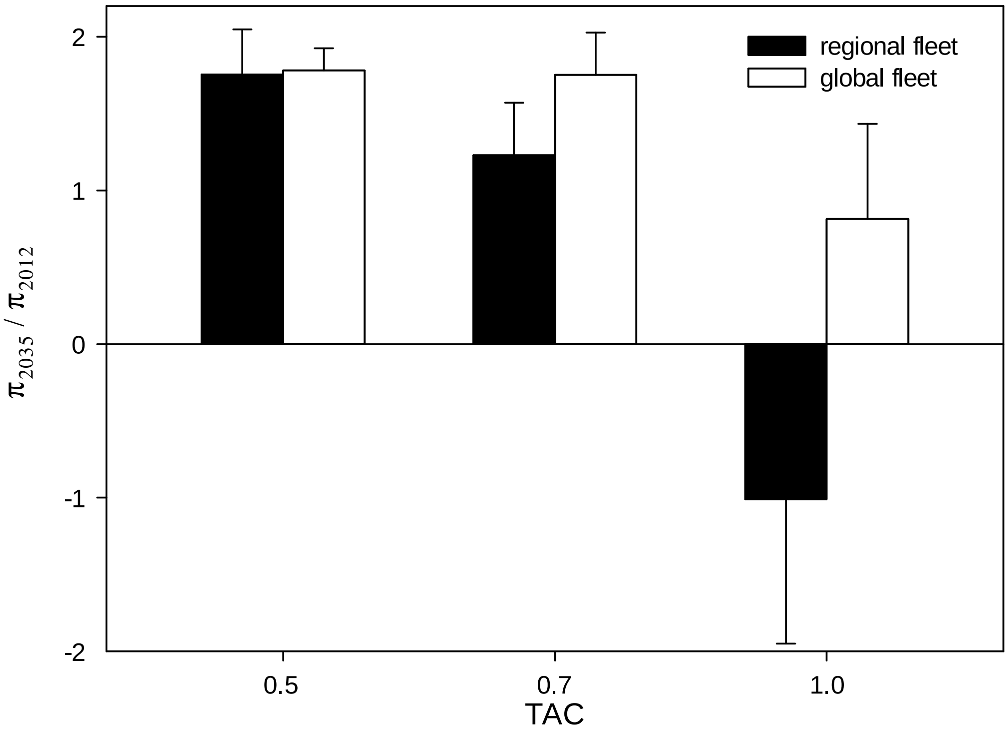


Figure 42 Mean (±SE) commercial profitability at the end of the simulation (2035) relative to that at the start of the projection period (2012), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility

Management objective 8, which required recreational CPUE to be greater than 3.5 kg/ dory-day, at least 50% of the time, was an attempt to convert the objective outlined from the stakeholder workshop of getting 50% of the bag limit in coral trout, 50% of the time. The only region for which this objective was achieved was the Swains, and achievement of the objective was irrespective of the commercial TAC or fleet mobility scenario (Figure 43). The actual recreational CPUE by region shows why this occurred. Recreational CPUE in the Swains was relatively high (about 12 kg/ dory-day) compared to the other regions (typically < 1 kg/ dory-day, Figure 44). This result occurred mainly because the recreational fishing model is static, and effort does not change from where it occurred historically. The amount of recreational effort that occurs in the Swains is typically smaller at 1,200 dory-days (Figure 45; note the log scale) being a region that is far from the coast. Nevertheless, this is higher than experienced historically in 2006 from data (8 dory-days).

Objectives 9 and 10 relating to the charter fleet CPUE differed between the regions south of Townsville (objective 9), and north of Townsville (objective 10). The objective for the charter fleet CPUE in the regions south of Townsville required CPUE to be greater than 8 kg/dory-day, and was not achieved in any region or scenario. Charter CPUE in these regions was rarely above 3.0 kg/dory-day (Figure 46). The objective of obtaining a 4.0 kg/dory of coral trout from the regions north of Townsville were similarly not achieved (Figure 47) because similar to the regions south of Townsville, the CPUE in regions north of Townsville was rarely above 3.0 kg/ dory-day (Figure 48).

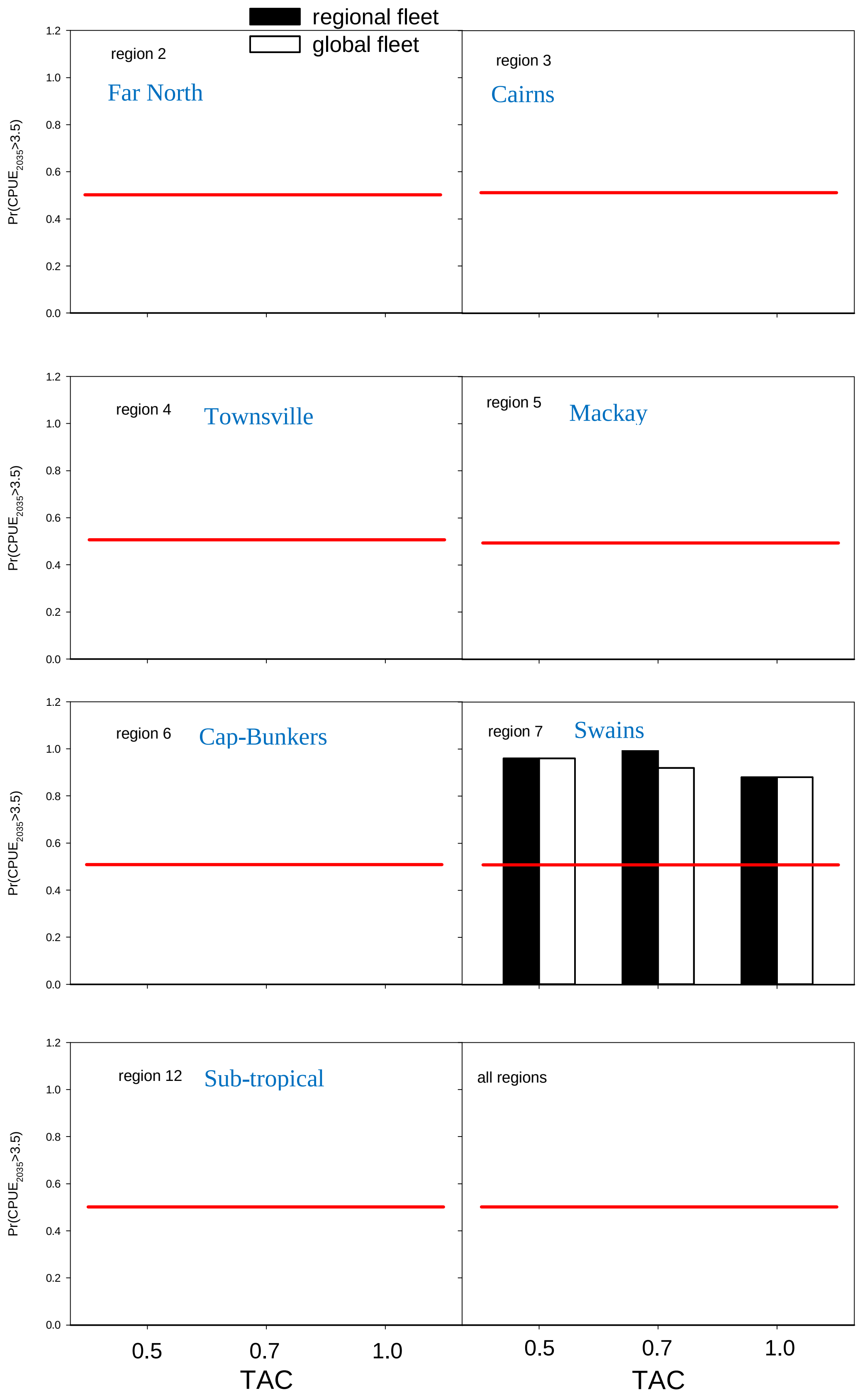


Figure 43 Proportion of simulations in which the recreational catch per unit effort (CPUE) in the different regions at the end of the simulation (2035) is above 3.5 kg/ dory day (interpreted as 50% of the bag limit) under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

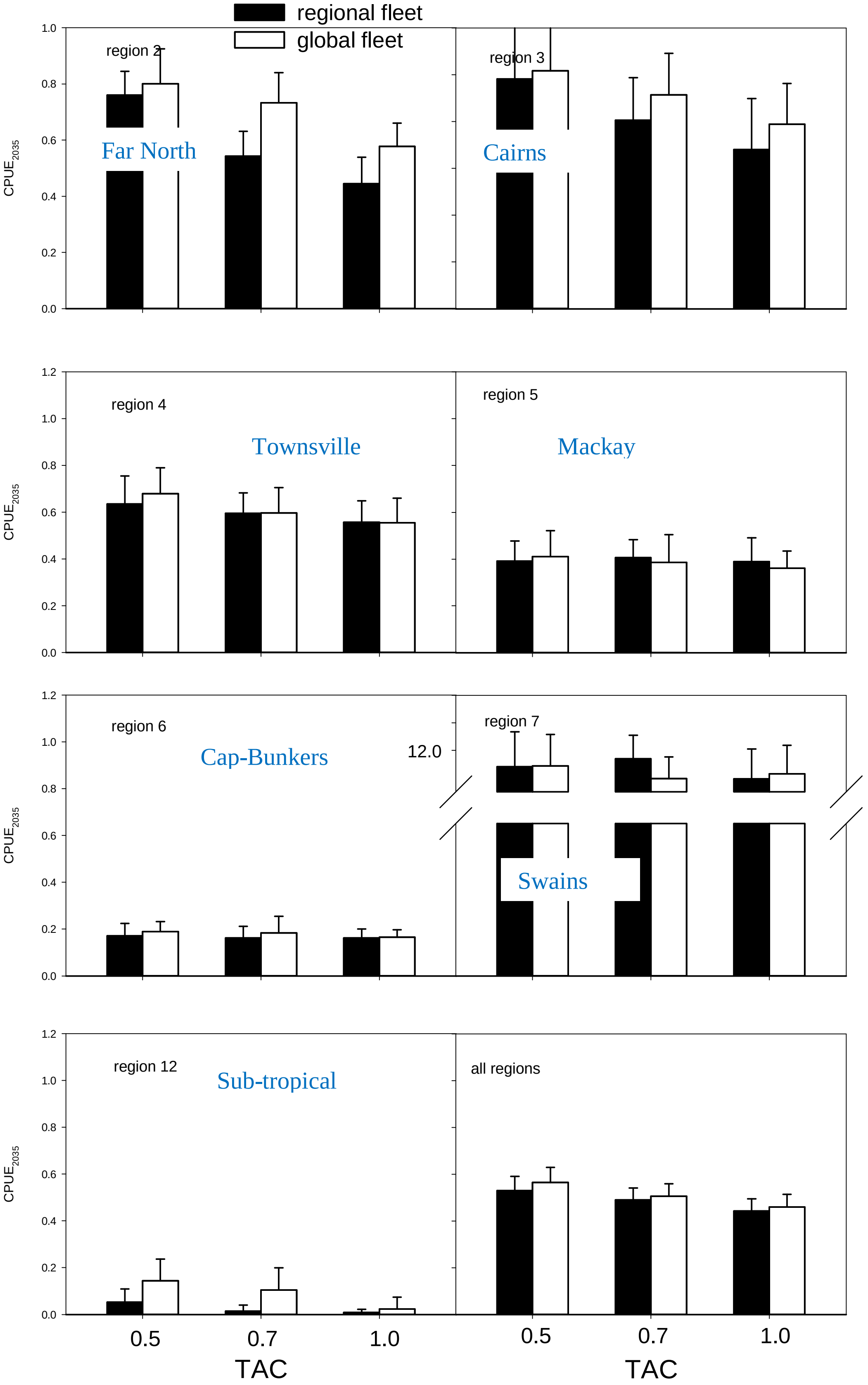


Figure 44 Mean (±SE) commercial catch per unit effort (CPUE) in the different regions at the end of the simulation (2035) relative to the 2006 values, under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

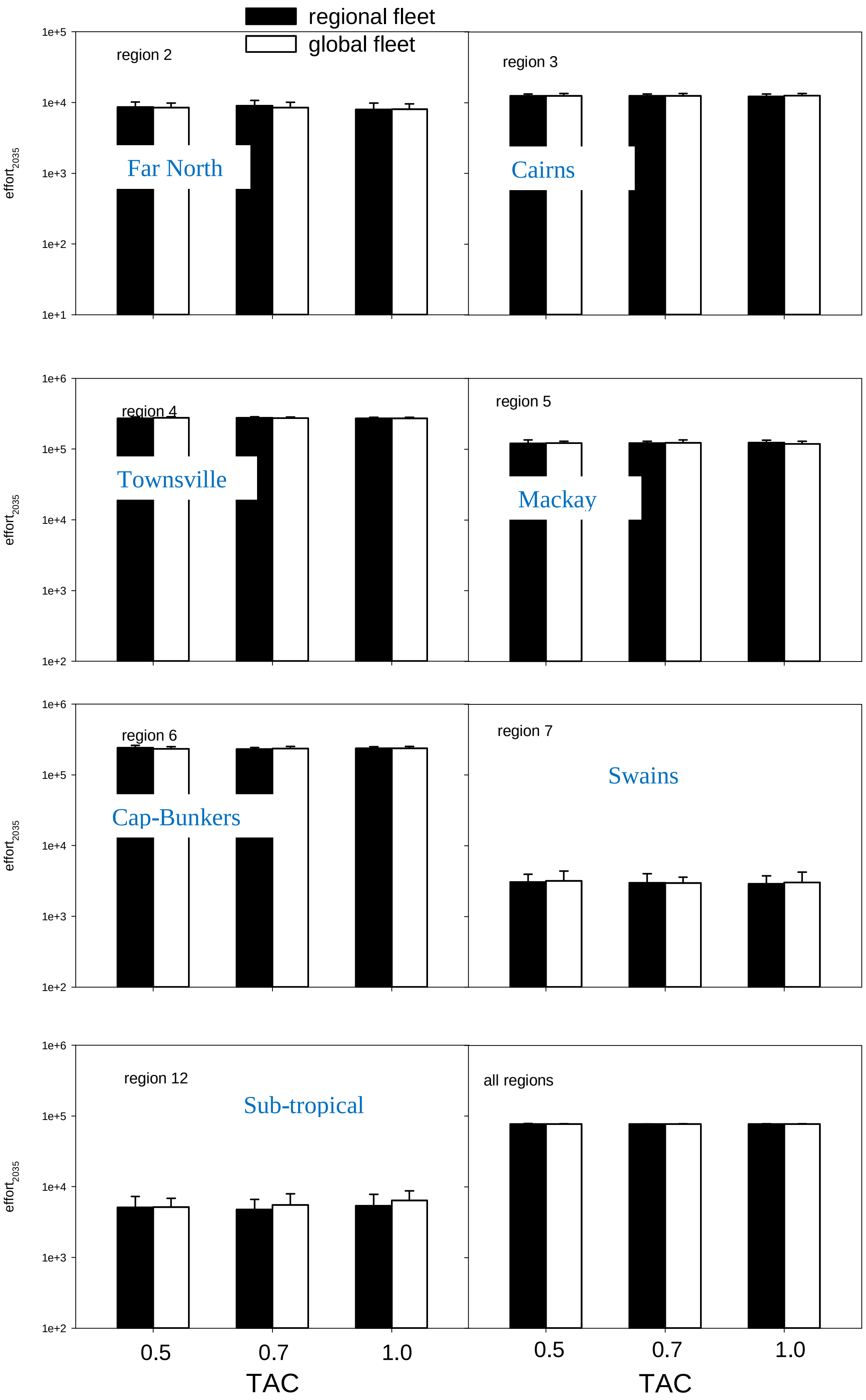


Figure 45 Mean (±SE) proportion of recreational effort distributed across the regions at the end of the simulation (2035), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

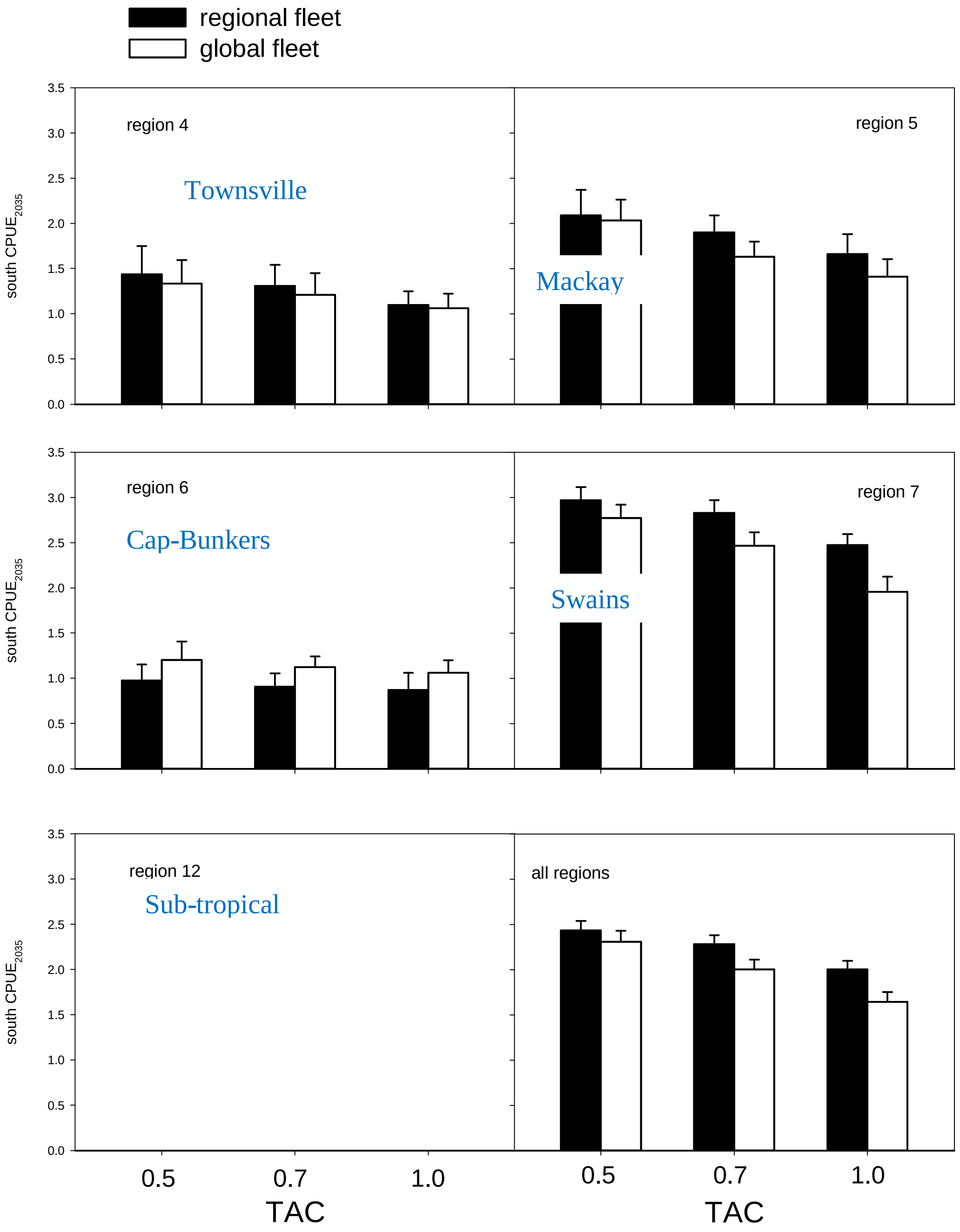


Figure 46 Mean (±SE) charter catch per unit effort (CPUE) in the different regions from reefs south of Townsville at the end of the simulation (2035), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

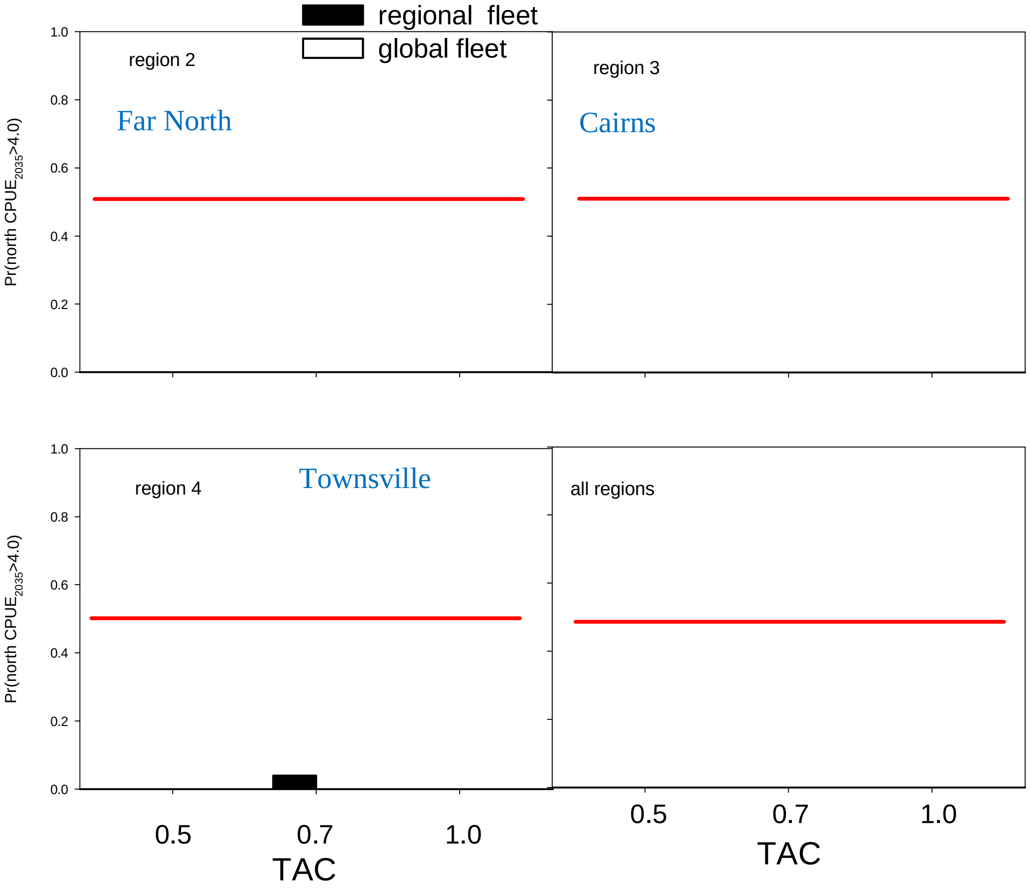


Figure 47 Proportion of simulations in which the charter catch per unit effort (CPUE) at the end of the simulation (2035) from reefs north of Townsville, is above 4 kg/ dory day (interpreted as the daily bag limit) under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. Red line indicates the management objective (Table 4). (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

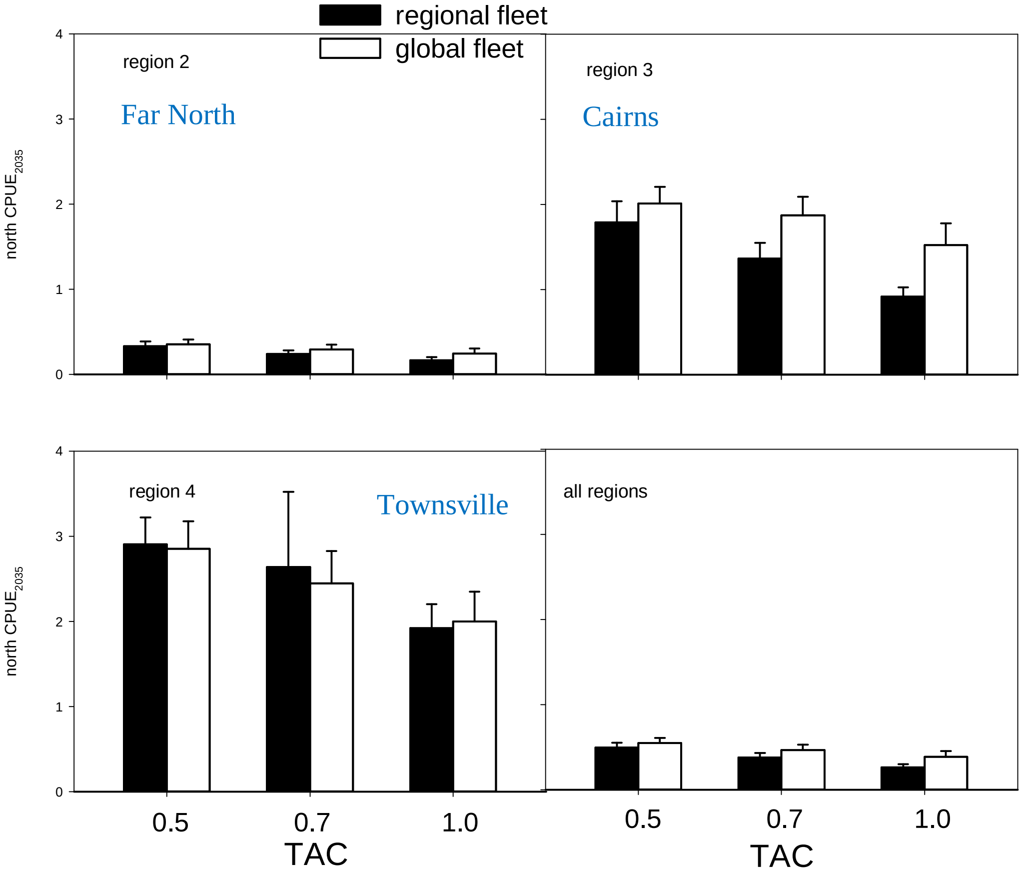


Figure 48 Mean (±SE) charter catch per unit effort (CPUE) in the different regions from reefs north of Townsville at the end of the simulation (2035), under six combinations of TAC (0.5, 0.7, and 1.0 as a proportion of the current TAC) and fleet mobility. (region 2: Far North, 3: Cairns, 4: Townsville, 5: Mackay, 6: Capricorn-Bunkers, 7: Swains, 12: Sub-tropical)

Discussion

Fisheries management strategies consist of three parts: the collection of data, the use or analysis of the collected data, and the associated management decision in light of management objectives and the analysis results. The use of simulation models to test the effect of these parts can be very helpful. This project sought to use an established simulation model for the CRFFF (ELFSim) to evaluate potential monitoring and decision components for the fishery. It explicitly focused on embedding a recently developed stock assessment model into the ELFsim operating model in an effort to determine the accuracy of the model estimation using different sources of data. The project achieved the objectives of the project in the following manner.

1. *To identify appropriate spatial and temporal fishery independent and fishery dependent monitoring strategies, and assessment and harvest control rules that use them.*

A catch-at age assessment model developed by DAF was implemented in ELFSim. It provided an estimate of the underlying coral trout state under a range of data that were fed to it. The data were obtained from simulated monitoring strategies that sampled the underlying ELFSim population. Monitoring included a simulated fishery-independent catch survey that collected CPUE, and age data, as well as a simulated fishery dependent observer survey that sampled commercially caught fish ages. Different scales of fishery dependent monitoring was achieved by aggregating data at increasing scales to represent observer programs that occurred in ports (i.e. across vessels in a port), as well as port-processors (across ports).

Similar work has been done by Giannini et al. (2010) who developed an MSE for several species in the Australian Small Pelagic Fishery, and tested the three tiers of HCRs. They concluded that the data intensive Tier 1 HCR typically results in higher catches and a lower risk the stocks will cross a limit reference point. However, it requires annually collected biological data, and a DEPM (daily egg production method) survey at least once every five years.

Monitoring and assessment that feeds data into an assessment procedure however incur financial costs which could be used on more active measures of species or stock protection and conservation (McDonald-Madden et al. 2010). Whether monitoring is needed and the degree it is required (Legg and Nagy 2006) or cost effective is important to determine. Boyce et al. (2012) took an economic approach to determining the usefulness of expensive aerial surveys of moose, and compared them to harvest dependent methods, showing that although an aerial survey every 10 years could allow a greater number of animals to be harvested, in terms of cost of management, it would be more cost effective to use harvest dependent monitoring.

In the CRFFF however, the cost difference between fishery independent and dependent monitoring may not be as great. Although fishery dependent monitoring could be achieved from vessels, ports or processors (Dept. Primary Industries and Fisheries 2005b), the main product form of coral trout is live trade, making biological samples from the industry difficult to obtain (Dept. Primary Industries and Fisheries 2005b). One option would be to purchase the live product. This would cost roughly $140,000, based on 2746 coral trout, the number caught in the 2007 LTMP survey, and average of 1.1 kg/fish, and a $47.00/kg live product, beach price. Only a small fraction of this cost could be recovered by selling the product as fillets. The estimated cost for a fishery independent structured line survey, like the LTMP, would require vessel and crew charter costs, in addition to biological processing, and generally are considered to be roughly between $350,000 and $400,000, but slightly lower with possibility of deducting product sale cost (as fillets). The Dept. Primary Industries and Fisheries (2005b) estimated the cost of such a monitoring strategy at about $12/ fish. If the costs of the monitoring strategies are thus comparable, the small increase in accuracy, and lower variability in the estimated biomass from the fishery independent survey might not be justified. Our concern is that the scenarios under which these results were determined are limited and a further more exhaustive examination should be undertaken before a definitive conclusion can be made.

In a recent meeting with the Fisheries Queensland’s Long Term Monitoring team in May 2015 (**Extension and Adoption**) plans were developed to establish a follow-up project between the Monitoring group and the Assessment group, with CSIRO and fishery manager involvement to address and resolve further the requirements regarding sampling protocols. The work will explore the sensitivies of the assessment model to sampling procedures and stock assessment diagnostics in greater detail.

Assessment and monitoring are an important part of both adaptive management, and state dependent management commonly used in fisheries (McDonald-Madden et al. 2010) as they are required to determine status for input to an HCR, and the resultant TAC. We implemented an HCR with input from the DAF developed stock assessment model, which gradually increased the TAC over the projection period, and correspondingly reduced the biomass, which remained at relatively high levels. The assessment model tended to overestimate the stock biomass. The implication of this is the potential to over-fish the stock, but this did not occur in the simulation, possibly because the stock started the projection high, or because the parameters of the HCR (C_{targ}, X_{targ} and X_{lim}), which were not estimated, were set to values that made this difficult. For example, although C_{targ} was determined from historical catches in the fishery may be below MSY. A more exhaustive examination of the HCR and the selection of the target reference point is required.

CPUE-based HCRs were also examined and seen to result in substantially lower catches (TACs), and corresponding higher biomass. It is important to distinguish that these types of HCRs are, in principle, empirical in the calculation of CPUE and associated reference points, and they do not statistically consider the life history or population dynamics of the stock in their derivation. The result could be that the target catch and target CPUE may not necessarily result in steady state. Reference points that choose desirable periods in the fishery should consider whether the fishery was in a transitory state or not in that period (Little et al. 2011). Furthermore, CPUE-based HCRs that use a subset of the commercial fleet to calculate the index of abundance, must also factor this into the derivation of the reference points.

The second objective of the project was:

2. *To update the economic and fisheries data used to determine cost effective management strategies.*

All of the most recent data available to incorporate into the model was used. Commercial, charter and recreational fisheries catch and effort data, at a monthly time scale and reef spatial scale were incorporated into the model at 2011. Since recreational data is only obtained periodically from surveys, the data had to be interpolated temporally between surveys, and distributed spatially (Mapstone et al. 2004).

A large portion of the commercial fleet was surveyed for their economic activity and the factors that may affect profitability (Thebaud et al. 2014). The economic survey (Thebaud et al. 2012) resulted in classification of vessels into three groups, characterised mainly by vessel physical characteristics, trip behaviour, and associated economic costs. These characteristics were implemented by updating the vessel characteristics in the vessel dynamics model (Little et al. 2007), and updating the vessel costs required for the model of quota trading (Little et al. 2009a; Little et al. 2009b). Future work exploring the importance of the survey results is critical, as social and economic factors could shed light on fishery outcomes (Innes et al. 2012).

Lastly, the project attempted:

3. *To give scientists and managers in DEEDI (DAF) their own ability to compare and contrast methods of data collection and analysis for the CRFFF, in order to aid the identification of appropriate harvest strategies.*

The simulations evaluating the QLD stock assessment and the proposed harvest control rules were performed by DAF. The department also proposed the candidate HCRs to examine, and participated extensively in the economic survey.

Future use of the model is available to DAF staff. An ELFSim code repository has been set-up at:

`https://svnserv.csiro.au/svn/ELFSim3.0`

and maintained at CSIRO, with DAF staff having read/ write privileges. The repository also warehouses a version of the DAF assessment model source code. DAF staff thus now have the capability of changing the code in tandem with other researchers in CSIRO and elsewhere, and performing further simulations with the model.

Conclusion

This project has fully met the following objectives:

1. To identify appropriate spatial and temporal fishery independent and fishery dependent monitoring strategies, and assessment and harvest control rules that use them.
    - Evaluation of using age frequencies from a fishery independent survey found marginal improvement over the use of age frequencies from fishery dependent sources, in the ability of the stock assessment model to accurately estimate the underlying biomass.
    - Increased spatial aggregation of fishery dependent age frequencies, at coarser spatial scales, did not noiticebly degrade the performance of the stock assessment model to estimate the underlying biomass.
    - The stock assessment model performed reasonably. It slightly over-estimated the simulated stock size, but the difference was within expectations given that the assumptions employed in the model differed from those in the underlying operating model.
    - A harvest control rule that used the stock assessment model performed adequately by increasing TACs over the levels currently in the fishery, but below the level targeted. and only marginally reduced biomass. However, more information is needed on the conditions that led to this conclusion, such as effect of the size of the underlying operating model biomass, and the sensitivity of the target reference point calculation.
    - Harvest control rules that were CPUE-based require careful consideration of the empirically derived reference points. The ones chosen in the current study indicate that achieving the stock state may not be possible given the choice of target catch and target CPUE.
    - Harvest control rules that use a non-random subset of the commercial fishing fleet to calculate the index of abundance (CPUE), should calculate reference points from the corresponding vessels. The reference points for the HCR were not calculated based on the vessels used to generate the CPUE in the HCR, which resulted in the failure to achieve the target stock state.

2. To update the economic and fisheries data used to determine cost effective management strategies.
    - Data informing the modelling exercise was critical to accurately representing the stock dynamics and the fishery.
    - The current snapshot of the fishery from the economic survey indicated that the fishing fleet for coral trout is diverse and has changed rapidly since the last time it was examined.
    - Fisheries data used for all sectors of the fishery were updated to 2011.

3. To give scientists and managers in QLD DAF their own ability to compare and contrast methods of data collection and analysis for the CRFFF, in order to aid the identification of appropriate harvest strategies.
    - QLD DAF staff developed the assessment model used in the MSE, integrated the stock assessment model into ELFSim and ran the simulations evaluating monitoring strategies, and assessment and harvest control rules.
    - QLD FQ were also critical particpants in the economic survey, and led the development of scenarios, and candidate monitoring strategies and harvest control rule that were evaluated.

Implications

Two outcomes result from this research:

1. Managers and stakeholder groups like QSIA will be provided with critical information for cost effective ways of monitoring and analysing the coral trout stock, which could lead to the implementation of harvest control rules for the fishery.

- The fishery has changed substantially since it was last surveyed and is likely to change rapidly again as the effect of the mining boom diminishes. It is important to consider this when reviewing the variable, and in particular labour costs to the fishery.
- Stock assessment model estimations based on fisheries dependent monitoring programs were comparable to fishery independent monitoring program. This was also true across a range of spatial scales. This opens up the possibility of exploring the cost effectiveness of spatial and temporal scale of monitoring using monitoring cost data.
- A carefully implemented harvest control rule could provide sustainable and economic benefit to the commercial coral trout sector, although more detailed exploration of CPUE-based rules is required.

2. Fisheries managers and the management agency will develop the skills and capability to do MSE simulation themselves with less reliance on obtaining funds to contract an external research agency. This will allow DAF to continually evaluate and improve monitoring design, abundance indicators, assessment techniques, and decision rules that are used for calculating TACs.

- The stock assessment model and its integration into ELFSim were undertaken by DAF in QLD, who now have the initial capability of using the model to explore fishery questions. All parties are committed to maintaining this capability in the future. Further research is being planned within FQ (**Further Development**).

Lastly, we stress that the modelling results shown are a first attempt at implementing these management arranagement into a very spatially complex fishery into a simulation framework and exploring their consequence, and that closer examination is needed, under a range of underlying condtions, to make any definitive advice.

Recommendations

Research

Economic state of fishery

1. Future economic surveys are needed. The economic state of the fishery is changing rapidly.

MSE and stock assessment model

2. More exhaustive management strategy evaluations are recommomended to capture a greater range of conditions in the under underlying ELFSim coral trout population, and provide greater confidence in stock assessment estimation and recommended monitoring strategies.
3. More attention to the stock assessment model diagnostics is needed.
4. Effort should be directed toward documenting possible mismatch between operating model, assessment model and historical data, and determining the effect of misalignment.

Management

Monitoring program

5. There was no indication from the simulations that fishery independent monitoring, primarily of age frequencies, was more effective than fishery dependent monitoring of age frequencies. This may indicate a role for fishery dependent collection of age frequencies.
6. The basis of this result however has been made in the idealised world of a simulation model. Incorporating greater realism in simulating the monitoring process within ELFSim is recommended, through greater involvement of the monitoring group of FQ, including further testing in an MSE framework as sampling protocols change.

Harvest control rules

7. A more detailed analysis is needed for estimating the parameters of the harvest control rule (HCR) associated with the catch-at-age stock assessment model.
8. More detailed exploration of empirically derived CPUE-based harvest control rules are needed for consideration for management purposes.
9. HCRs that combine a periodic full quantitative stock assessment with annual empirically derived CPUE-based decisions are recommended.
10. It is recommended that any CPUE-based HCR be periodically confirmed by a more comprehensive catch-at-age stock assessment model developed by DAF.

Further Development

Adoption of this research requires further work to explore in greater detail the sensitivies of the assessment model to sampling procedures. Stock assessment diagnostics also need to be examined in greater detail. Further work is being discussed and planned between FQ LTMP, and other FQ scientists and fisheries managers. Specifically, an internal FQ follow-up project is being developed between the Monitoring group and the Assessment group, with CSIRO and fishery manager involvement to address and resolve further the requirements regarding sampling protocols. The work will explore the sensitivies of the assessment model to sampling procedures and stock assessment diagnostics in greater detail. This is being followed-up and pursued by CSIRO.

Extension and Adoption

The project was extended and communicated to the end-users in several ways:

1. CSIRO have highlighted the research on a website: http://author.csiro.au/en/Research/OandA/Areas/Marine-resources-and-industries/Sustaining-Australian-fisheries/Coral-reef-fishing

2. A media release was made and sent to relevant organisations to inform them of the project details and main point of contact (see **Project coverage**)
3. A flyer was developed advertisinfg the project mainly to increase the exposure of the project in order to get parties interested on participating in the economic survey (see section **Project materials** developed
4. Project flyer)
5. An article was submitted in the Queensland Seafood Magazine for general information and to get parties interested on participating in the economic survey.
6. A website was developed for the project for general information and to get parties interested on participating in the economic survey (ses section **Web survey tool**)
7. Two stakeholder workshops were also held:
    a. The first was a workshop with managers and industry leaders to design the economic survey (see **Survey design workshop, October 2011**, Brisbane). The purpose of this workshop was to get buy-in from the main leaders in the fishery, and obtain any important information they might have that could affect the success of the project.
    b. The second was a workshop held in Townsville (see **Stakeholder Workshop, November 2012**) as the first attempt to show some of the results that we had gathered from the fishery. In particular, the workshop:
        i. Showed the preliminary results of the economic survey
        ii. Showed progress in the development of the stock assessment model
        iii. Re-visited fisheries management objectives that are held by stakeholders
8. A seminar was given in May 2015 in Brisbane to the Fisheries Queensland, Long-term Monitoring Program team conveying the results of the project.
9. Conferences:

    a. MODSIM 2013 Adapting to Change: the multiple roles of modelling. 1-6 December 2013 Adelaide.
    b. IIFET (International Institute of Fisheries Economics and Trade) 2014. 7-11 July. QUT Brisbane, Australia.
10. Published papers:
    a. Innes, J., Thebaud, O., Norman-Lopez, A. and Little L.R. (2014) Does size matter? An assessment of quota market evolution and performance in the Great Barrier Reef Fin-Fish Fishery. Ecology and Society 19, 13
    b. Innes, J., Thebaud, O., Norman-Lopez, A., Little, L.R., Kung, J. (2014) Evidence of package trading in a mature multi-species ITQ market. Marine Policy 46, 68-71
    c. Thebaud, O., Innes, J., Norman-Lopez, A., Cameron, D., Cannard, T., Tickell, S., Kung, J., Kerrigan, B., Williams, L. and Little, L.R. (2014) Micro-economic drivers of profitability in an ITQ-managed fishery: an analysis of the Queensland Coral Reef Fin-fish Fishery. Marine Policy 43, 200-207

11. Adoption of this research requires further work which is being discussed and planned between FQ LTMP, and other FQ scientists and fisheries managers. Specifically, an internal FQ follow-up project is being developed between the Monitoring group and the Assessment group, with CSIRO and fishery manager involvement to address and resolve further the requirements regarding sampling protocols. The work will explore the sensitivies of the assessment model to sampling procedures and stock assessment diagnostics in greater detail. This is being followed-up and pursued by CSIRO

Project coverage

Below are the details of these extension efforts that were made in the project:

Media Release

A media release was made on the CSIRO website and a link sent to the following organisations

Marine Stewardship Council;

World Wildlife Fund;

Queensland Seafood Industry Association;

Seafood Australia;

Queensland Reef Line Council;

Oh Food Services;

Fishing Monthly Magazine;

SETFIA;

Sustainable Fisheries Partnership;

QLD DAF

FRDC;

AFMA;

Coral trout. Photo: Fisheries Queensland, Department of Agriculture, Fisheries and Forestry.

Live coral trout. Photo: Fisheries Queensland, Department of Agriculture, Fisheries and Forestry.

Coral trout fisher. Photo: Fisheries Queensland, Department of Agriculture, Fisheries and Forestry.

Media Release: Research to strengthen the Coral Reef fishing industry

Fishing industry operators and managers are helping scientists build a risk management tool for the Coral Reef Fin Fish Fishery of the Great Barrier Reef (GBR), which was valued at almost $40 million in 2009–2010.

Fisheries scientists in Queensland will use the tool to devise and test monitoring and assessment programs that improve the fishery’s resilience to environmental and economic risks.

Project leader Rich Little of CSIRO says the computer-based tool will be like a ‘flight simulator’ that lets ideas be tested before being tried in reality.

The CSIRO Wealth from Oceans Flagship is leading the project, which involves the Queensland Department of Agriculture, Fisheries and Forestry, the Great Barrier Reef Marine Park Authority and James Cook University, with funding from the Fisheries Research and Development Corporation.

The fishing industry is supporting the research through the Queensland Seafood Industry Association and the Reef Line Council, and by taking part in a confidential economic survey.

Dr Little says the Coral Reef Fin Fish Fishery implements world best practice fisheries management that includes spawning closures, restricted fishing licenses and catch quotas, all within a framework that includes no-take areas.

Commercial line fishing for coral reef fin fish is concentrated between Cooktown and Fraser Island off Queensland. The catch is mainly exported live to Asia where coral trout, the main targeted species, are highly prized for their bright red colouring.

While some 30% of coral trout habitat is protected by no-take zones, the fishery still faces considerable environmental and economic risk.

For example, while storms are a normal part of the GBR environment, cyclones as large and intense as the category 5 tropical cyclones *Hamish and Yasi* are historically rare, recurring every 200–300 years or more.

Cyclone *Yasi* caused severe damage to some six per cent of coral reef in the marine park in February 2011, and in 2009, tropical cyclone Hamish was the most destructive cyclone to hit the reef since the early 1900s.

Together these events have caused a five million dollar (more than 10 per cent) loss in value to the Coral Reef Fin Fish Fishery through fish dispersal, habitat destruction and lost opportunities for fishing.

Dr Little says the new tool will help the fishery prepare for such risks in its planning and management.

“The ultimate aim is to have an economically prosperous and ecologically sustainable fishery,” he says.

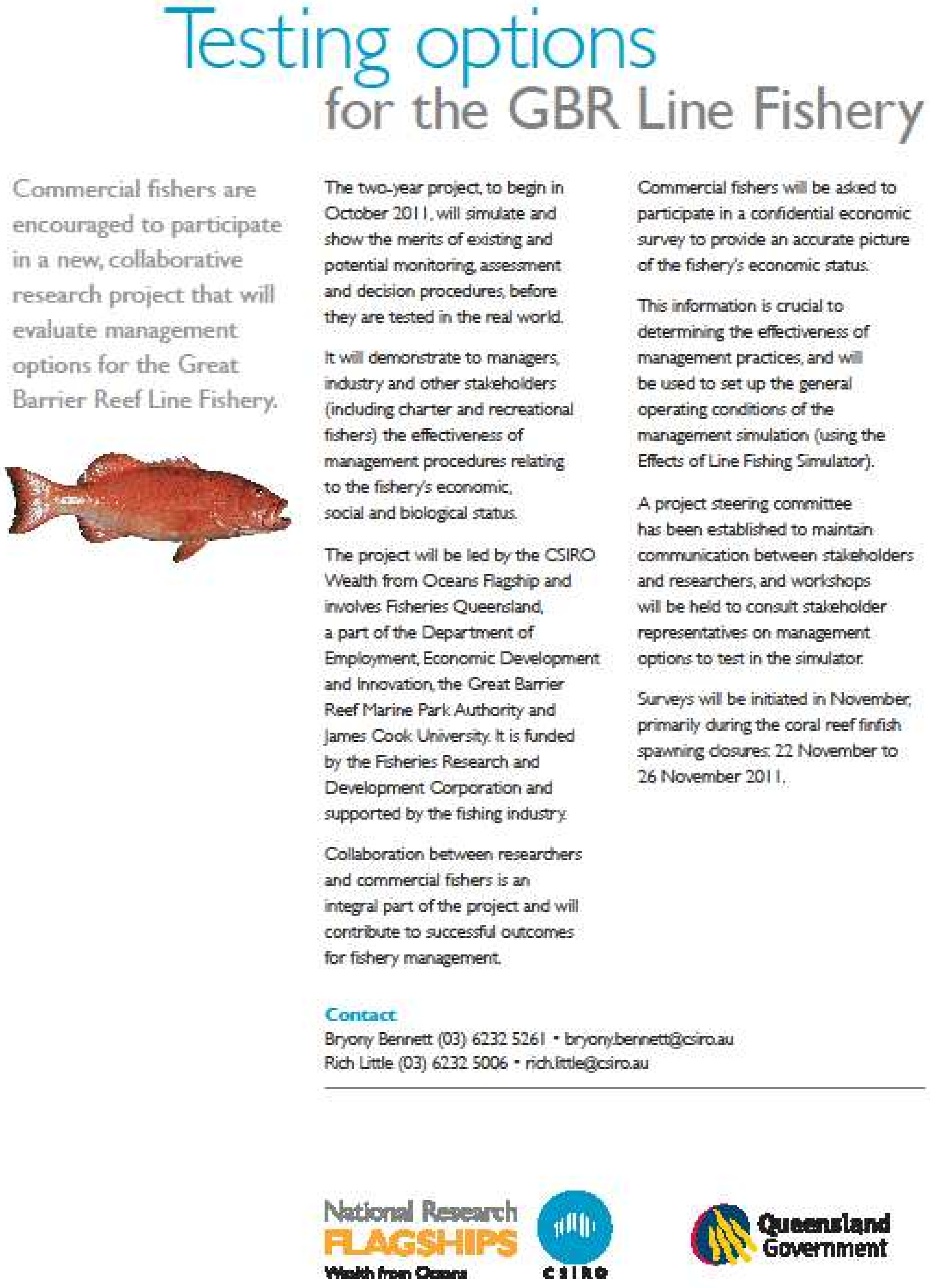
Contact

Bryony Bennett (03) 6232 5261, bryony.bennett@csiro.au

Rich Little (03) 6232 5006, rich.little@csiro.au

Project materials developed

Project flyer



Testing options for the GBR Line Fishery

Commercial fishers are encouraged to participate in a new, collaborative research project that will evaluate management options for the Great Barrier Reef Line Fishery.

The two-year project, to begin in October 2011, will simulate and show the merits of existing and potential monitoring, assessment and decision procedures, before they are tested in the real world.

It will demonstrate to managers, industry and other stakeholders (including charter and recreational fishers) the effectiveness of management procedures relating to the fishery's economic, social and biological status.

The project will be led by the CSIRO Wealth from Oceans Flagship and involves Fisheries Queensland, a part of the Department of Employment, Economic Development and Innovation, the Great Barrier Reef Marine Park Authority and James Cook University. It is funded by the Fisheries Research and Development Corporation and supported by the fishing industry.

Collaboration between researchers and commercial fishers is an integral part of the project and will contribute to successful outcomes for fishery management.

Commercial fishers will be asked to participate in a confidential economic survey to provide an accurate picture of the fishery's economic status.

This information is crucial to determining the effectiveness of management practices, and will be used to set up the general operating conditions of the management simulation (using the Effects of Line Fishing Simulator).

A project steering committee has been established to maintain communication between stakeholders and researchers, and workshops will be held to consult stakeholder representatives on management options to test in the simulator.

Surveys will be initiated in November, primarily during the coral reef finfish spawning closures: 22 November to 26 November 2011.

Contact

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Rich Little (03) 6232 5006 • rich.little@csiro.au

National Research FLAGSHIPS
Wealth from Oceans
CSIRO
Queensland Government

Web survey tool

The front page of the web survey tool is accessible at https://cffecon.csiro.au/. The home page is accessible to the general public and was used to report progress of the survey to anyone with an interest. The interview information, hosted survey documents, and survey-transcription forms are accessible only to members of the survey team who have private logins.

The web survey tool also was designed to allow information about each potential interviewee to be stored and reported in several formats separate from the survey transcriptions, including a calendar of upcoming interviews, a map of interview locations, and simple statistics to indicate overall progress of the survey. This part of the survey tool was used regularly to track survey progress and to track information follow-up efforts.

Survey design workshop, October 2011

Economic survey of the Queensland Coral Reef Fin-Fish Fishery; 27 October 2011 (0900 – 16:00); Floor 2 Conference Room, Primary Industries building; 80 Anne St., Brisbane

A two-year project, beginning in October 2011, aims to simulate the existing and potential monitoring, assessment and management procedures for the Queensland Coral Reef Fin-Fish Fishery, before they are tested in the real world. The project is led by the CSIRO Wealth from Oceans Flagship and involves Fisheries Queensland, a part of the Department of Employment, Economic Development and Innovation (DEEDI), the Great Barrier Reef Marine Park Authority (GBRMPA) and James Cook University (JCU). It is funded by the Fisheries Research and Development Corporation and supported by the fishing industry.

The project is based on the "Effects of Line Fishing Simulator" (ELFSim) which is used to simulate the biology of key target species as well as fishing. ELFSim includes a description of the activity and economics of the fishing fleet. In order to base these simulations on the current description of the fishery, CSIRO is conducting an economic survey of the commercial operators in the CRFFF. Information collected via this survey will allow us to establish an updated description of the status of the fishery.

The survey will be carried out via face-to-face interviews using a paper questionnaire. We would like to invite you to attend a one-day workshop to discuss the proposed approach to the survey. A preliminary agenda for the meeting is provided below.

Agenda

1/ Presentation of project and project team

2/ Presentation of the survey objectives and approach

3/ Presentation and discussion of a typology of the coral reef fishing industry on which to base the survey

4/ Presentation and discussion of the questionnaire

5/ Open discussion on other aspects to consider in survey design and implementation

Participants

CSIRO: Rich Little, Olivier Thebaud, James Innes, Ana Norman

DEEDI: Brigid Kerrigan, Steph Slade, Tom Roberts

INDUSTRY: Dino Focas, Carl D'aguar, Greg Smith, Steve Howe, Gareth Andrews, Terry Must (apologies), Dave Pidduck (apologies), Nathan Donaldson.

GBRMPA: Darren Cameron

Stakeholder Workshop, November 2012

A stakeholder workshop on current research projects in the Coral Reef Fin fish Fishery was conducted on 11-12 November 2012, which sought to show participants research that is currently being done in the fishery, which included an update on the development of a stock assessment model for coral trout, and the preliminary results of an economic survey conducted in the fishery.

A major aim of the workshop was to revisit operational stakeholder objectives and present management strategies that have been developed for evaluation and application in the simulation environment. It was intended that participants would leave the workshop with a clear idea of what to expect in the conclusion of the projects This summary document provides participants with a record of the workshop proceedings.

Workshop objectives

1. present the current state of the coral trout stock assessment, including the data that will be used and the reflected assumptions
2. present the preliminary results of an economic survey conducted on the commercial fishing fleet
3. familiarise stakeholders with simulation modelling and the MSE (Management Strategy Evaluation) approach, including potential monitoring strategies and scenarios that will be tested in the model
4. to resolve stakeholder management objectives that reflect the needs and desires of the stakeholders

Welcome and Introductions (See attendance list)

Chair: John Pollock

The Chair stressed that this was information sharing not a management decision-making meeting.

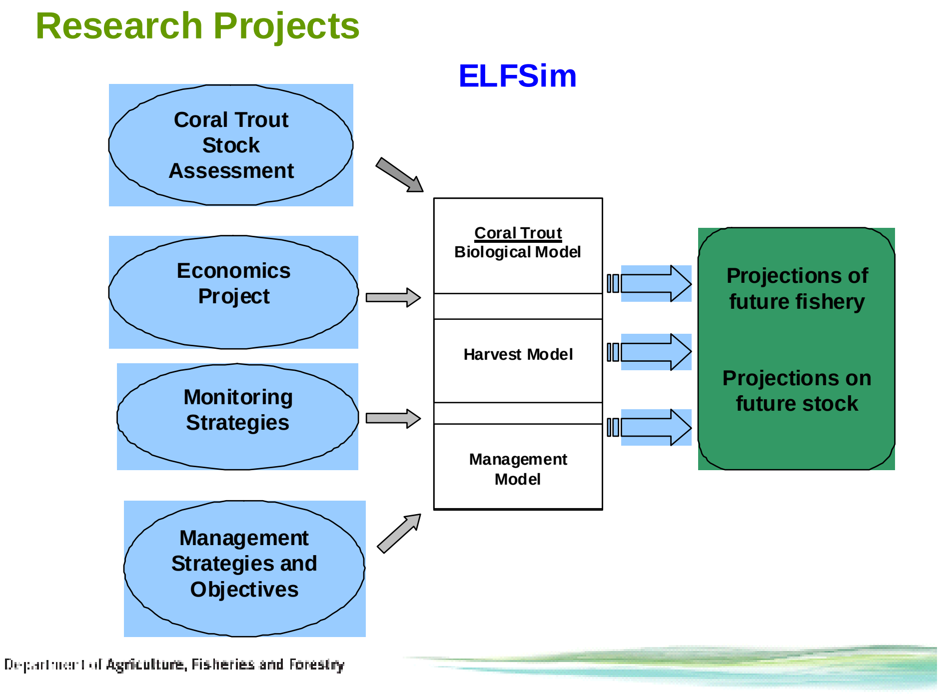
Current Research projects how they fit together

Presenter: John Kung

The recent value of the Coral Reef fin fish fishery is about $30M. There are currently two research projects on the fishery.

1. a stock assessment model is being developed to estimate the state of the stock
2. a management strategy evaluation project is being conducted
    a. to evaluate the effects of monitoring strategies and other management scenarios on the fishery using the Effects of Line fishing Simulator (ELFSim)
    b. conduct an economic survey of the commercial fleet
    c. transfer the operational capability of the simulation model to QLD DAF

The projects and various components fit together like the following figure:



Research Projects

ELFSim

Coral Trout Stock Assessment

Economics Project

Monitoring Strategies

Management Strategies and Objectives

Coral Trout Biological Model

Harvest Model

Management Model

Projections of future fishery

Projections on future stock

Department of Agriculture, Fisheries and Forestry

Why do a stock assessment model?

Presenter: John Kung

The stock assessment model integrates all of the knowledge and information of a stock and attempts to statistically estimate the size. It does this by using principles of population dynamics, life history information such as

1. growth rates,
2. weight at length, and
3. maturity

as well as time trend data on a stock such as:

1. catch
2. CPUE
3. age and length structure

Historical management decisions can be captured in the stock assessment through changes in parameter values and different trends in the data. Stochastic effects, like that of cyclones are also usually captured by stock assessment models.

Coral Trout stock assessment input data and progress results:

Presenter: George Leigh

George Leigh showed the species of coral trout. Catch allocation etc.

CD brought up the validity of data, particularly rec data.

RL (Rich Little) said that there are several projects trying to develop procedures of collecting rec data.

BP (Barry Pollock) stated that the rec survey is world best practice.

BK (Brigid Kerrigan) stated that QLD has led the way naturally for this.

RL said that the uncertainty can be dealt with in MSE.

1. Input data, catch rates ad population model
2. Coral trout problematic – CPUE usually an indicator of abundance – George seems to say that CPUE is not useful
3. Green zones compared to blues difference could show the fishing mortality
    a. Problem is how much fishing occurs in green zones
    b.

DC (Darren Cameron) raise the point of information sharing on the stock assessment and data.

JK (John Kung) said that technology creep is an important factor that needs to be considered.

1. Fishing power

SS2 (Shawn Stiff) brought up extreme events.

Data validity seemed to be an important topic. Many brought up other factors that affect the data going into the assessment.

JP (John Pollock) raised the point that there are other projects to determine the validity and other data factors that influence the of stock assessment and the data going into it.

BP said that coral trout rec catches are by proportion low. JK and GL said that the rec catches of coral trout in the northern areas are high – ie there is a regional effect.

GL (George Leigh) said that rec survey prior to most recent probably overestimated the rec catch taken from the fishery.

Data include

1. Log book 1988
2. Rec surveys
3. QLD fish board 62-81
4. Age freq 1990-2009
5. UVS 83 to present
6. Biological data

SS2 and CD (Carl D'aguar) expressed a concern about the state of the fishery, and ask the question whether the data is keeping up with the state of the fishery.

RO (Randall Owens) said that this is part of the process to collect the current data, and set it in historical perspective.

JK said that the meeting is to determine whether the current data is consistent with what they are seeing on the water.

SS2 asked about rotational closures. JP said this is beyond the scope of the current stock assessment. DC stated that the purpose of green zones is not fisheries management but conservation of biodiversity.

GL showed different reef types, and different reef habitats.

CD asked about the relation about the Torres Strait. Is there anything from Torres Strait that can be learned?

JP asked how we can learn from the two fisheries. Confusion about whether George wants to extend the stock assessment to Torres strait. DC stated that this needs to be considered carefully because of species catch composition. There are also other oceanographic factors that might separate the two areas.

DC rec survey good. Has concern about extrapolating up in rec survey.

After lunch GL went through the data.

Catches are highest in MacKay.

Effect of cyclones: Justin (1997) catches declined, restructure, Hamish and Yasi all resulted in reduced catches. No data on effort was presented.

Rec data for 2011 estimated 105000 fish caught. Highest in Cairns and Townsville.

RO said asked whether the survey considered the MacKay fishermen from the mines were considered since they don’t have landline phones. SH said that the analysis considered this.

DW (Dave Williamson) mentioned that the inshore catches have a relatively large number of non-leopardus species.

GL show standardised CPUE. Highest in north declining in south. There is general belief that some of the areas in the north (Lizard Island) actually have smaller population densities than in Townsville.

GL presented a times series of std CPUE across whole GBR. AT pointed out that the CPUE has halved since CPUE in early 1990’s.

Variability in CPUE could be due to recruitment variation. Model will fit recruitment residuals.

GL showed relation between catch and “habitat” as he has defined. Includes submerged reefs and bommie fields.

Sian (SB) asked whether the log books before 1997 and after 1997 could be compared for accuracy and inflating catch for impending quota allocation.

SS (Shane Smith) raised the concept of fishing closures protect the aggregations. They used to target the aggregations, which seems t imply that with the spawning closures there have been a reduction in fishing power.

DW and SS2 indicate that aggregations range geographically variable.

AT (Andrew Tobin) said that logbook analysis show no signal from spawning aggregations. (being reviewed in Fisheries Research)

Sustainability. AT questioned the conclusion of the current sustainability of the stock based on the CPUE declining trend. DW commented on the future threat to the stock from global warming. The south seems to be more vulnerable to the north since the habitat is more based on coral in the south and non-coral (rock) in the south.

Introduction to MSE and Monitoring Strategies

Presenter: Rich Little

Fisheries management is about managing risks. Risk is composed to two elements:

1. the probability of an event
2. the consequence of an event

Activities can be done to reduce risk, but regular monitoring combined with a decision action is needed to actively manage risk. The combined monitoring and decision procedure is called a management strategy by fisheries management.

Fisheries management strategies usually require monitored information of a fish stock, which is usually integrated into some form of analysis like a stock assessment model.

Management strategy evaluation (MSE) implements management strategies in a computer setting and tests to see if management activities will achieve the management objectives. Thus, MSE can determine if the monitoring strategies and stock assessment requirements are sufficient to estimate the size of a known stock in the computer.

	Monitoring strategy		
1.	Structured line survey	Fishery independent, 24 reefs visited once per year	age, lengths, CPUE
2.	On board sampling	Fishery dependent, spatial	age, lengths
3.	Port sampling	Fishery dependent, spatial	age, lengths
4.	Processor sampling	Fishery dependent,	age, lengths

Preliminary Economic survey results

Presenter: Olivier Thebaud

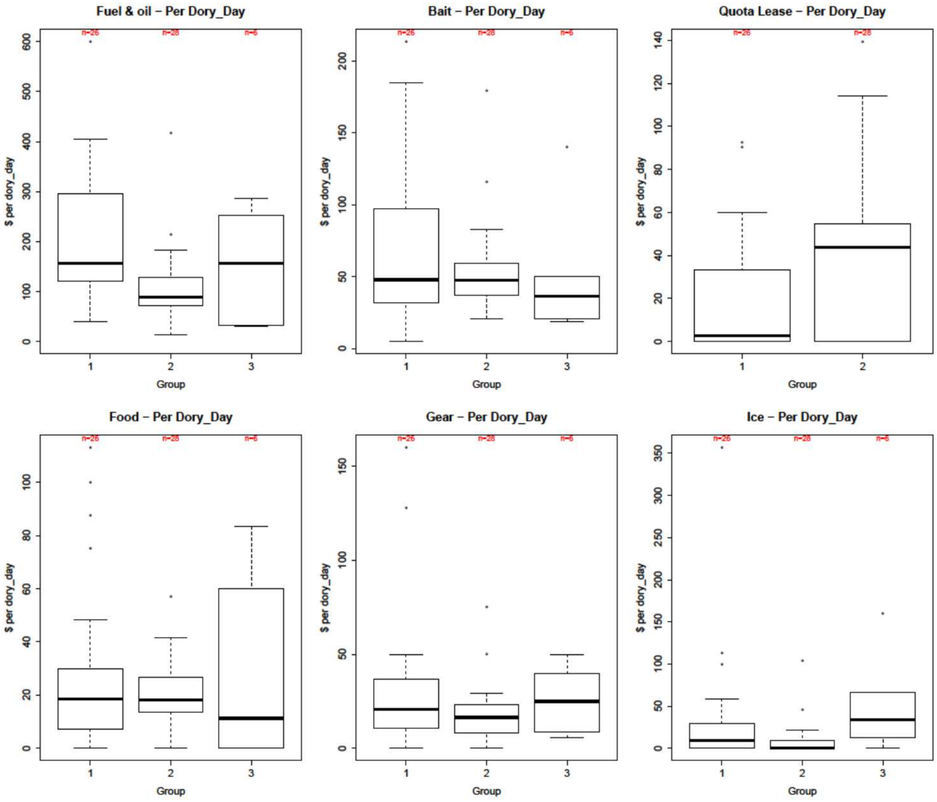
The survey used existing information to create a fleet profile based on the vessel characteristics and fishing activity. The fleet was then classified into groups:

1. generalists (133 vessels) have a roughly equal RQ and non-RQ fishing component
2. dedicated live CT fishers (56 vessels) strong CT targeting component
3. diversified fishers (24 vessels) have a strong non-RQ fishing component

Quota ownership analysis indicated that a large number of lease dependent fisheries that account for 69% of the catch, and a large number of investors who own 42% of the quota.

Good representative coverage was obtained spatially across the fishery in the three groups. In total 62 fishers were interviewed. In general, industry were pleased at the results and indicated that they thought were an accurate representation of the fishery.

The preliminary economic analysis culminated in various costs to fishing operations by group:


Fuel & oil – Per Dory_Day
n=26
n=28
n=6
$ per dory_day
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100
200
300
400
500
600
1
2
3
Group
Bait – Per Dory_Day
n=26
n=28
n=6
$ per dory_day
0
50
100
150
200
1
2
3
Group
Quota Lease – Per Dory_Day
n=26
n=28
$ per dory_day
0
20
40
60
80
100
120
140
1
2
Group
Food – Per Dory_Day
n=26
n=28
n=6
$ per dory_day
0
20
40
60
80
100
1
2
3
Group
Gear – Per Dory_Day
n=26
n=28
n=6
$ per dory_day
0
50
100
150
1
2
3
Group
Ice – Per Dory_Day
n=26
n=28
n=6
$ per dory_day
0
50
100
150
200
250
300
350
1
2
3
Group

Management Strategy Evaluation and Decision Analysis

Presenter: Rich Little

Conservation objectives:

Spawning Biomass on closed reefs > 90%: 80% of the time

Spawning Biomass on all reefs > 50% 1965: 80% of the time

Stock objectives:

Available Biomass on open reefs > 40% 1965:90% of the time

Available Biomass on open reefs > 48% 1965:90% of the time

CPUE objectives:

Rec: 50% bag limit 50% of time

There were no commercial CPUE objectives because it was thought that profitability better integrates the biological and economic conditions under which the commercial fleet operates.

Commercial profitability objective:

Comm. profitability > current conditions: 80% of time

Harvest objective:

Total comm. CT catch > 80% TAC 90% of the time

Participant List:

Name	Organisation
John Pollock	Chair
John Kung	FQ
Rich Little	CSIRO
Olivier Thebaud	CSIRO
Brigid Kerrigan	Observer
Barry Pollock	Sunfish
Shane Smith	Sunfish
Jo Harris	Sunfish
Andrew Tobin	JCU
Carl D'aguar	Comm fisher

Dani Ceccarelli	JCU
Dave Williamson	JCU
George Leigh	QDAF
Darren Cameron	GBRMPA
Dave Pidduck	Comm fisher
Shawn Stiff	Comm fisher
Ana Norman	CSIRO
James Innes	CSIRO
Hugh Sweatman	AIMS
Sue Helmke	QDAF
Randall Owens	GBRMPA
Steve Howe	Comm fisher
Sian Breen	WWF
Eric Perez	QSIA
Michael O’Neill	QDAF

References

1. Boyce, M.S., Baxter, P.W.J., and Possingham, H.P. 2012. Managing moose harvests by the seat of your pants. Theoretical Population Biology 82, 340-347.
2. Daurès, F., M.-J. Rochet, et al. 2009. Fishing fleet typology, economic dependence, and species landing profiles of the French fleets in the Bay of Biscay, 2000-2006. Aquatic Living Resources 22, 535-547.
3. Department of Primary Industries and Fisheries, 2005a. Fisheries long term monitoring program sampling protocol – Coral Reef Fin Fish: (2005 onwards). Department of Primary Industries and Fisheries, Ql05135, Brisbane, Australia.
4. Department of Primary Industries and Fisheries, 2005b. Fisheries long term monitoring program – Monitoring requirments for the management of the Coral Reef Fin Fish Fishery in Queensland. Department of Primary Industries and Fisheries, Ql05135, Brisbane, Australia.
5. Fisheries Queensland 2011. Annual status report 2010 - Coral Reef Fin Fish Fishery. Brisbane, The State of Queensland, Department of Employment, Economic Development and Innovation.: 23.
6. Fisheries Queensland 2012. Fisheries Long Term Monitoring Program Sampling Protocol – Coral Reef Fish (2008-2009) Section 1.Department of Agriculture, Fisheries and Forestry, Brisbane, Australia.
7. Giannini, F., Hobsbawn, P.I., Begg, G.A., and Chambers, M. 2010. Management strategy evaluation (MSE) of the harvest strategy for the Small Pelagic Fishery. Report to the Fisheries Research and Development Corp. pp. 161.
8. Great Barrier Reef Marine Park Authority (GBRMPA), 2004. Great Barrier Reef Marine Park zoning plan 2003. http://www.gbrmpa.gov.au/__data/assets/pdf_file/0015/3390/GBRMPA-zoning-plan-2003.pdf
9. Innes, J., Thebaud, O., Norman-Lopez, A., Little L.R. 2014. Does size matter? An assessment of quota market evolution and performance in the Great Barrier Reef Fin-fish Fishery. Ecology and Society 19, 13 (http://www.ecologyandsociety.org/vol19/iss3/art13/).
10. Innes, J., Thebaud, O., Norman-Lopez, A., Little, L.R., Kung, J. 2014. Evidence of package trading in a mature multi-species ITQ market. Marine Policy 46, 68-71.
11. Johansen, S. 1988. Statistical analysis of cointegration vectors. Journal of Economic Dynamics and Control 12, 231-254.
12. Johansen, S. and K. Juselius 1990. Maximum likelihood estimation and inference on cointegration - with applications to the demand for money. Oxford Bulletin of Economics and Statistics 52, 169-210.
13. Legg, C.J., and Nagy, L. Why most conservation monitoring is, but need not be, a waste of time. J. Environmental Management 78, 194-199.
14. Little L.R., Begg G.A., Goldman B., Ellis N., Mapstone B.D., Punt A.E., Jones A, Sutton S, Williams A. 2007. Modelling multi-species targeting of fishing effort in the Queensland Coral Reef Fin Fish Fishery. Report to the Fisheries Research and Development Corporation, Australia, pp 280.
15. Little L.R., Begg G.A., Goldman B., Williams, A.J., Mapstone B.D., Punt A.E., Russell, M., Kerrigan, B., Officer, R., Slade, S., Muldoon, G., and Penny, A. 2009a. Modelling individual transferable quota as a management tool in the Queensland Coral Reef Fin fish Fishery. Fishing and Fisheries Research Centre Technical Report No. 3, Fishing and Fisheries Research Centre, James cook University, Townsville, Australia, pp 166.
16. Little, L.R., Grafton, R.Q., Kompas, T., Smith A.D.M., Punt, A.E., and Mapstone, B.D. 2010. Complementarity of no-take marine reserves and individual transferable catch quotas for managing the line fishery of the Great Barrier Reef. Conservation Biology 25, 333-340.
17. Little L.R., Punt A.E., Mapstone, B.D., Begg G.A., Goldman B., Williams, A.J. 2009b. An agent-based model for simulating trading of multi-species fisheries quotas. Ecological Modelling 220, 3404-3412.
18. Little L.R., Punt A.E., Mapstone, B.D., Pantus F., Smith, A.D.M., Davies, C.R., and McDonald, A.D. 2007. ELFSim – A model for evaluating management options for spatially structured reef fish populations: An illustration of the "larval subsidy" effect. Ecological Modelling 205, 381-396.
19. Little, L.R., Wayte, S.E., Tuck, G.N., Smith, A.D.M., Klaer, N., Haddon, M., Punt, A.E., Thomson, R., Day, J., and Fuller, M. 2011. Development and evaluation of a cpue-based harvest control rule for the southern and eastern scalefish and shark fishery of Australia. ICES Journal of Marine Science, 68: 1699–1705.
20. Mapstone, B.D., Davies, C.R., Little, L.R. Punt, A.E. Smith, A.D.M. Pantus, F., Lou, D.C., Williams, A.J., Jones, A., Russ, G.R., MacDonald, A.D. 2004. The Effects of Line Fishing on the Great Barrier Reef and Evaluation of Alternative Potential Management Strategies, FRDC Project 97/124, CRC Reef Research Centre, Townsville.
21. McDonald-Madden, E., Baxter, P.W.J., Fuller, R.A., Martin, T.G., Game, E.T., Montambault, J., and Possingham, H.P. 2010. Monitoring does not always count. Trends in Ecology and Evolution 25, 547-550.
22. Pascoe, S., C. Robinson, et al. 1996. Economic and financial performance of the UK English Channel fleet. CEMARE Report. Portsmouth, UK, University of Portsmouth: 55.
23. Queensland Government (2003). Fisheries (Coral Reef Fin Fish) Management Plan 2003. No.212, Department of Primary Industries. Brisbane. https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/F/FisherCRFFMP03.pdf
24. RDC Team. 2010. R: A language and environment for statistical computing. Vienne, Austria: R Foundation for Statistical Computing. Retieved from http://www.R-project.org

25. Samoilys, M. and Lunow, C. P. 2012. Fisheries long term monitoring program sampling protocol - Coral Reef Fin fish 1999-2004. Department of Agriculture, Fisheries and Forestry, Brisbane, Australia.
26. Smith, A.D.M., Smith, D.C., Tuck, G.N., Klaer, N., Punt, A.E., Knuckey, I., Prince, J., Morison, A., Kloser, R., Haddon, M., Wayte, S., Day, J., Fay, G., Pribac, F., Fuller, M., Taylor, B., and Little, L.R. 2008. Experience in implementing harvest strategies in Australia's south-eastern fisheries. Fisheries Research 94, 373-379.
27. Teetor, P. 2011. R Cookbook, O'Reilly Media, Inc.
28. Thébaud, O., Innes, J., Norman, A., Cameron, D., Tickell, S., Cannard, T., Slade, S., Kung, J., Kerrigan, B., Little, R., and Williams, L. 2012. Economic survey of the Queensland Commercial Coral Reef Fin-fish fishery. CSIRO Marine and Atmospheric Research, Brisbane Australia.
29. Thébaud, O., Innes, J., Norman-López, A., Cameron, D., Cannard, T., Tickell, S., Kung, J., Kerrigan, B., Williams, L. and Little, L.R. (2014) Micro-economic drivers of profitability in an ITQ-managed fishery: an analysis of the Queensland Coral Reef Fin-fish Fishery. Marine Policy 43, 200-207
30. Van Iseghem, S., E. Quillérou, et al. 2011. Ensuring representative economic data: survey data-collection methods in France for implementing the Common Fisheries Policy. ICES Journal of Marine Science 68, 1792-1799.

Appendices

A. Economic survey of the Coral Reef Fin-fish Fishery

Survey design

Simulation tools used to support the evaluation of alternative fisheries management strategies increasingly seek to include the dynamic response of fishing operators to changes in their economic, ecological and regulatory circumstances (Fulton et al. 2011; van Putten et al. 2011). This is because consideration of such responses may be critical in assessing management options, and their likely economic and social consequences.

The Effects of Line Fishing Simulator (ELFSim) was developed to examine potential management strategies for the Coral Reef Fin-Fish Fishery (CRFFF) on the Great Barrier Reef (Little et al. 2007; Little et al. 2009). ELFSim simulates the CT and RTE populations on almost 4,000 individual reefs. The model captures the spatial complexity of fish larval movement on the ocean currents, and the size, age and sex structure of the species across the region. To complement these simulated stocks, ELFSim also simulates the fishing activity of commercial fishing vessels across the region, as well as the charter and recreational components of the fishery. ELFSim contains an explicit representation of the behaviour of commercial fishing operators, represented as individual agents, including fishing effort, its spatial and temporal distribution, as well as quota trading. A quota trading model was developed and calibrated using economic data from the late 1990s (Muldoon 2009). At the time, the fishery was experiencing a transition from the landing of mostly dead fish, to the landing of both live and dead fish, the former attracting much higher prices. The fishery in mid 2004 also transitioned from a regulatory system based on input controls, to a mixed system including introduction of total allowable commercial catch limits and transferable quotas (ITQs), maintenance of input restrictions, and increased marine reserves (Fernandes et al. 2005).

As part of this project, an economic survey of the commercial operators currently active in the CRFFF was requested, to update the description of the fishery which is used as a basis for the calibration of ELFSim. Given that harvesting decisions are represented at the level of individual fishing vessels in the model, this is the level at which the information needed updating. The primary focus of the survey was thus on collecting information regarding fishing activity, costs and revenues of the commercial fishing vessels operating in the CRFFF in 2010-11. At the same time, it was considered useful to also collect broader information on decision-making by commercial operators, as well as their perception of the current difficulties and opportunities encountered in the fishery.

The main expected outputs from this survey are expected to be, first, a set of updated indicators to be used to calibrate ELFSim, and assist in the definition of simulation scenarios and in the evaluation of simulation outcomes; and second, an updated economic description of the fishery which can serve as a new baseline from which the situation of the fishery may be re-assessed in the future

Survey approach

From its inception, a number of principles were adopted to structure the survey approach:

1. In order to gain an understanding of the latest situation of commercial businesses involved in the fishery, it was decided to focus data collection on the financial year 2010-11, and to centre the data collection efforts on the businesses associated with the management of vessels that had been active in the fishery in 2010/11. This could involve a diversity of respondents depending on the business structure encountered, including vessel owners, owner-operators or operators.
2. Pre-existing information on the fishery, as well as expert knowledge from a range of stakeholders including industry representatives and managers of the fishery, was used to establish an initial description of the commercial fishery on the basis of which to develop the survey. This led to identify a large diversity of operations involved in the fishery in 2010-11.
3. The survey was aimed at representing this diversity, and random sampling to minimize any potential biases in the information collected.

4. Given the complexity and sensitivity of the information collected, face-to-face interviews were preferred, in order to ensure that the data gained from the interviews was of the highest possible quality.
5. The central focus of the survey was on the vessel characteristics and activity, as well as associated costs and earnings. However, given the resources required to carry out individual interviews, and the difficulties to which businesses were being confronted when the survey was carried out, it seemed useful to also collect additional information on individual decision-making and perceptions by operators of the key drivers of profitability in the fishery.
6. The survey roll-out and data-entry was carried out with the help of a web-based tool, allowing real-time monitoring of progress in the surveys, and data entry and storage by different members of the survey team into a central database managed for consistency, anonymity and confidentiality.
7. The survey obtained approval from the CSIRO Social Science Human Research Ethics Committee.

Figure 49 presents a summary timeline of the survey, from the initial phase of background analysis to the presentation of results at a stakeholder workshop in Townsville, in November 2012. The survey was developed in close collaboration with active participants in the CRFFF, licence and quota holders, Fisheries Queensland and the Great Barrier Reef Marine Park Authority.

A workshop was held in October 2011 to present and discuss the initial fleet profile developed by CSIRO and Fisheries Queensland, as well as the proposed approach to carrying out the survey, and the questionnaire. The workshop was attended by six industry members representing different areas and types of businesses, as well as four CSIRO staff including the project PI, three Fisheries Queensland staff involved in the management of the CRFFF, and a GBRMPA staff also involved in the project. The approach proposed was validated and approved by the participants. Feedback from the workshop was used to revise the fleet profile, and adapt the questionnaire which was also piloted in early November.

Significant efforts were also made to communicate the survey plans broadly at the scale of the industry, and to facilitate the establishment of contacts with potential respondents. A one-page flyer (**Project flyer**) was developed to present the FRDC project and the economic survey, and was circulated with the assistance of the Queensland Seafood Industry Association (QSIA) through the Queensland Fisherman magazine, as well as of the Reef Line Council through its regular email newsletter.

In order to facilitate the interview process regarding the description of the annual activity and catch of vessels operating in the CRFFF, Fisheries Queensland also prepared annual data summaries of fishing effort and catch which were sent in November 2011 to all the holders of line fishing licenses which had been active in the CRFFF in 2010-11. Overall, response to the survey was positive, leading to a large number of surveys being completed (Table 15). The interviews were initiated during the second 2010-11 spawning closure, (November 2011). This first stage of the survey interviewed operators who were willing to participate and also in port. The rest of the interviews had to be carried out over a longer period of time, from December 2011 to August 2012, depending on the availability of respondents who had agreed to participate. As much as possible, the team aimed to adapt the timing and location of the interviews to minimize the constraint they represented for the respondents. Interviews took place in a variety of locations depending on this, from the respondent's home to their boat, or a local coffee shop in the home port for their vessel.

Figure 49 Timeline of the economic survey to November 2012

Key methods and results of the survey are reported in the methods (**2.1 The Economic Survey**) and results (**3.1 The Economic Survey**) sections above. The report Thebaud et al. (2012) outlines the economic survey in totality, and the following sections reproduce those results.

Results

The CRFFF in 2010-11

The commercial fleet of the CRFFF targets a diversity of tropical reef fish using hand-held lines with baited hooks. The main species by order of decreasing value include several species of Coral Trout (*Plectropomus* and *Variola spp.*, CT), landed predominantly as live fish and exported to Asia, as well as Red Throat Emperor (*Lethrinus miniatus*, RTE) and a wide range of other reef fish species (OS) including other cods (mainly Serranidae), other emperors (Lethrinidae) and tropical snappers (mainly Lutjanidae), landed as dead fish or processed as fillets, and sold on the domestic market. The fishery spans a broad geographical range, from Cape York (10ºS) to the southern Great Barrier Reef, off Bundaberg (24ºS).

The cluster analysis results shown in Figure 50 indicate the groups that were used to stratify the stratified random sample, taking into account the regional distribution of vessel types.

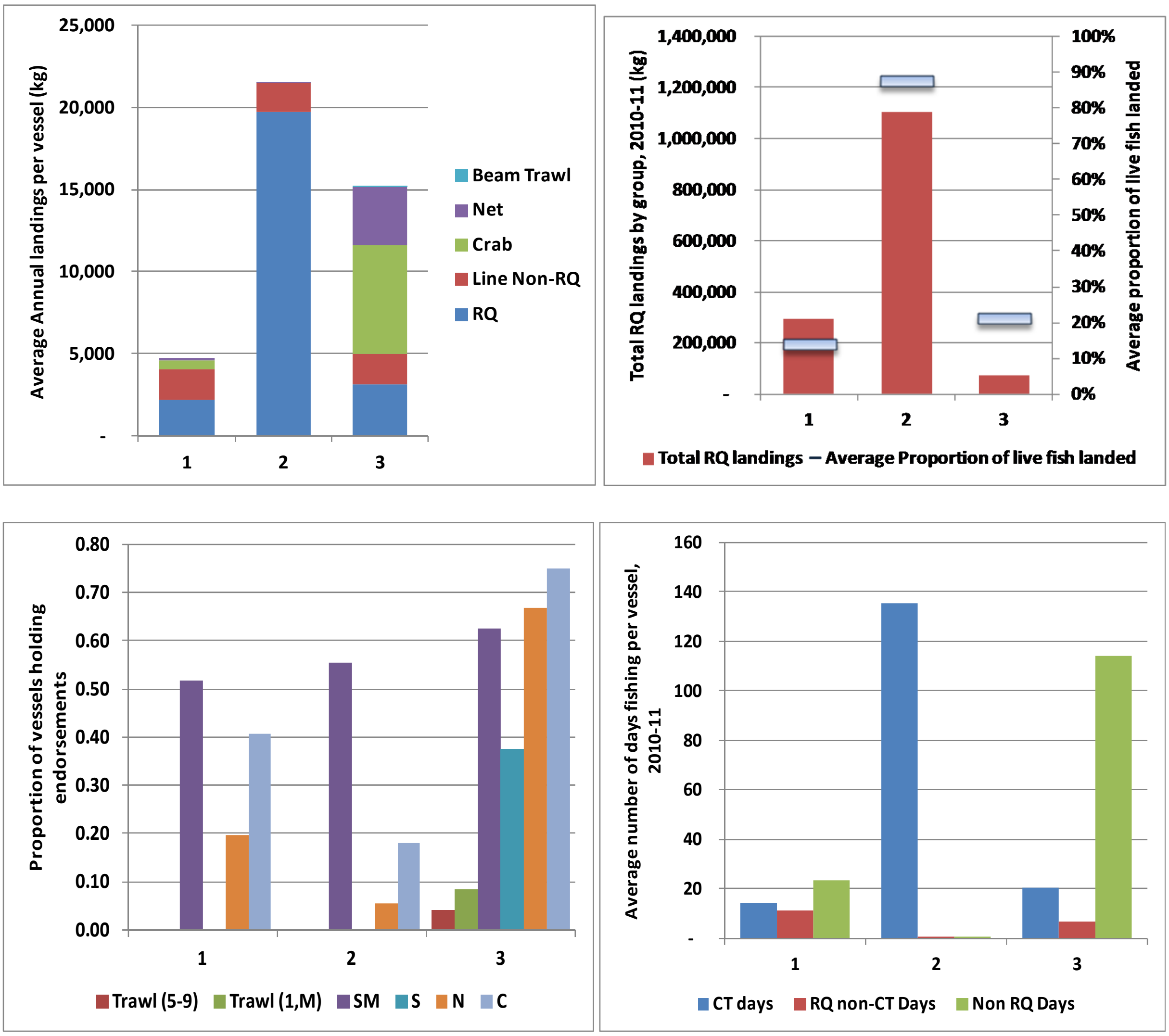


Figure 50 Main characteristics of the vessels in each group. (Source: own results based on Fisheries Queensland data) 1: Generalist line fishers; 2: Dedicated live CT fishers; 3: Diversified fishers. Top left panel: average annual landings per vessel (kg); Top right panel: Total RQ landings by vessel group (kg) (red bars, left axis) and proportion of fish landed live (white bars, right axis); Bottom left: proportion of vessels holding endorsements for Trawl (5-9), Trawl (1,M), Spanish Mackerel (SM), Shark (S), Net (N) and Crab (C) fisheries; Bottom right: average number of fishing days per vessel in 2010-11

Another important dimension in the characterization of the CRFFF relates to the structure of quota ownership in the fishery. We used the typology developed by (van Putten and Gardner 2010) for the Tasmanian rock lobster fishery to describe the status of agents involved in the quota market for CRFFF species. This typology distinguishes between different positions agents may have on the quota market, depending on whether they are actively involved in fishing or in ITQ trading. The categories of the typology were “investors”, who hold quota which they lease out; “independent fishers” who catch the quota they own and do not participate in the quota market; “income supplementers” who derive income from both fishing their quota and leasing some out; “lease dependent” operators who depend on leasing in quota for their catch; and “quota redistributors” who are involved in both leasing quota in and leasing quota out. Given the economic importance of live CT landings for the fishery, this typology was applied to ownership and usage of CT quota units in 2010-11.

CT quota unit ownership was distributed across all of these groups, with the group of investors holding the greatest share (42%) of total CT units. Lease dependent fishers held only 11% of total CT units but harvested more than two thirds (69%) of the total CT units utilized in 2010-11. Independent operators held 13% of total CT quota units and landed a similar proportion of total landings. The same proportion of CT quota units was held by operators who derived income from both catching some of their CT quota, and leasing part of it out. A group of inactive quota owners was also identified, who neither leased nor fished the quota they owned in 2010-11. In addition, a number of quota owners appeared to be inactive in 2010-11, in that they neither caught nor traded the quota they held on the quota market. This would seem to indicate the existence of transaction costs on this market which discourage trades from occurring, despite this leading to costs for quota owners who decide not to fish their quota themselves, in terms of both cash costs (annual fees payed on units owned) and opportunity costs of not leasing their quota out. (see Thébaud et al. 2012 for more details).

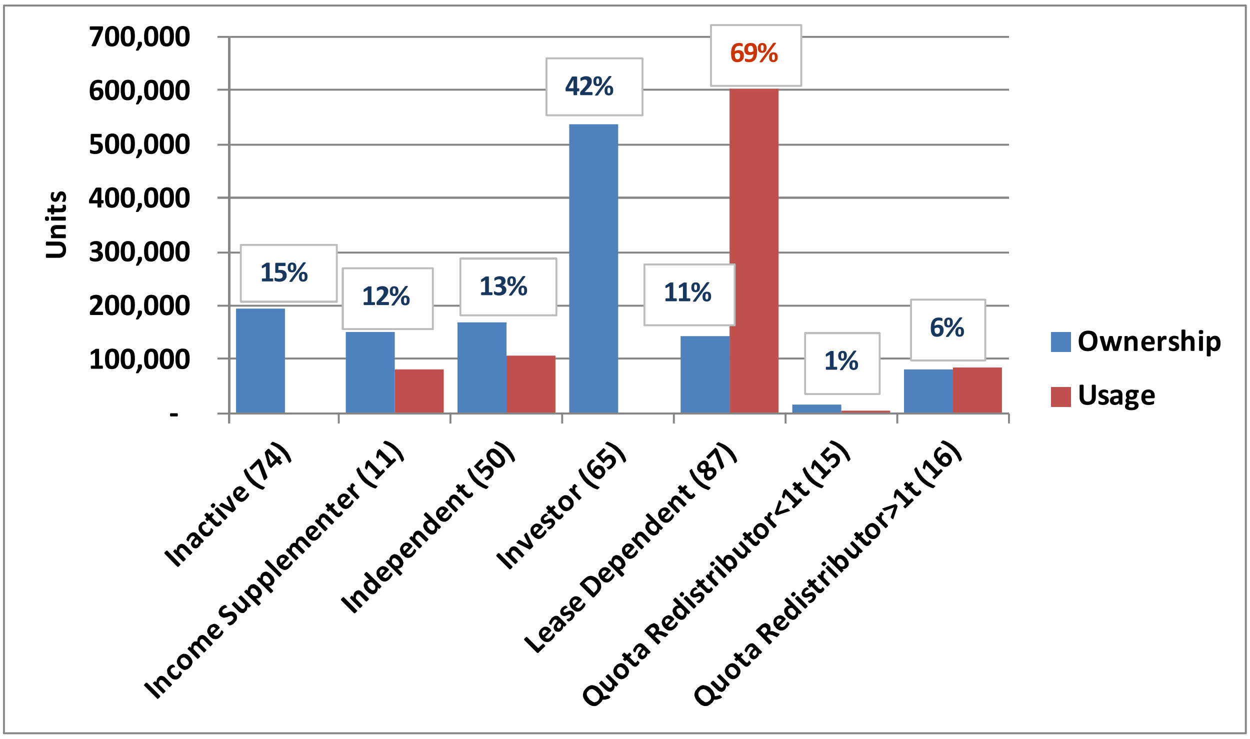


Figure 51 CT quota ownership & usage by type of operator, 2010-11 (Source: Fisheries Queensland)

Figure 52 summarizes the location and timing of the interviews along the Queensland coast, the way in which respondents were selected (via the random sampling approach, through volunteering of respondents or via referral by peers), as well as the timing of the data entry following the interviews. Table 15 shows the number of sampled interviews from the fleet, which was stratified by region (Table 16).

Sample characteristics

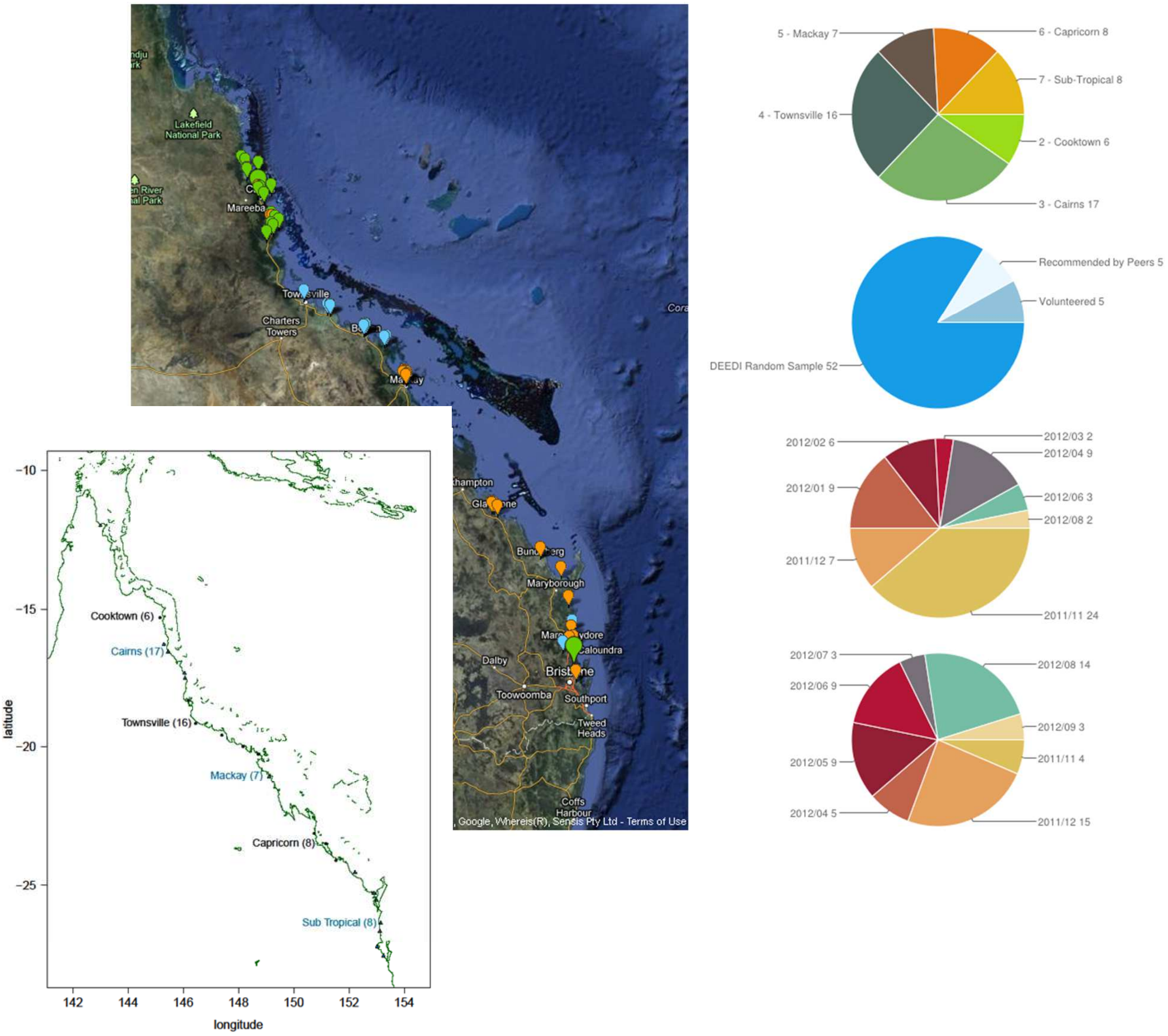


Figure 52 Location and timing of surveys

Table 15 Population and sample per group. Vessel group 1: Generalist line fishers; 2: Dedicated live CT fishers; 3: Diversified fishers

Group	Total number in group	Number surveyed	% surveyed
Group 1	130	24	18%
Group 2	60	32	53%
Group 3	23	6	26%
Total	**213**	**62**	**29%**

Table 16 Regional & group break-down. Vessel group 1: Generalist line fishers; 2: Dedicated live CT fishers; 3: Diversified fishers

TARGET SAMPLE				
Sampling region	**Group 1**	**Group 2**	**Group 3**	**Total**
1 - Cooktown	1	4		5
2 - Cairns	10	3	2	15
3 - Townsville	6	5	1	12
4 - Mackay	1	6		7
5 - Capricorn	8	5	2	15
6 - Sub-Tropical	15		2	17
Grand Total	**41**	**23**	**7**	**71**

REALIZED SAMPLE				
Sampling region	**Group 1**	**Group 2**	**Group 3**	**Total**
1 - Cooktown	2	4		**6**
2 - Cairns	9	4	4	**17**
3 - Townsville	5	9	2	**16**
4 - Mackay		7		**7**
5 - Capricorn	2	6		**8**
6 - Sub-Tropical	6	2		**8**
Grand Total	**24**	**32**	**6**	**62**

REALIZED SAMPLE / TARGET SAMPLE				
Sampling region	**Group 1**	**Group 2**	**Group 3**	**Total**
1 - Cooktown	200%	100%		**120%**
2 - Cairns	90%	133%	200%	**113%**
3 - Townsville	83%	180%	200%	**133%**
4 - Mackay	0%	117%		**100%**
5 - Capricorn	25%	120%	0%	**53%**
6 - Sub-Tropical	40%		0%	**47%**
Grand Total	**59%**	**139%**	**86%**	**87%**

REALIZED SAMPLE - TARGET SAMPLE				
Sampling region	**Group 1**	**Group 2**	**Group 3**	**Total**
1 - Cooktown	1	0	0	**1**
2 - Cairns	-1	1	2	**2**
3 - Townsville	-1	4	1	**4**
4 - Mackay	-1	1	0	**0**
5 - Capricorn	-6	1	-2	**-7**
6 - Sub-Tropical	-9	2	-2	**-9**
Grand Total	**-17**	**9**	**-1**	**-9**

Figure 53 presents a comparison of the distributions (density plots) of selected variables describing individual operations (primary vessel length and main engine power, number of dories and annual fishing days), for the overall sample (62 vessels, in blue) and the 2010-11 active fleet (213 vessels, in red). The survey sample obtained provides a good representation of the overall profile of the 2010-11 active fleet in terms of these characteristics. As a result of the response rates described above, the sample has very good representation of operations characterized by medium to larger vessels with an annual activity of 90+ days fishing. Smaller operations with less than 50 days fishing, while present in the sample, were represented in lower proportions in the sample than in the population.

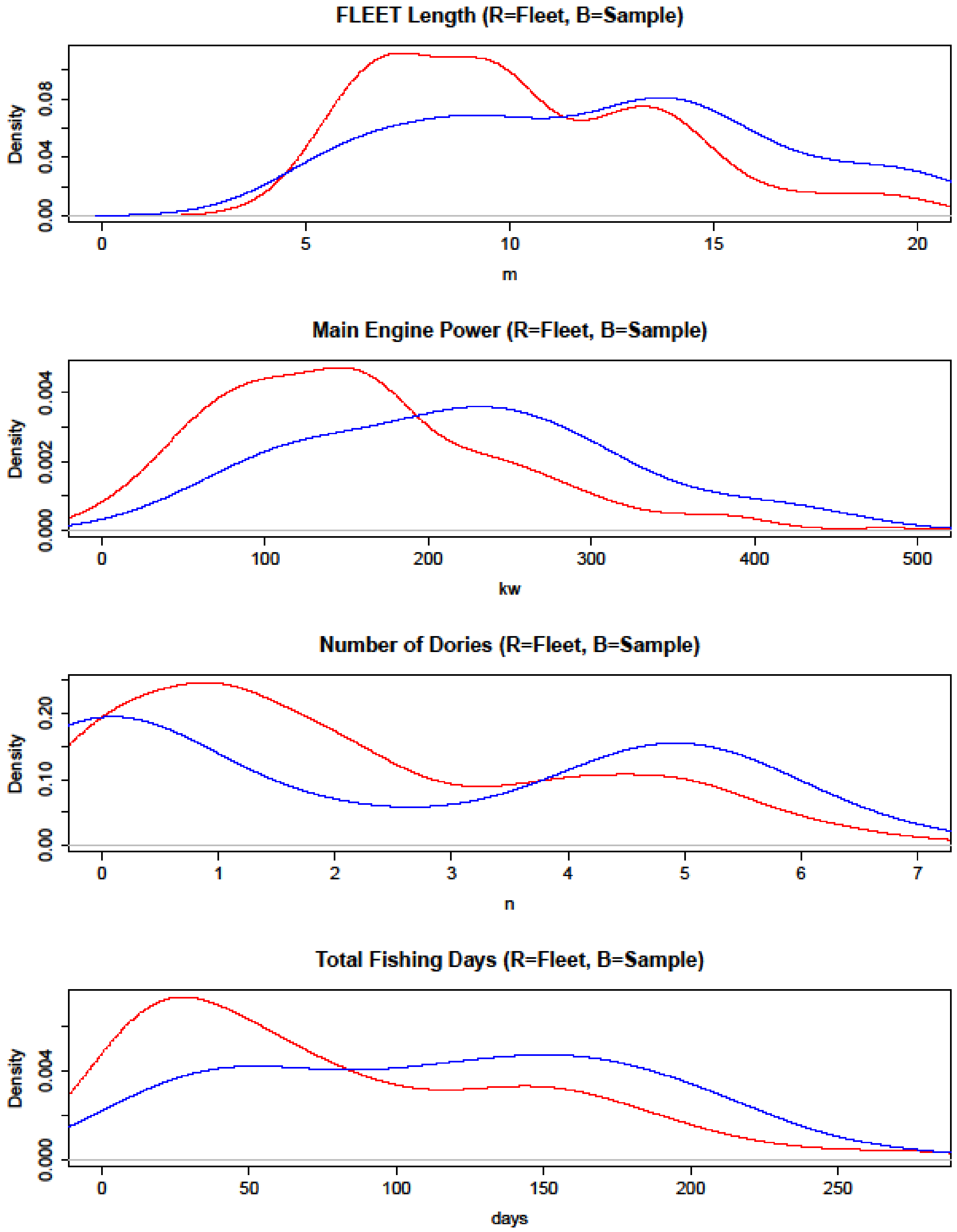


Figure 53 Population versus sample characteristics

Demographics

The following table (Table 17) and figure (Figure **54**) present the main demographic characteristics of the survey respondents as well as the factors that were important to them when they first entered the CRFFF. There were no significant differences between the age, years in fishing and years in the CRFFF between respondents in the three groups of the fleet profile.

Table 17 Demographic characteristics of the survey respondents

Status		n	na	mean	sd	median	min	max	range	se
Owner-operator (46)										
	AGE	46	0	**48**	10	47	33	72	39	1
	Years_in_fishing	45	1	**25**	10	24	5	46	41	2
	Years_in_CRFFF	44	2	**21**	10	20	4	46	42	2
Owner (11)										
	AGE	11	0	**60**	12	60	38	75	37	4
	Years_in_fishing	11	0	**22**	12	23	2	36	34	3
	Years_in_CRFFF	11	0	**21**	11	23	2	36	34	3
Other* (5)										
	AGE	5	0	**56**	14	60	34	71	37	6
	Years_in_fishing	5	0	**26**	13	21	14	46	32	6
	Years_in_CRFFF	5	0	**12**	6	13	3	18	15	3
All										
	AGE	62	0	**51**	12	51	33	75	42	1
	Years_in_fishing	61	1	**24**	10	24	2	46	44	1
	Years_in_CRFFF	60	2	**20**	10	19	2	46	44	1

*"Other" includes Director, Operator, Part-owner and a missing value

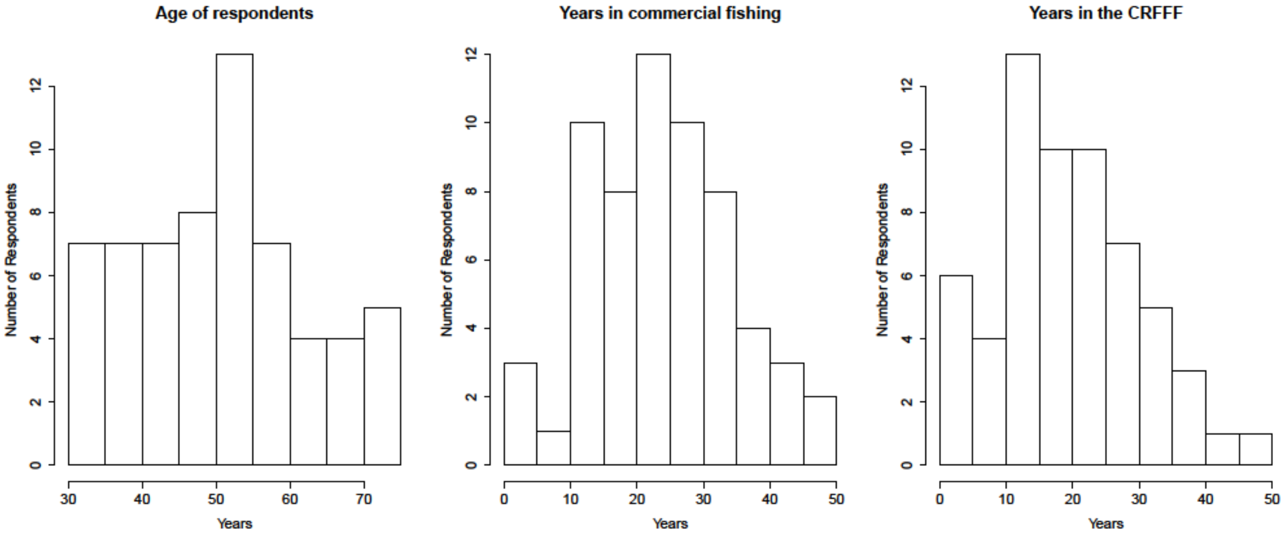


Figure 54 Demographic characteristics of the survey respondents (All Respondents)

Responses to the survey question regarding what brought the respondent to the fishery were classified by importance. 31% of the respondents responded that lifestyle was a very important factor (n=37 out of 110 responses referring to rank=5). Figure 55 shows that 37% indicated that the least important factor was management of the industry/marine parks (n=33 out of 96 responses referring to rank=1).

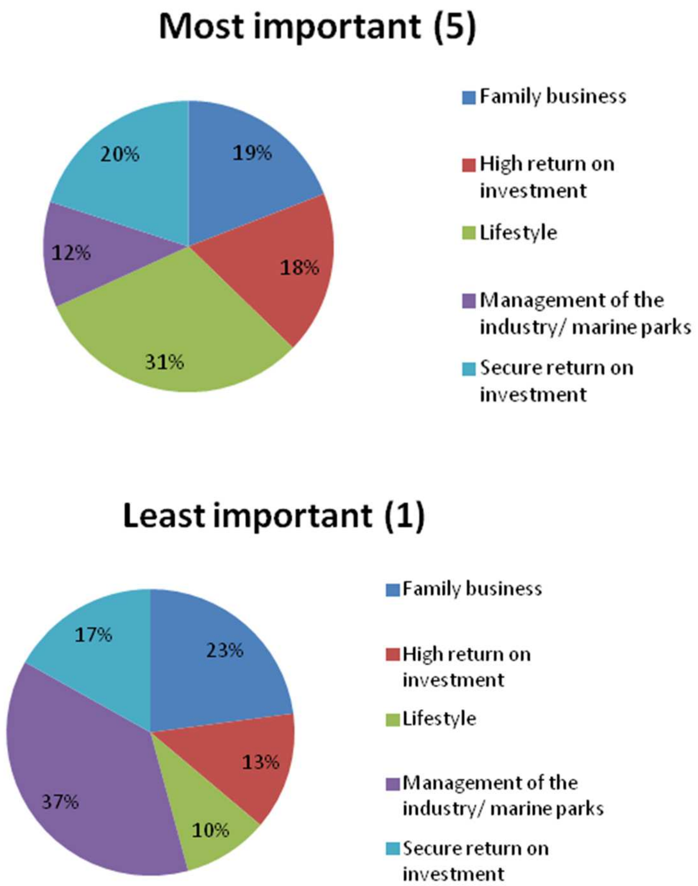


Figure 55 Most frequently cited very important and not important at all factors for respondents when they entered the fishery

Vessel characteristics

The following tables (Tables 18-20) and figures (Figures 56-62) present the characteristics of the vessels surveyed, including technical characteristics and storage capacity of primary vessels, capital value of primary vessels, as well as technical characteristics and capital value of the dories used in the operation in 2010-11. Table 21 and Figures 63-65 show the characteristics of the dories in the fleet that operate from mother vessels.

Table 18 Primary vessel characteristics (All Respondents)

	n	na	mean	sd	median	min	max	range	se
Length (m)	62	0	**12.2**	4.4	12.6	5.0	20.0	15.0	0.6
Draft (m)	62	0	**1.5**	0.7	1.5	0.3	3.2	2.9	0.1
Beam (m)	62	0	**4.0**	1.2	4.2	1.7	6.4	4.7	0.2
Berths (n)	62	0	**4.7**	2.9	4.0	0.0	10.0	10.0	0.4
Dories (n)	62	0	**2.4**	2.4	2.0	0.0	7.0	7.0	0.3
Fuel Capacity (L)	60	2	**4,861**	7,110	1,700	75	38,000	37,925	918
Main Engine Power (kw)	60	2	**239**	138	224	45	855	810	18
Year built	58	4	**1988**	12	1985	1964	2010	46	2
Steaming speed (knots)	62	0	**12.1**	6.9	8.0	5.0	30.0	25.0	0.9

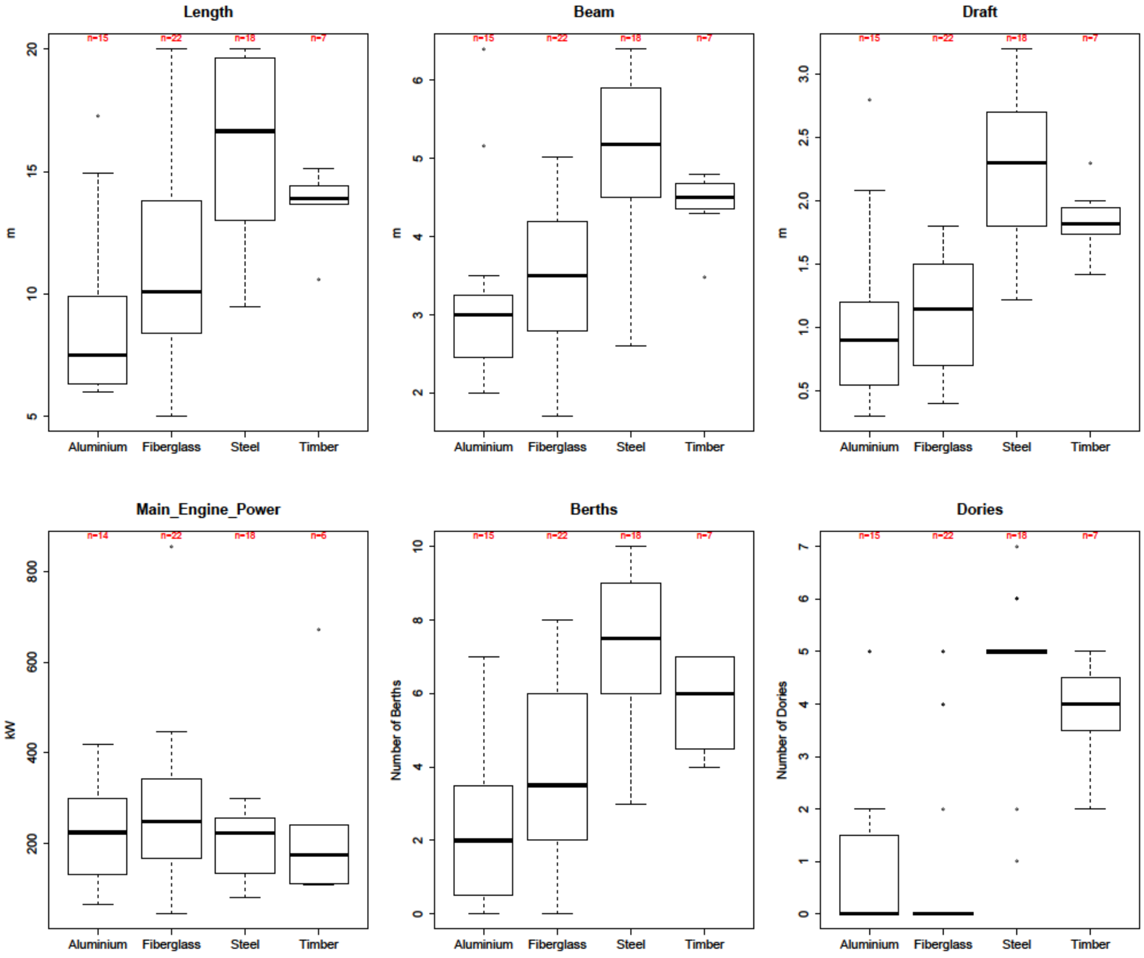


Figure 56 Primary vessel characteristics per construction of vessel

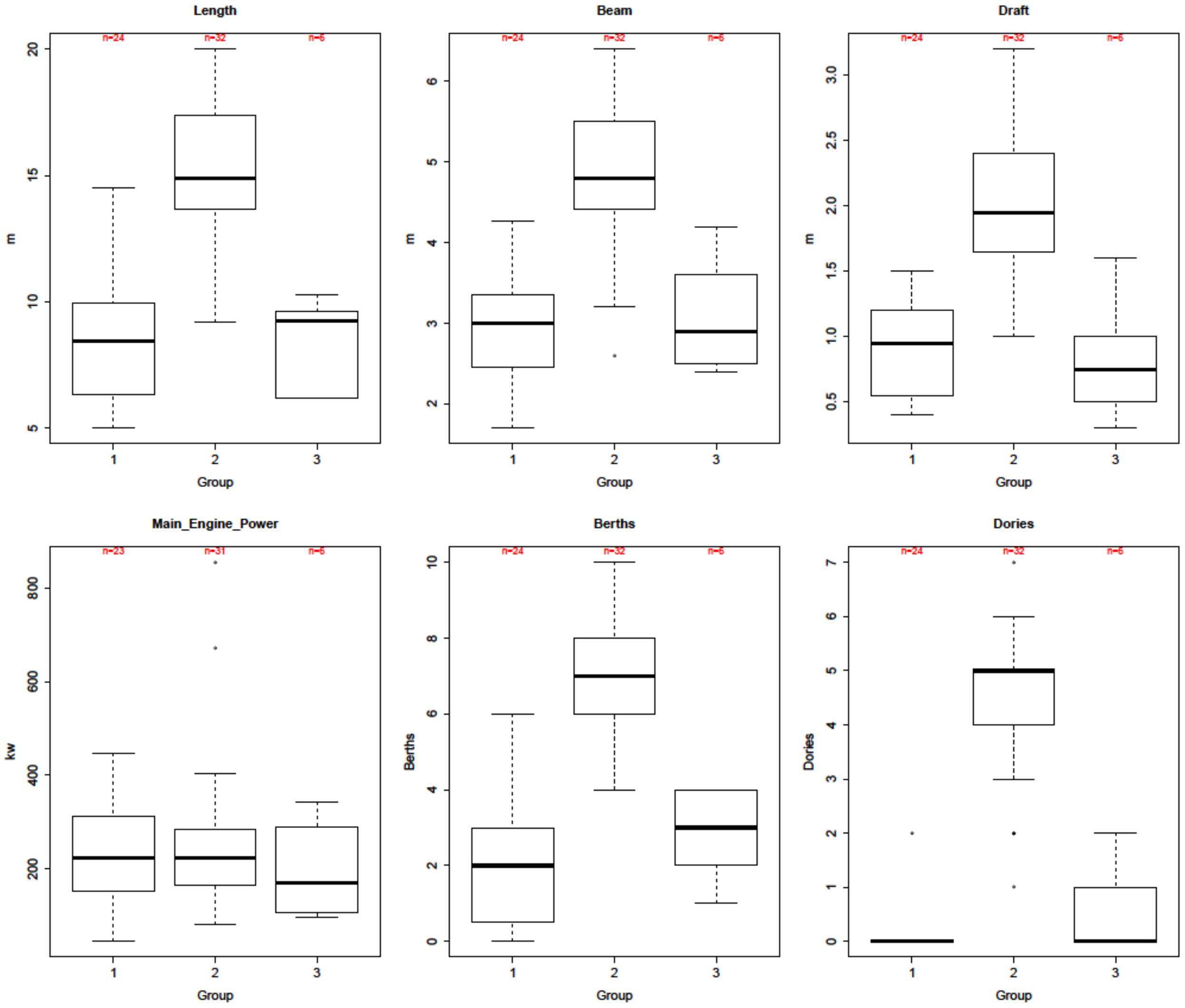


Figure 57 Primary vessel characteristics per group of operators

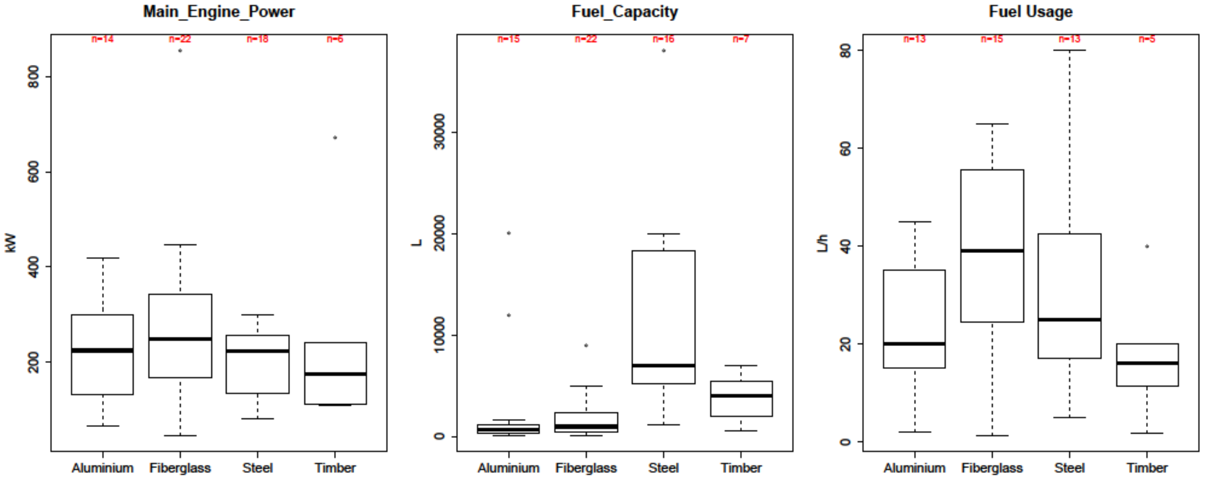


Figure 58 Primary vessel characteristics per construction type

Storage characteristics

Table 19 Storage capacity for refrigerated and live fish

	n	na	mean	sd	median	min	max	range	se
Refrigerated Storage Capacity									
Holding Capacity (kg)	34	28	**1,772**	2,685	**900**	70	14,000	13,930	461
Snap Freezing Capacity (kg)	19	43	**2,516**	3,671	**1,000**	200	15,000	14,800	842
Total Refrigeration Capacity (kg)	41	21	**2,635**	3,787	**1,200**	70	17,500	17,430	591
Live Storage Capacity									
Internal Live Tank Capacity (L)	22	40	**11,886**	8,812	**10,000**	200	26,000	25,800	1,879
Internal Live Tank Flow (L/h)	14	48	**114,954**	160,280	**66,000**	1,000	609,176	608,176	42,837
External Live Tank Capacity (L)	24	38	**2,026**	2,207	**1,350**	150	10,000	9,850	451
External Live Tank Flow (L/h)	15	47	**30,546**	40,636	**12,000**	1,000	150,000	149,000	10,492
Total Live Storage Capacity(L)	35	27	**8,861**	9,219	**4,500**	150	28,000	27,850	1,558
Live Fish Storage									
Total Live Storage Capacity (Fish)	34	28	**1,293**	935	**1,060**	60	3,100	3,040	160
Average Live Fish Density (Fish/L)	29	33	**0.26**	0.23	**0.20**	0.04	1.15	1.11	0.04

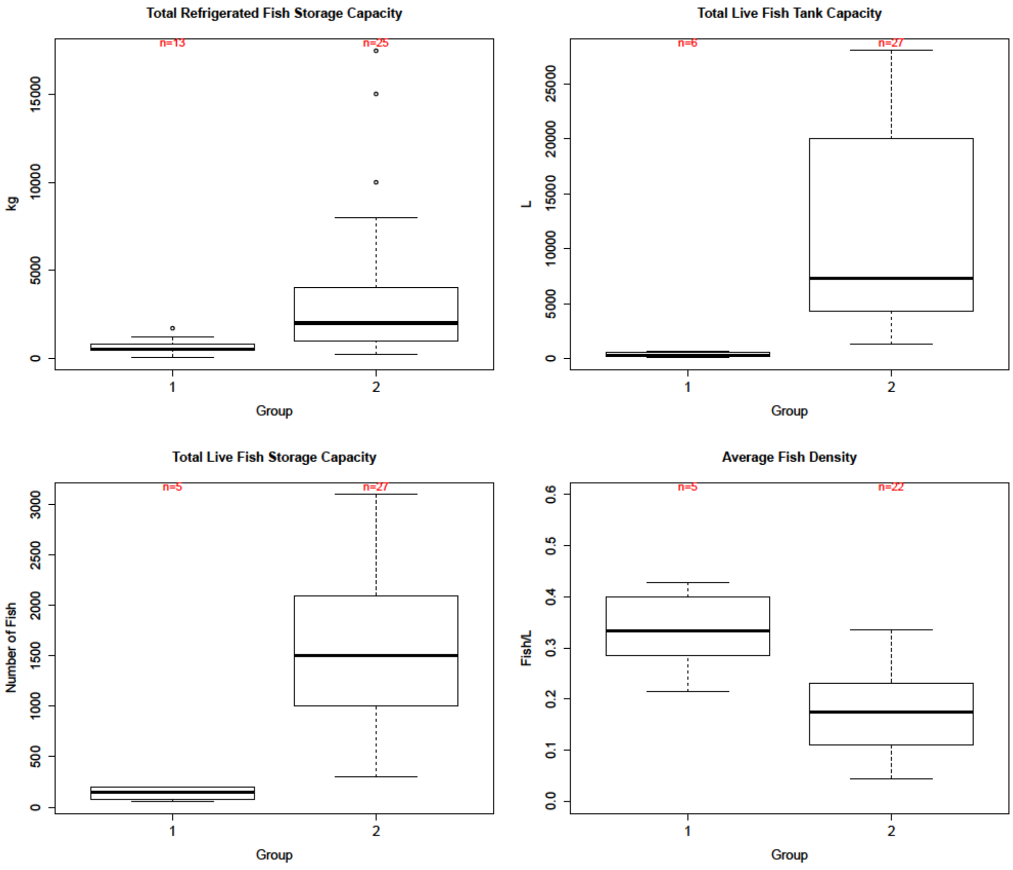


Figure 59 Storage characteristics per group of operator

Capital Value of Primary Vessels

Table 20 Primary vessel value estimates

	n	na	mean	sd	median	min	max	range	se
Year of Acquisition	61	1	2004	5	2006	1988	2010	22	1
Acquisition Price	59	3	181,669	189,581	110,000	2,500	770,000	767,500	24,681
Current Market Value	60	2	146,042	159,982	100,000	10,000	850,000	840,000	20,654
Insured Value	58	4	152,879	179,172	85,000	-	742,000	742,000	23,526
Replacement Value (New)	57	5	637,658	702,646	350,000	29,000	3,000,000	2,971,000	93,068

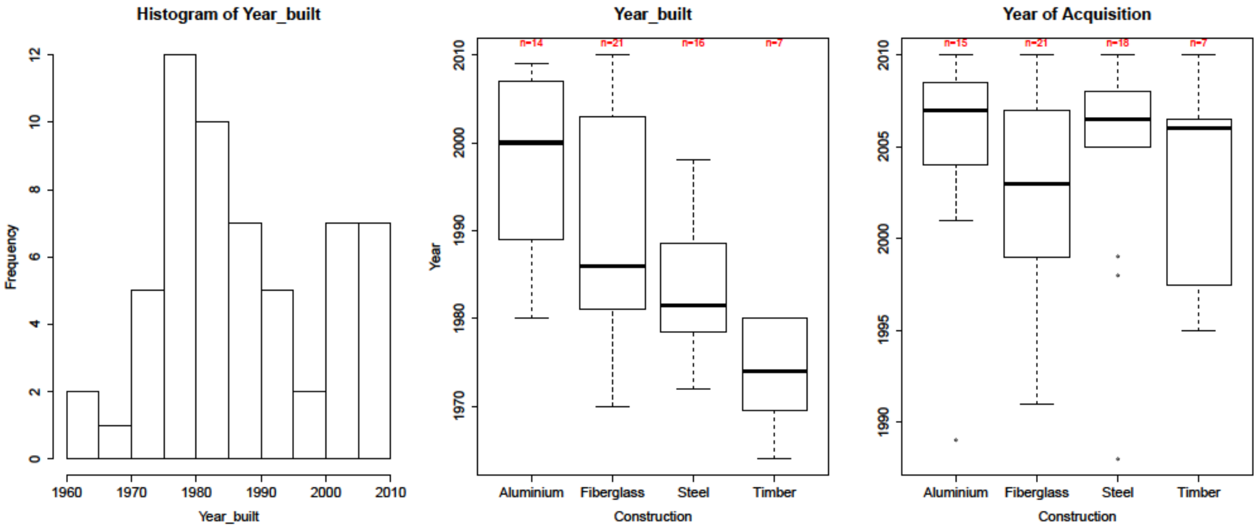


Figure 60 Primary vessel year built (left) and year built per construction type (right)

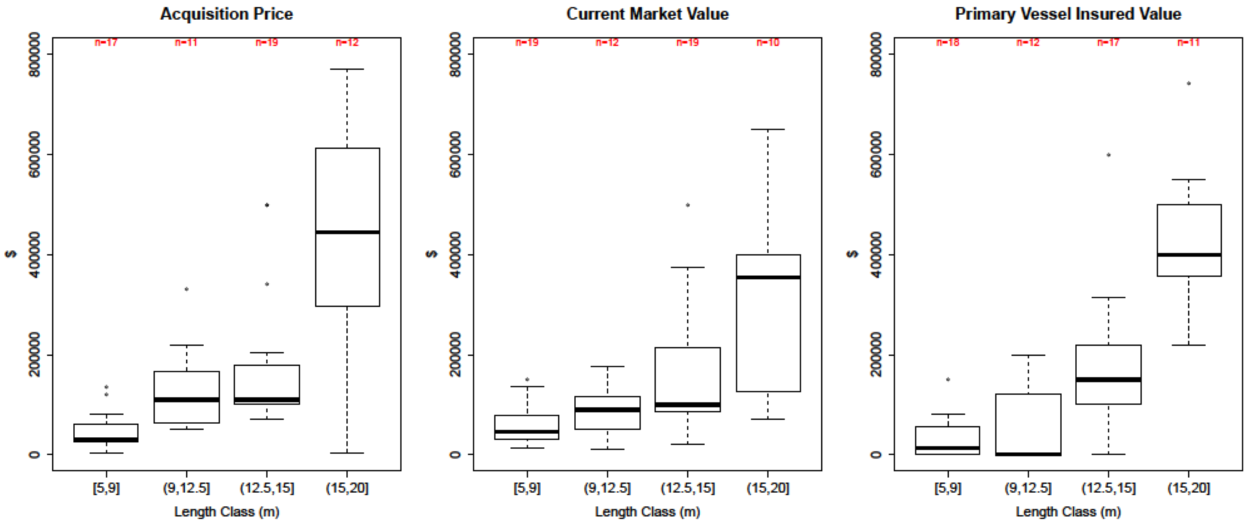


Figure 61 Primary vessel value estimates per vessel length class

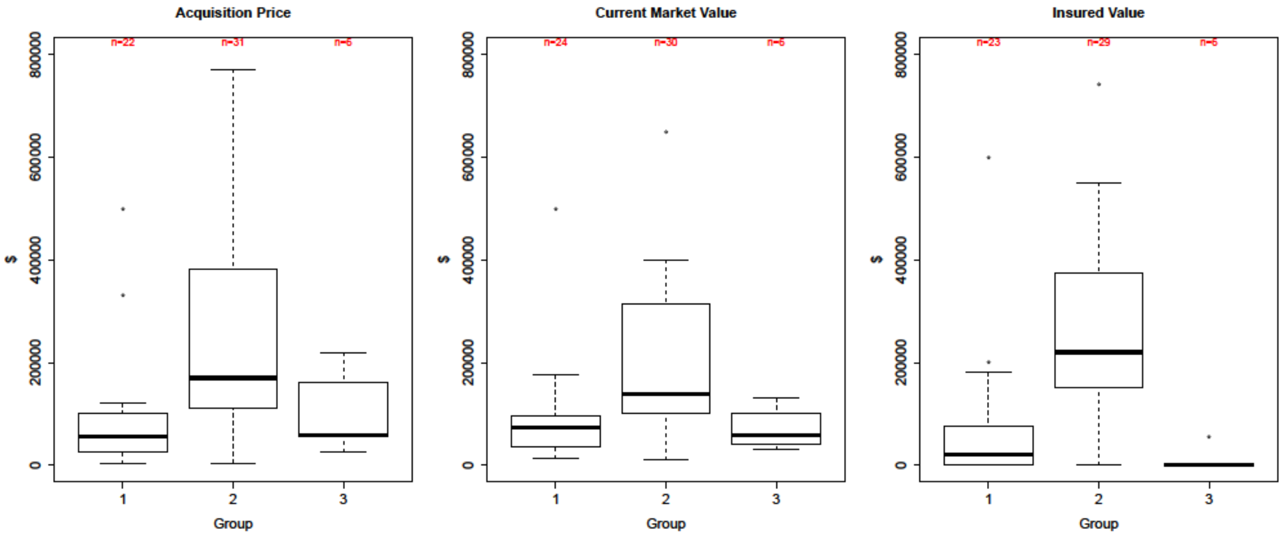


Figure 62 Primary vessel value estimates per group of operators

Dory characteristics

Table 21 Characteristics of dories

	n	na	mean	sd	median	min	max	range	se
Year of Acquisition	162	0	**2007**	4	**2007**	1993	2011	18	0
Year Built	145	17	**2004**	8	**2007**	1970	2011	41	1
Length (m)	162	0	**5.0**	0.5	**5.0**	3.1	7.0	3.9	0.0
Live Tank_(L)	126	36	**162**	68	**200**	-	250	250	6
Outboard (HP)	141	21	**50**	17	**50**	10	200	190	1
Year Installed	130	32	**2009**	3	**2010**	1993	2012	19	0
Acquisition Price ($)	134	28	**16,308**	9,262	**13,500**	-	50,000	50,000	800
Market Value ($)	159	3	**9,431**	5,736	**8,000**	-	30,000	30,000	455
Replacement Value New ($)	158	4	**24,519**	10,462	**25,000**	3,000	110,000	107,000	832

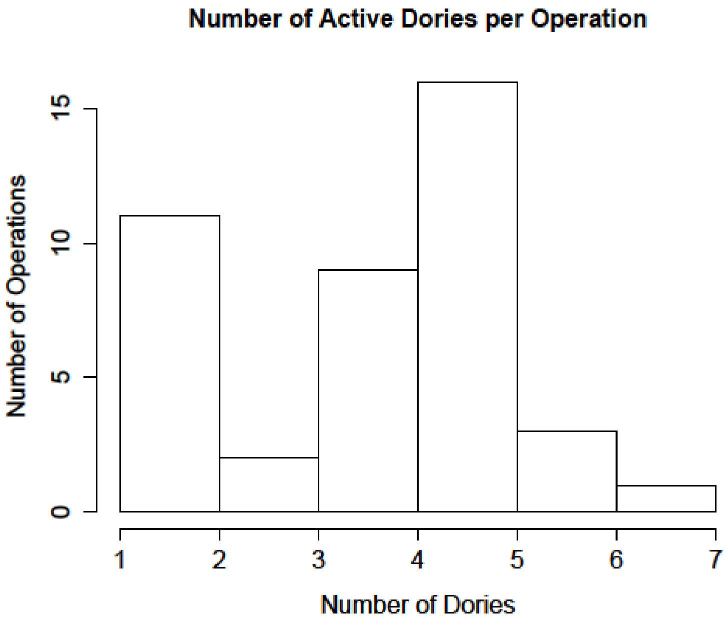


Figure 63 Number of dories per operation

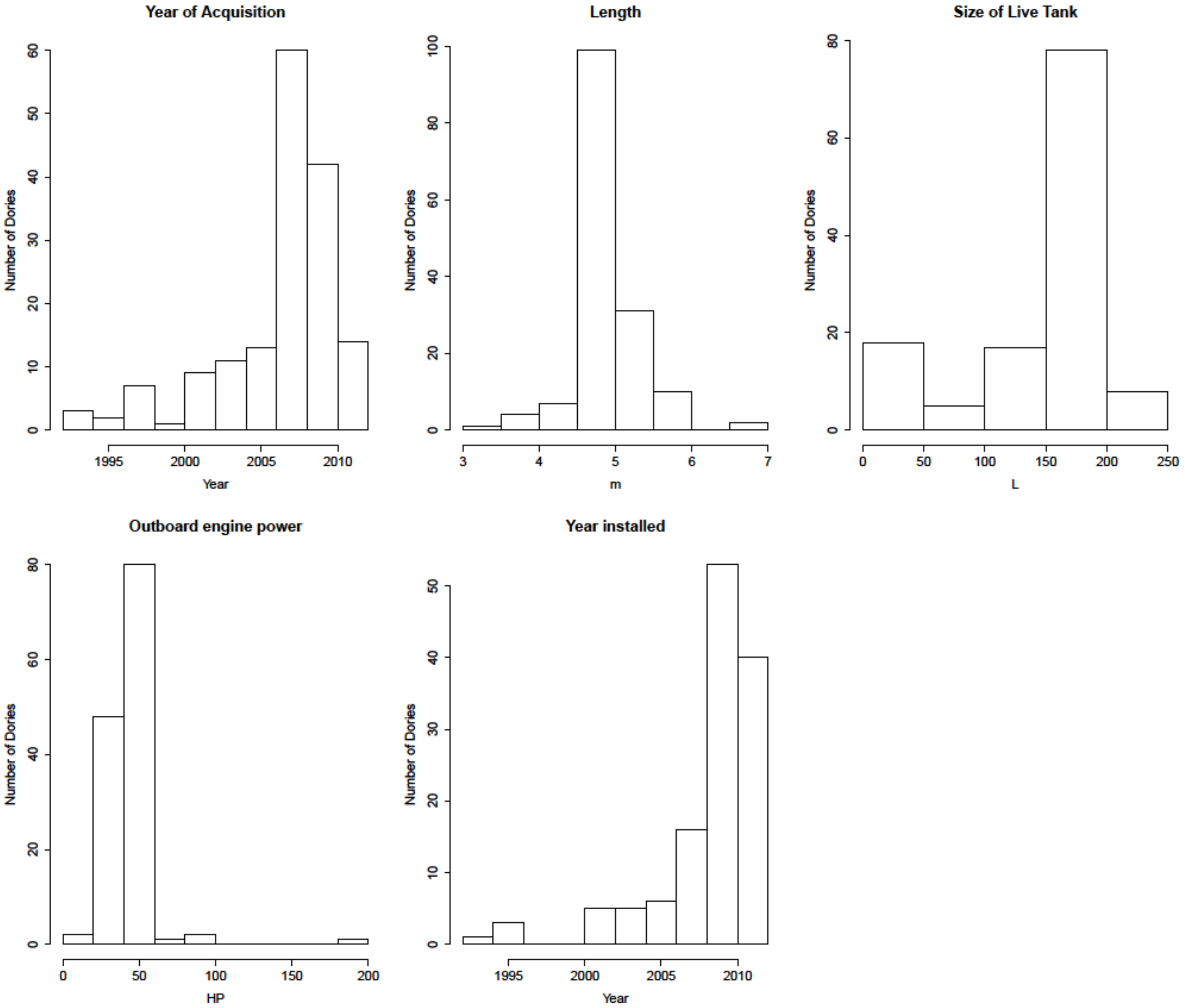


Figure 64 Characteristics of dories

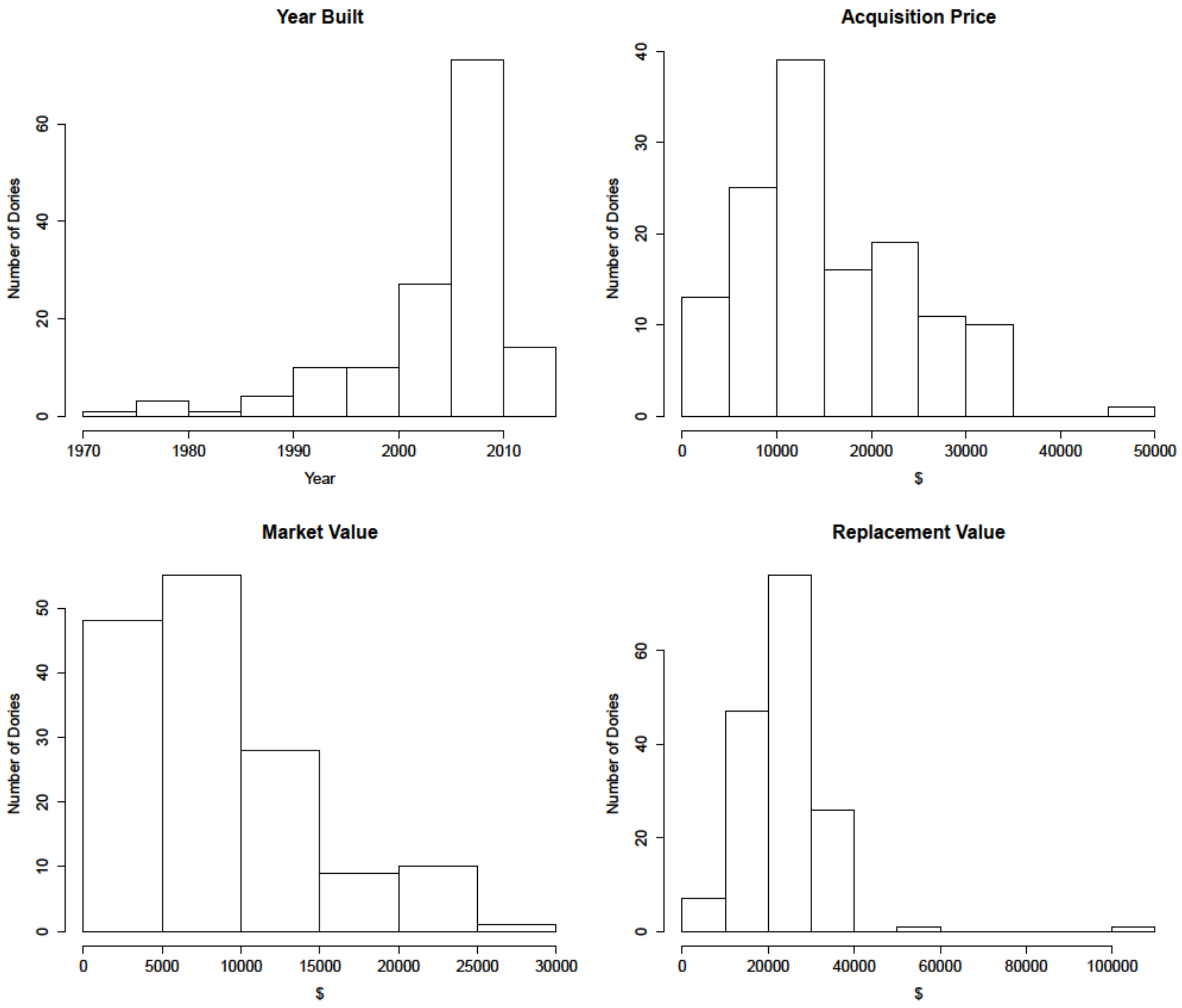


Figure 65 Estimated capital value of dories (numbers in table supra)

Fishing endorsements held by respondents

This section presents the information collected regarding the fishing rights held by respondents, including but not limited to the fishing rights used in 2010-11 to access the CRFFF. The section covers both licenses and the associated fishing endorsements as well as quota, owned or leased-in.

Fishing endorsements owned / leased-in to operate the vessel in 2010/11

53 respondents owned, 9 leased and 1 is unknown.

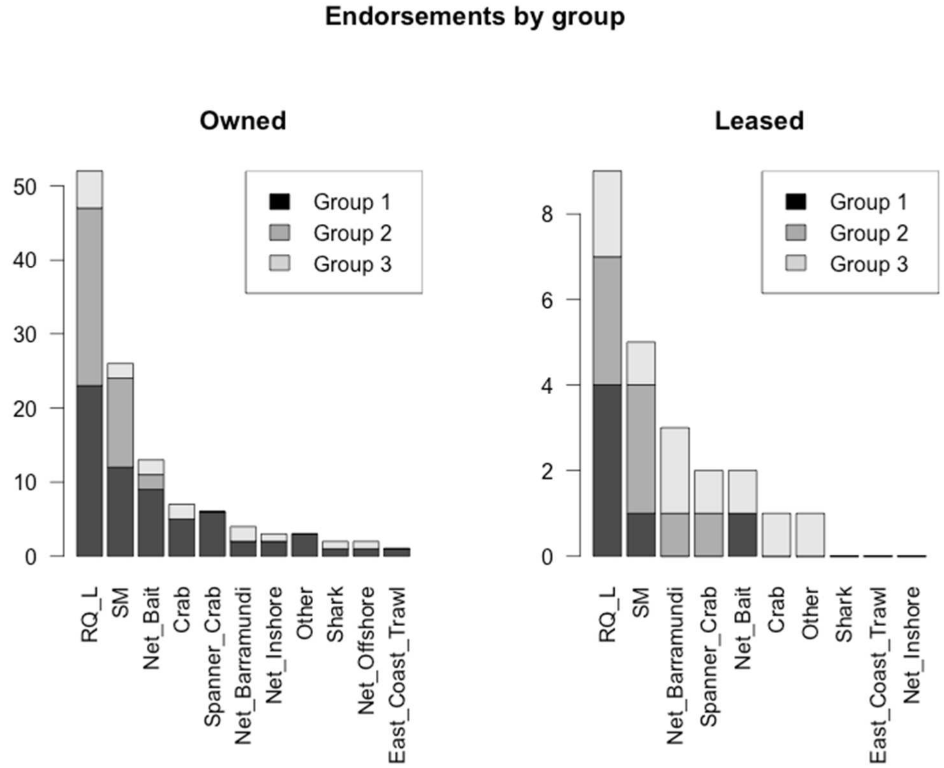


Figure 66 Specific endorsements held at the group level

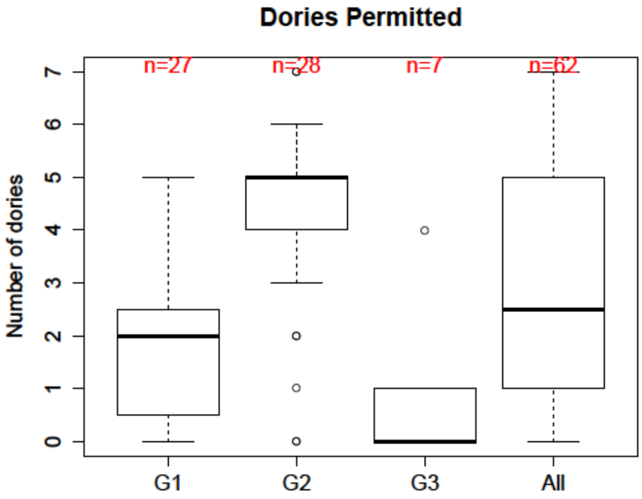


Figure 67 Permissible number of dories

Quota owned / leased in to operate the vessel in 2010/11

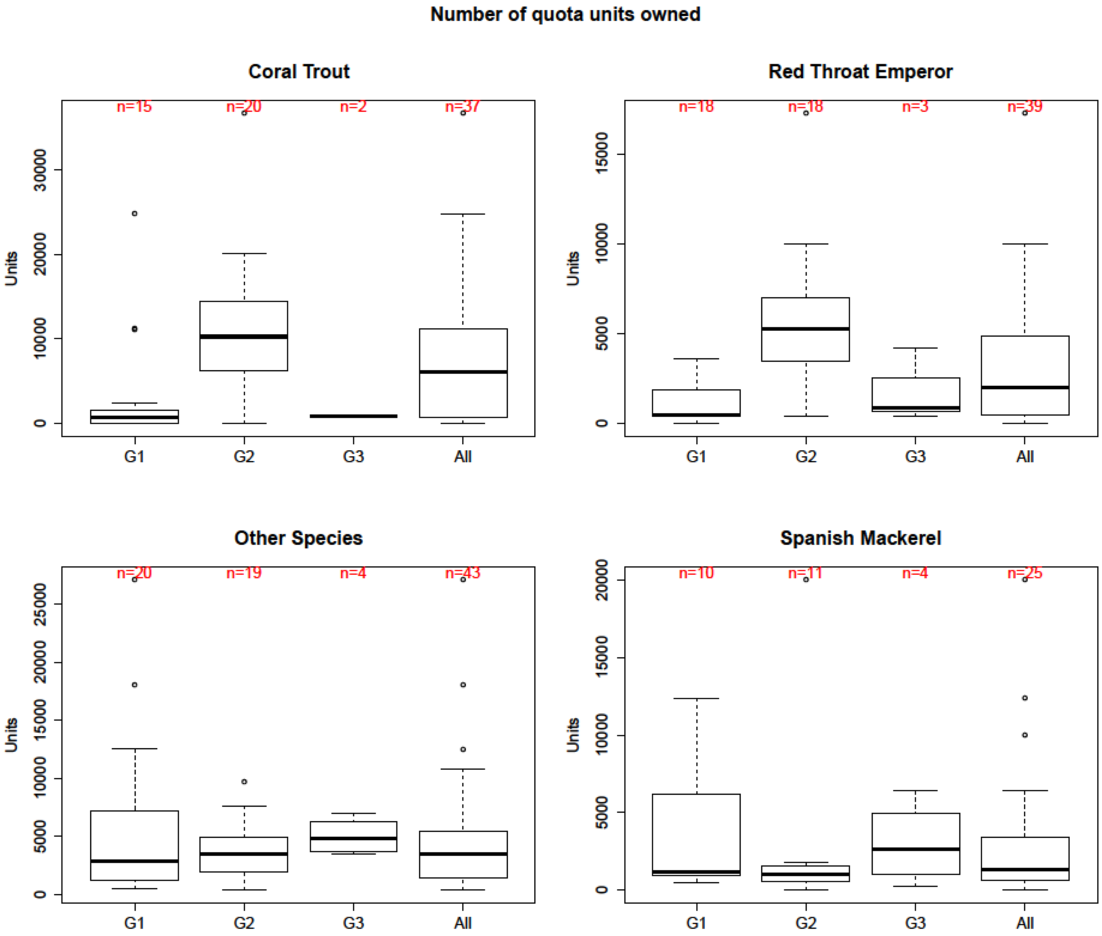


Figure 68 Units of quota owned by species and group

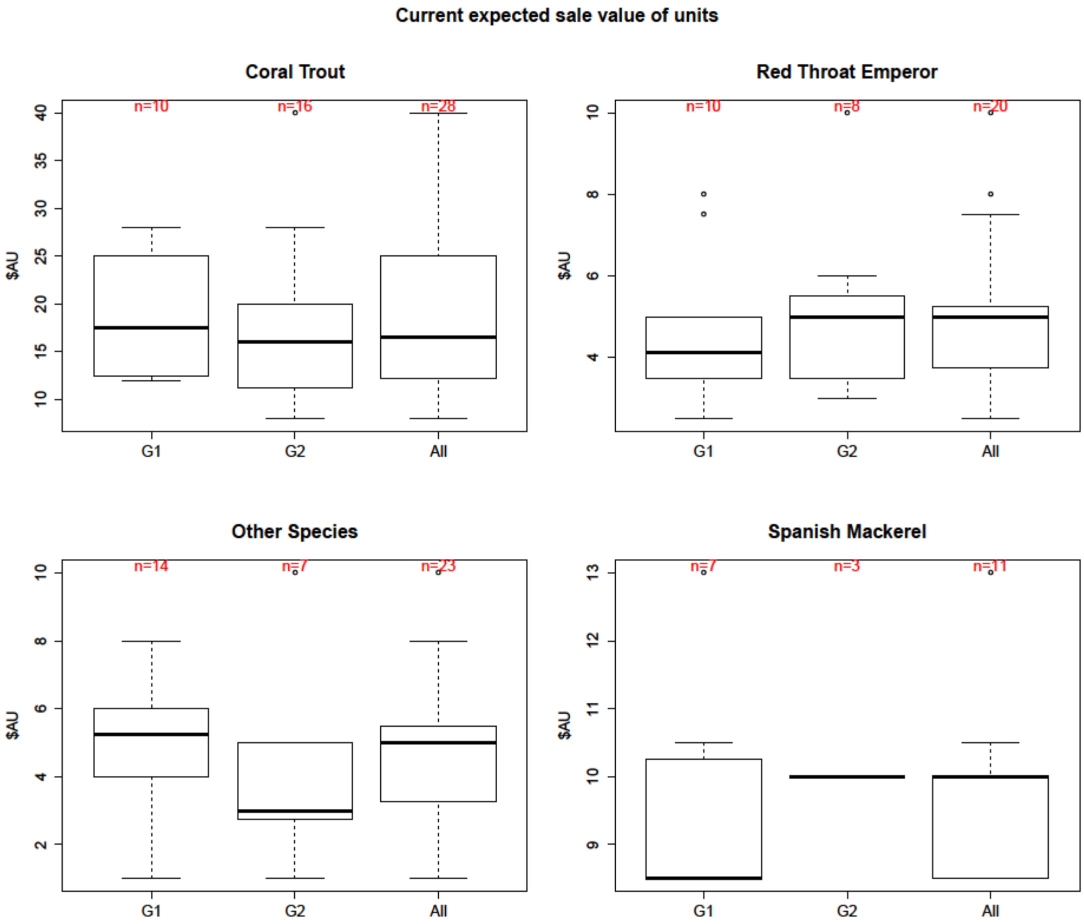


Figure 69 Expected current sale value of quota units for groups 1, 2 and the sample as a whole

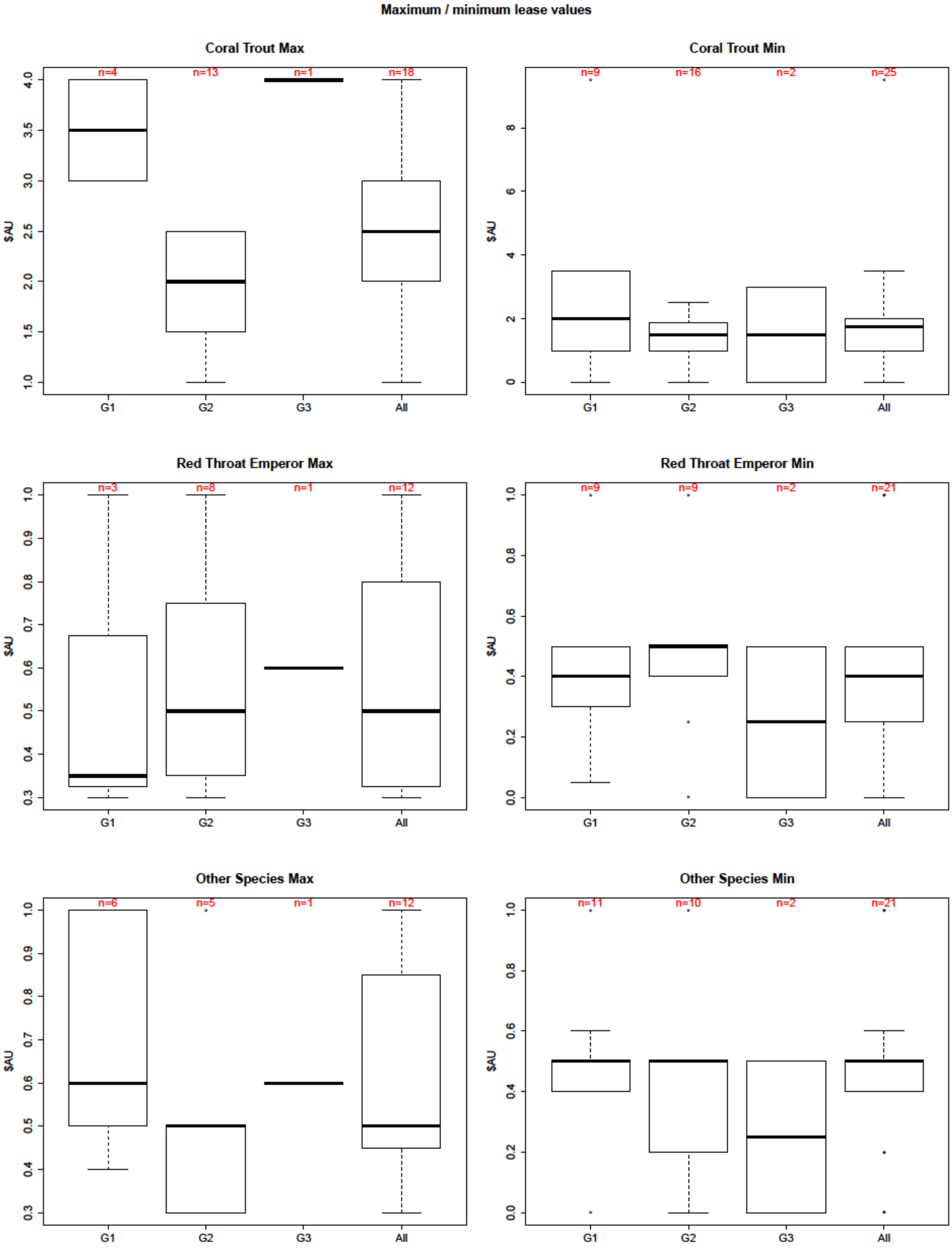


Figure 70 Minimum and maximum expected lease values by group

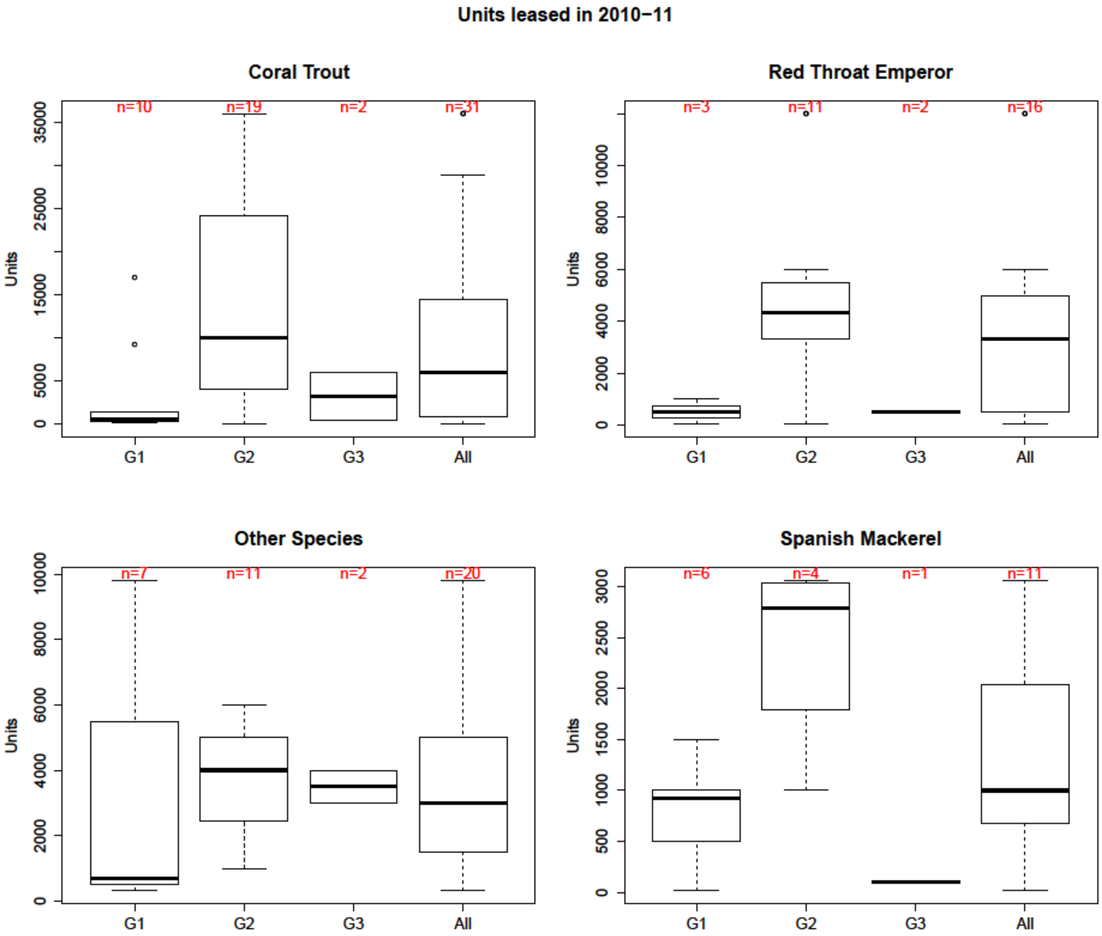


Figure 71 Number of units leased by group in the financial year 2010-11

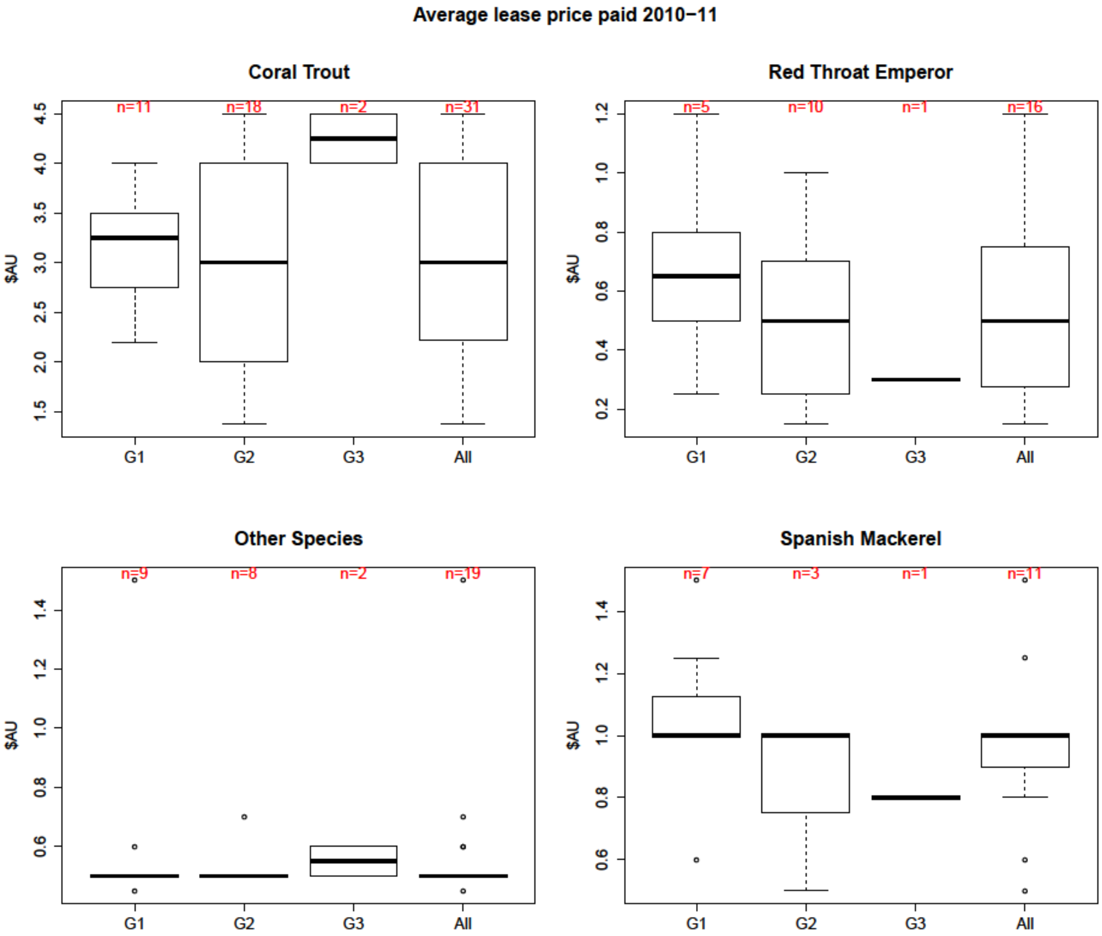


Figure 72 Average quota lease prices paid by group of operators

Vessel activity

Annual activity

Two initial questions related to the overall perception of the 2010-11 year by respondents, in terms of having been a full year of activity and a typical year for them. In addition, respondents were asked whether they considered the CRFFF to be their primary fishery.

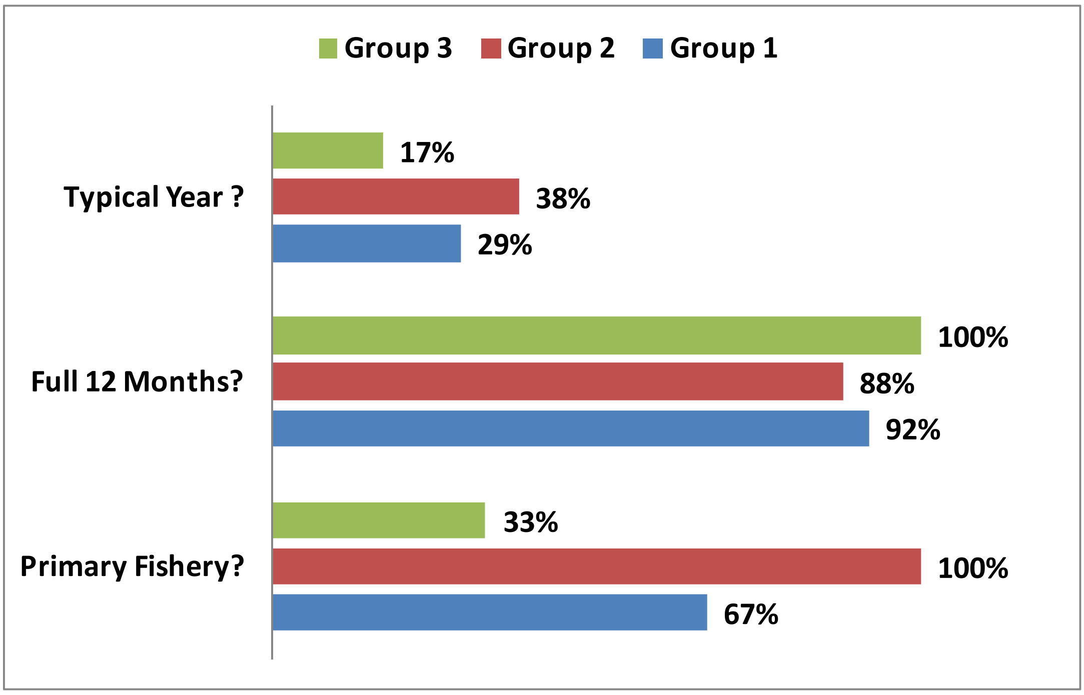


Figure 73 Summary of annual activity questions

Respondents who did not consider the CRFFF as their primary fishery indicated that their primary fishery was one of the following:

- Spanish Mackerel fishery
- Net Fishery
- Net fishing, Crabbing (2 respondents)
- Net - Barramundi
- Split 50/50 between RQ and Spanish Mackerel
- Crab fishing
- Spanner Crab
- Commonwealth SESSF
- Mud crab fishery (2 respondents)
- 25% of fishing time and economic dependence from different fisheries

On average, respondents who responded that they had not operated for a full year in 2010-11 operated for 7 months (minimum 3 months, maximum 10 months). The reasons for partial activity included regulatory decisions to stop the vessel from fishing, cyclones and their impact on the reef/catch rates, generally poor weather conditions, displacement of fishing effort following cyclones, purchase of vessel during the year, sale of vessel during the year, vessel immobilization due to refit/engine repair, business decisions to change or modify main fishing activity.

Landing Port

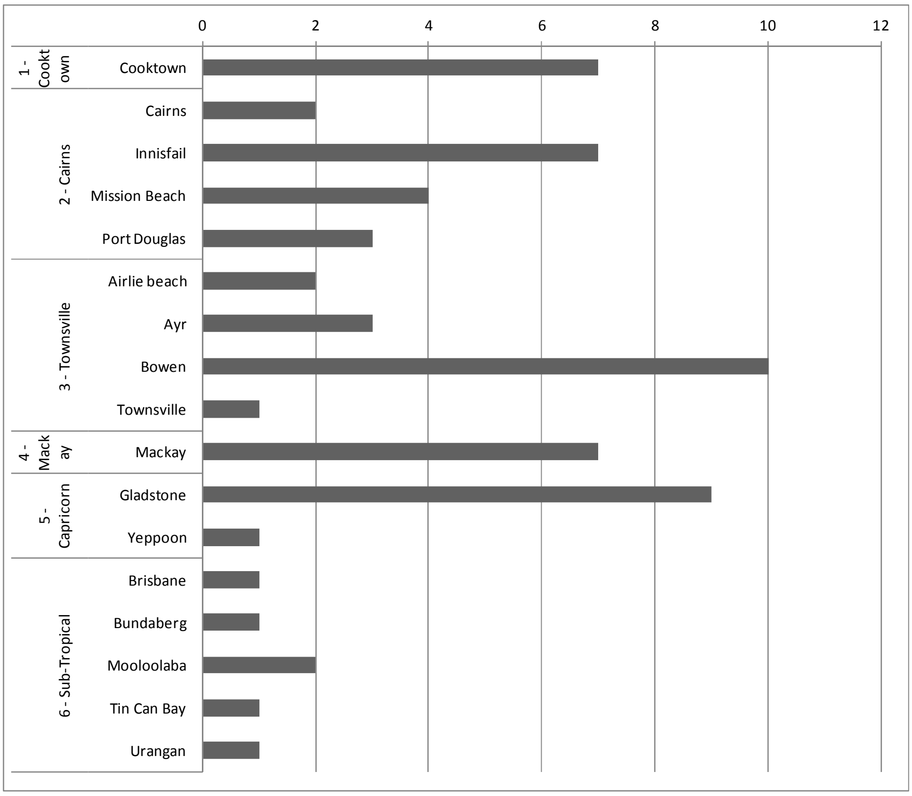


Figure 74 Main unloading port cited by respondents for 2010-11

The questionnaire included a question on the reasons for the choice of the main landing port (Figure 74). Reponses to this question are presented in Figure 75. At the whole of survey level, "family" (interpreted as the location of the family home) was cited most frequently (27%) as the driver for the choice of landing port, followed by "higher catch rates" (16%) and "water quality" (14%).

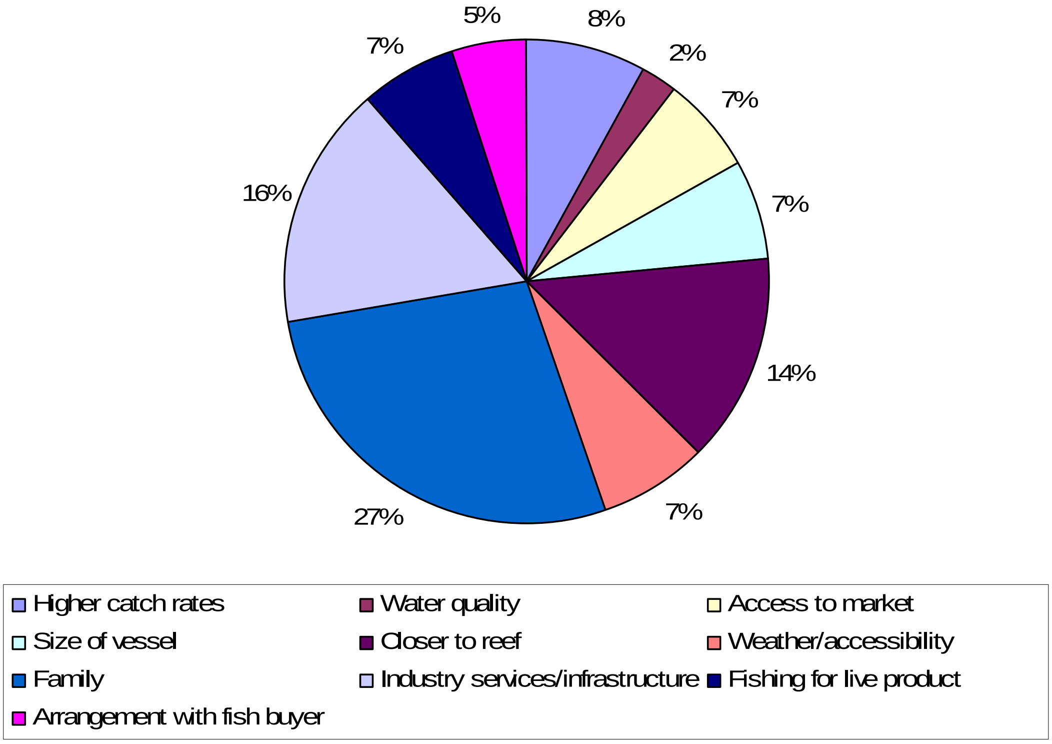


Figure 75 Main reasons for choice of primary landing port

From the 62 surveys, 35 reported having landed to additional ports for periods of at least a month in the last 3 years. Max 5, Ave 1.1

Fishing days

The "activity calendar" section of the questionnaire was used to reconstruct the annual profile of activity of the operation, including number of days fished per month in the different fishing activities in which the operation engaged. The figures below present the number of vessels in the sample that were active, in each month of 2010-11, for each group of operators. The information included in these figures reflects the entire activity of the vessels, including both RQ and non-RQ fishing, where the latter was also pursued during the year. The impact of cyclone Yasi in February 2011 is visible, particularly for the smaller operations (Live CT < 15m and Diversified Fishers).

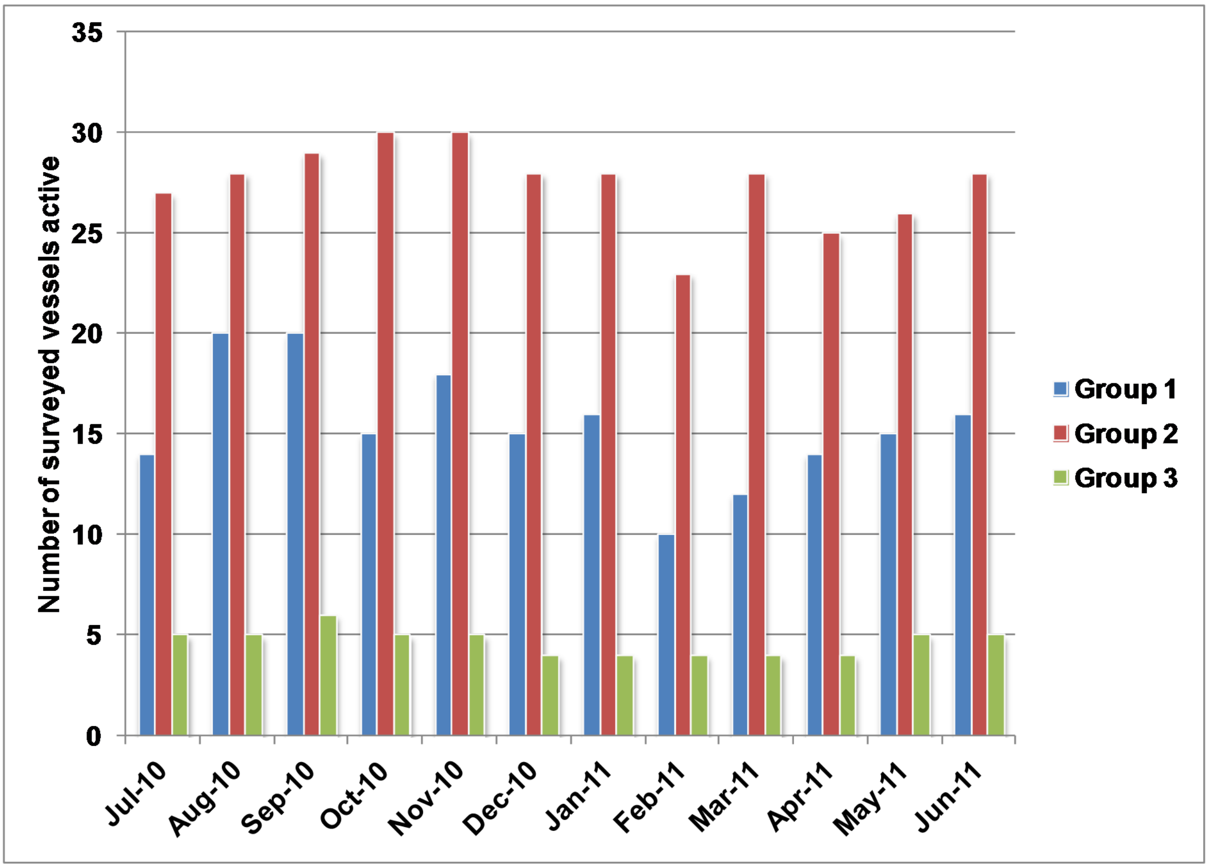


Figure 76 Number of surveyed vessels active per month, 2010-11, by group of operators

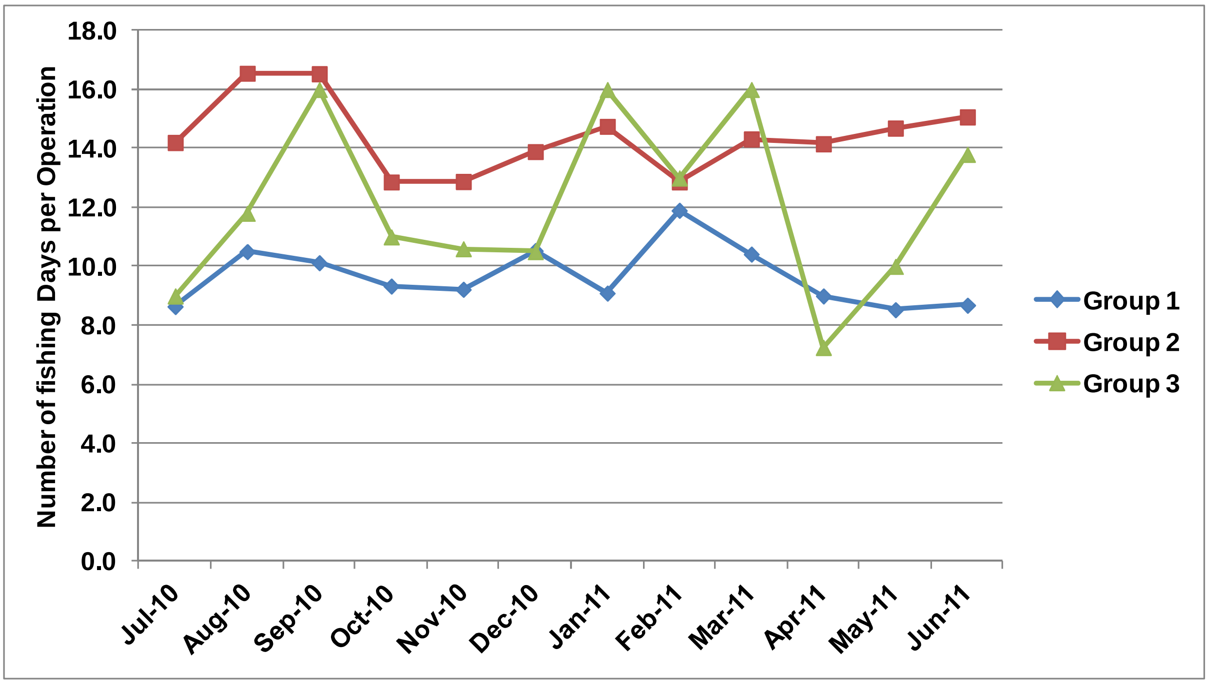


Figure 77 Average number of days fishing per vessel by month, 2010-11, by group of operators

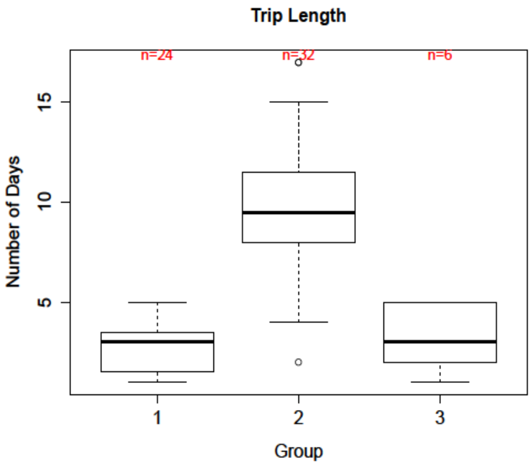


Figure 78 Average trip length per group of operators

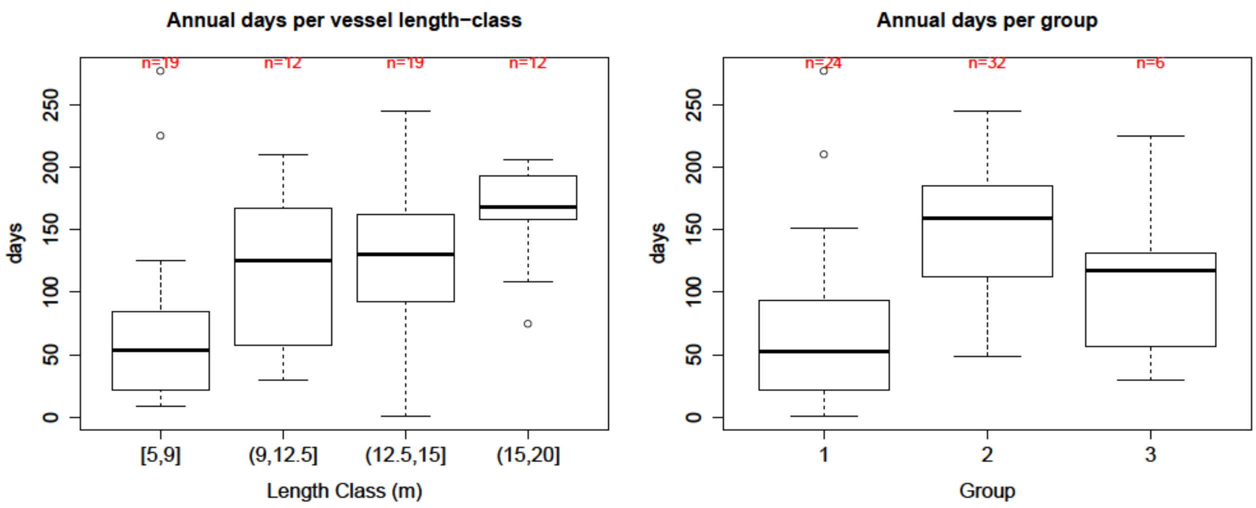


Figure 79 Total annual fishing days per size class of vessel (left) and per group of operators (right)

Income

This section presents the information collected regarding annual fish sales of operations.

Table 22 Total Fish Sales and Fish Sales Composition per Group of Operators

	n	na	mean	sd	median	min	max	range	se
GROUP 1									
Total Annual Fish Sales ($)	23	1	**62,436**	52,488	**50,000**	1,525	200,000	198,475	5,880
RQ Annual Fish Sales ($)	24	0	**27,577**	28,806	**15,168**	-	87,517	87,517	4,474
CT Annual Fish Sales ($)	24	0	**13,286**	21,918	**3,810**	-	80,971	80,971	1,366
RTE Annual Fish Sales)$)	22	2	**2,941**	6,407	**419**	-	22,267	22,267	3,510
OS Annual Fish Sales ($)	24	0	**11,595**	17,195	**5,242**	-	68,477	68,477	5,322
Line non-RQ Annual Fish Sales ($)	17	7	**19,139**	21,941	**8,897**	-	81,303	81,303	23,889
Other non-RQ Annual Fish Sales ($)	8	16	**56,102**	67,568	**31,152**	388	192,367	191,979	6,514
GROUP 2			-	-	-	-	-	-	-
Total Annual Fish Sales ($)	32	0	**548,746**	289,840	**522,437**	122,570	1,084,255	961,685	50,400
RQ Annual Fish Sales ($)	32	0	**540,478**	285,105	**518,653**	121,857	1,082,255	960,398	47,574
CT Annual Fish Sales ($)	32	0	**494,643**	269,120	**448,462**	110,083	1,011,785	901,702	5,260
RTE Annual Fish Sales)$)	30	2	**33,944**	28,812	**32,570**	-	126,655	126,655	3,081
OS Annual Fish Sales ($)	32	0	**14,012**	17,427	**9,420**	-	87,465	87,465	1,807
Line non-RQ Annual Fish Sales ($)	31	1	**8,534**	10,061	**4,198**	-	36,996	36,996	-
Other non-RQ Annual Fish Sales ($)	1	31	-	-	-	-	-	-	-
GROUP 3			-	-	-	-	-	-	-
Total Annual Fish Sales ($)	5	1	**77,294**	60,108	**50,998**	45,282	184,300	139,018	28,381
RQ Annual Fish Sales ($)	5	1	**44,043**	63,461	**20,000**	1,468	156,448	154,980	29,358
CT Annual Fish Sales ($)	5	1	**31,657**	65,647	**622**	-	148,902	148,902	1,120
RTE Annual Fish Sales)$)	5	1	**1,648**	2,504	**479**	-	5,961	5,961	3,426
OS Annual Fish Sales ($)	5	1	**10,737**	7,661	**10,644**	989	20,000	19,011	6,266
Line non-RQ Annual Fish Sales ($)	3	3							
Other non-RQ Annual Fish Sales ($)	3	3							

Table 23 presents an calculation of total fish sales divided by (i) the crew size (including the skipper when a skipper is employed part- or full-time), (ii) by the crew size (including the skipper) and number of days fishing, and (iii) by the number of fishing units (including dories and primary vessel) included in the operation and the number of fishing days. In cases where no fishing takes place from the primary vessel, which is more likely to be the case for larger operations, the latter indicator will underestimate the sales strictly related to the operation of dories. However, the calculation provides a way of accounting for the fact that the primary vessel is necessary to take the dories to fishing grounds in larger operations.

Table 23 Total Fish Sales per Crew and Dory-Day

	n	na	mean	sd	median	min	max	range	se
Group 1									
Annual per Crew* ($/Crew)	23	1	**35,906**	31,240	**26,481**	1,525	110,000	108,475	6,514
Sales per Crew-Day ($/Fishing Day)**	23	1	**992**	1,473	**248**	27	5,556	5,528	307
Sales per Dory-Day* ($/Dory Day)**	23	1	**1,539**	2,323	**767**	27	9,167	9,139	484
Group 2	0		-	-	-	-	-	-	-
Annual per Crew* ($/Crew)	32	0	**94,958**	40,556	**94,355**	20,506	180,709	160,203	7,169
Sales per Crew-Day ($/Fishing Day)**	32	0	**997**	725	**790**	137	2,929	2,792	128
Sales per Dory-Day* ($/Dory Day)**	32	0	**997**	696	**790**	148	2,929	2,781	123
Group 3	0		-	-	-	-	-	-	-
Annual per Crew* ($/Crew)	5	1	**31,636**	16,938	**25,499**	20,000	61,433	41,433	7,575
Sales per Crew-Day ($/Fishing Day)**	5	1	**381**	298	**322**	126	850	724	133
Sales per Dory-Day* ($/Dory Day)**	5	1	**711**	619	**377**	220	1,700	1,480	277

*Crew including skipper; **Crew including skipper; ***Number of dories includes primary vessel.

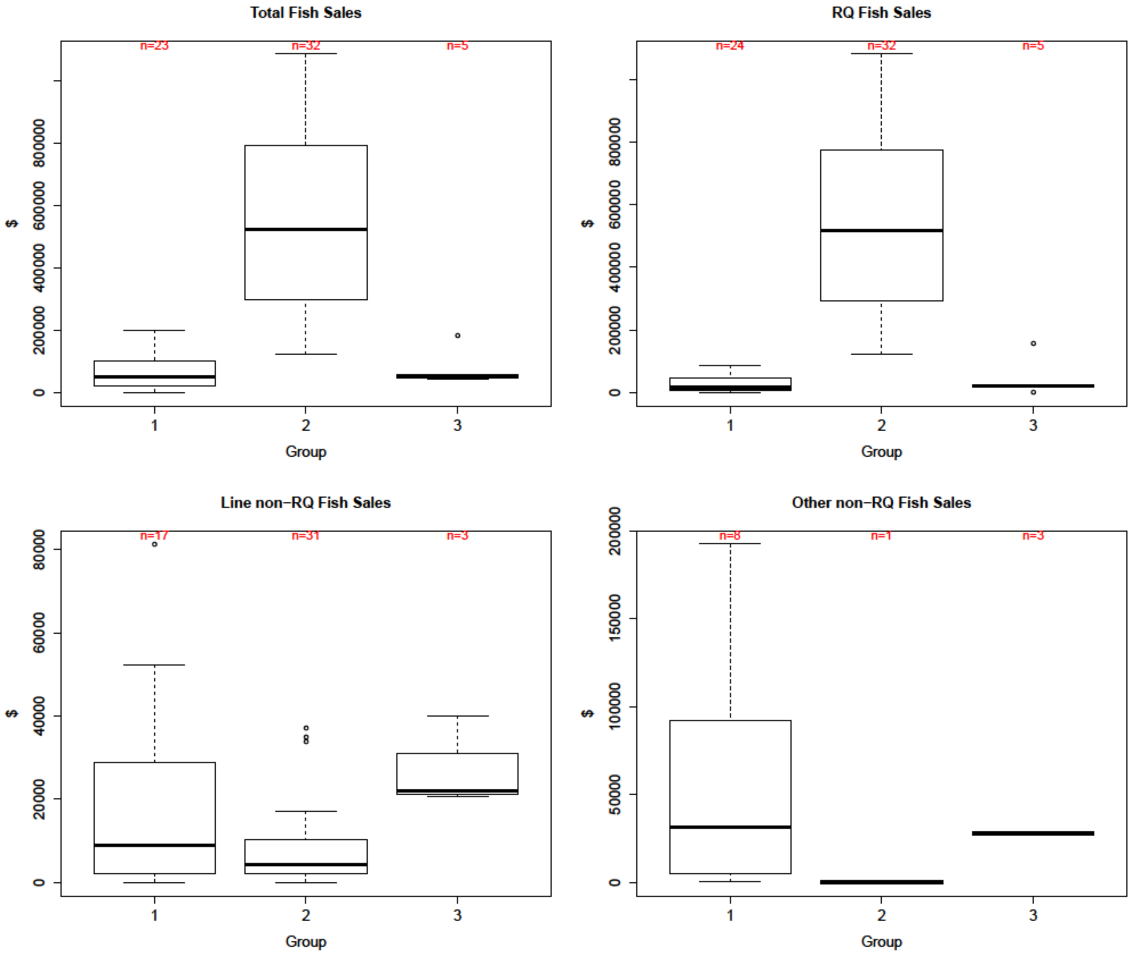


Figure 80 Annual Fish Sales Per Operation, by Group of Operators

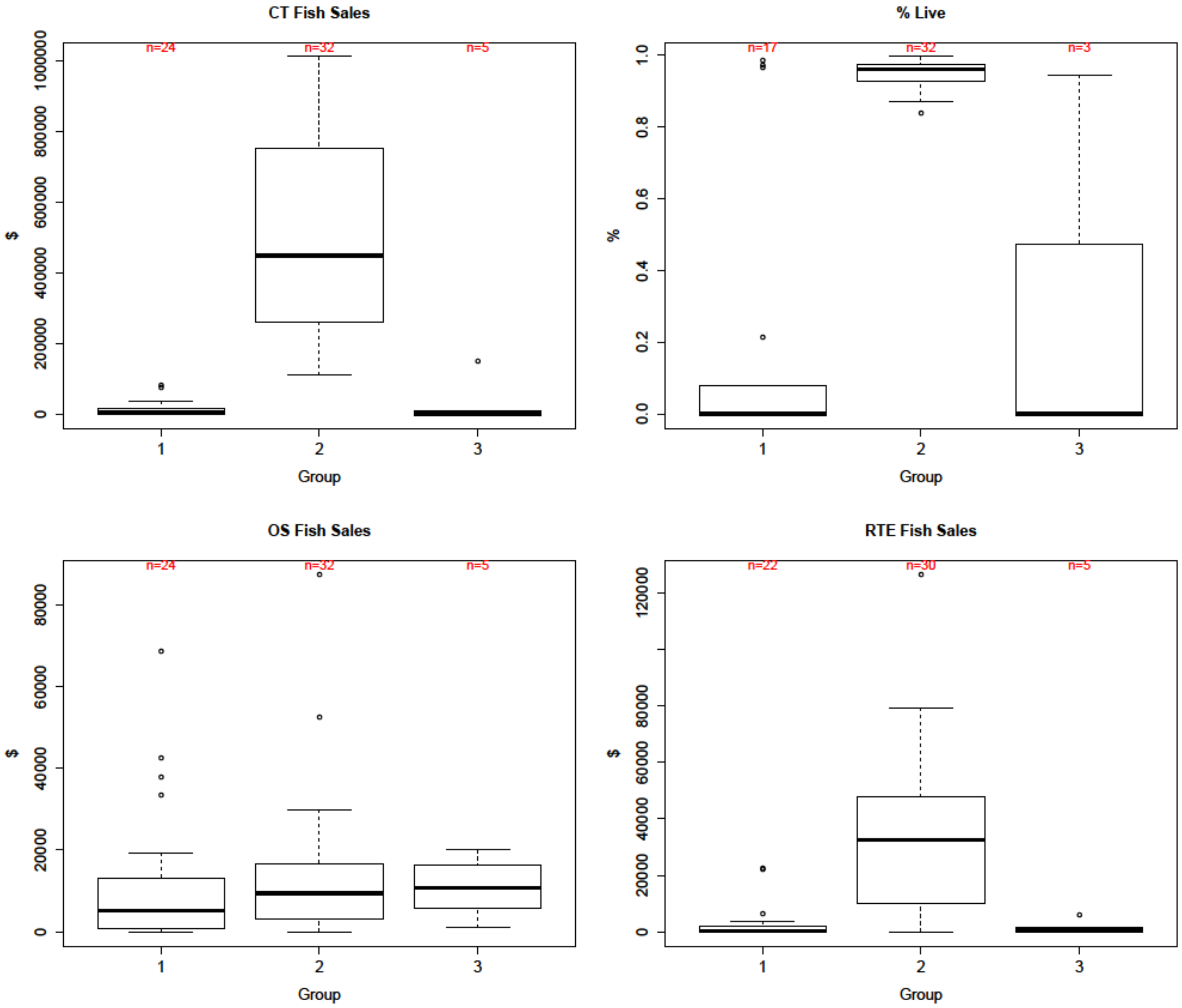


Figure 81 Annual RQ Fish Sales per Operation, by Group of Operators

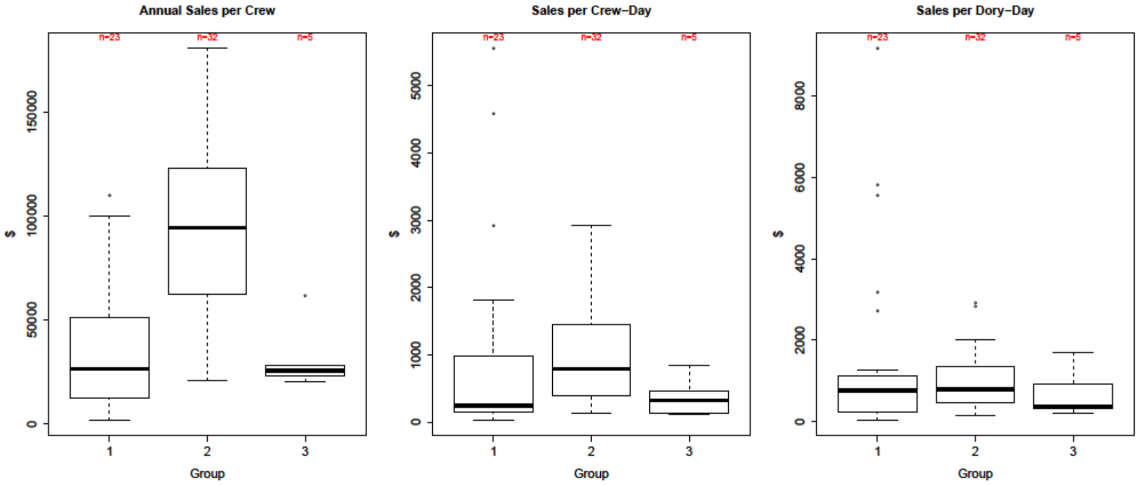


Figure 82 Total Fish Sales per Crew (incl. Skipper) and Dory-Day

Composition of fish sales in 2008-09?

Responses were aggregated by species group, into perception of higher sales (Much higher or slightly higher), comparable sales, and lower sales (slightly lower or much lower).

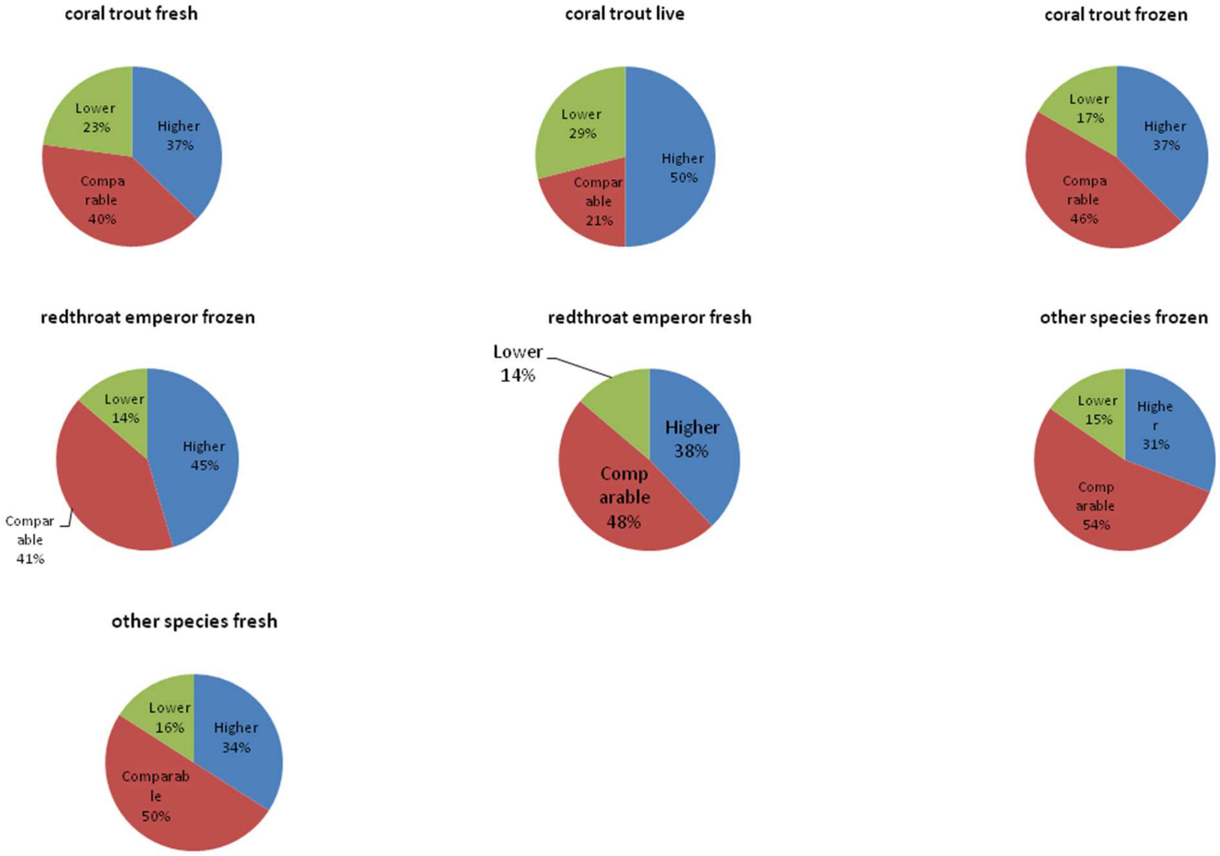


Figure 83 Perceived changes in the value of fish sales in 210-11 as compared to 2008-09

Crew characteristics

This section presents the preliminary results obtained regarding crew characteristics and crew costs. The questionnaire included questions on whether the operators hired skippers to operate their vessel for all or part of the year, as well as whether some of the operating costs were being shared between the vessel owner and the crew before the crew share was paid. Where some costs were shared, efforts were made to identify the nature of these costs. Responses to these questions are presented in Figure 85.

Table 24 Crew size and crew costs per group of operators

	n	na	mean	sd	median	min	max	range	se
Group 1									
Crew Size (incl. Skipper)	22	2	1.8	0.9	2.0	1.0	4.0	3.0	0.2
Annual Fishing Days (Days)	24	0	70	68	53	1	277	276	14
Annual Crew Payments - All of Group ($)	22	2	10,104	23,117	-	-	100,000	100,000	5,045
Crew Payments per Day ($ / Day)	23	1	109	201	-	-	662	662	43
Annual Individual Crew Payments ($ / Year)	10	14	11,082	15,780	5,231	100	50,000	49,900	5,260
Individual Crew Payments per Day ($ / Day)	10	14	125	124	78	3	331	329	41
Group 2									
Crew Size (incl. Skipper)	32	0	5.7	1.3	6.0	3.0	8.0	5.0	0.2
Annual Fishing Days (Days)	32	0	151	48	160	49	245	196	9
Annual Crew Payments - All of Group ($)	31	1	225,315	141,979	183,632	38,002	504,967	466,965	25,099
Crew Payments per Day ($ / Day)	31	1	1,412	751	1,147	365	3,742	3,377	133
Annual Individual Crew Payments ($ / Year)	31	1	38,354	21,104	35,288	8,921	84,161	75,240	3,731
Individual Crew Payments per Day ($ / Day)	31	1	246	103	220	117	468	351	18
Group 3									
Crew Size (incl. Skipper)	6	0	2.1	0.8	2.0	1.0	3.0	2.0	0.3
Annual Fishing Days (Days)	6	0	113	68	118	30	225	195	28
Annual Crew Payments - All of Group ($)	4	2	-	-	-	-	-	-	-
Crew Payments per Day ($ / Day)	4	2	-	-	-	-	-	-	-
Annual Individual Crew Payments ($ / Year)	4	2	-	-	-	-	-	-	-
Individual Crew Payments per Day ($ / Day)	4	2	-	-	-	-	-	-	-

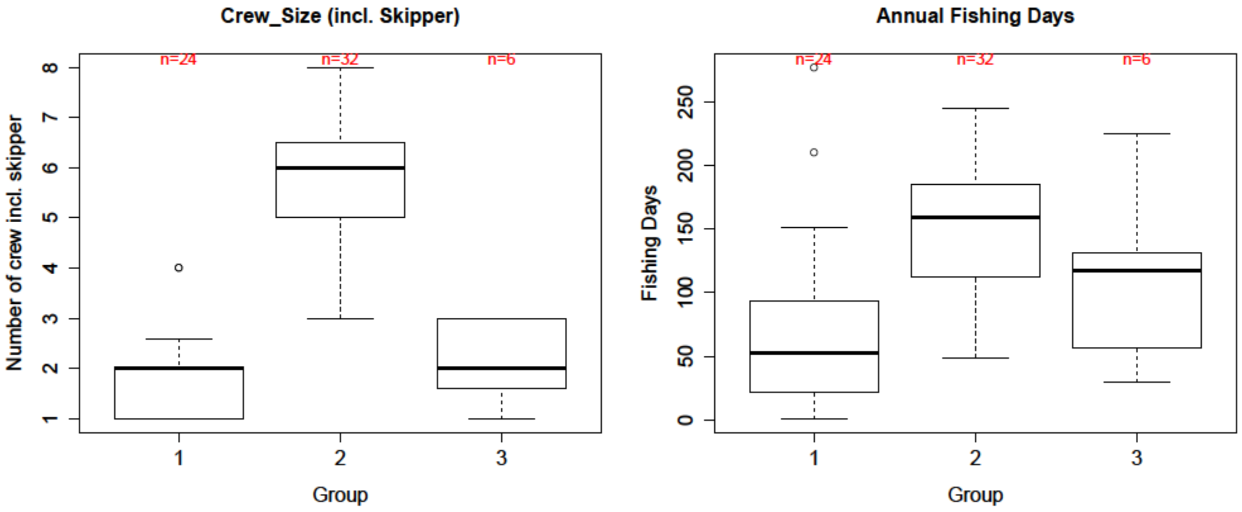


Figure 84 Crew size and annual fishing days per group of operators

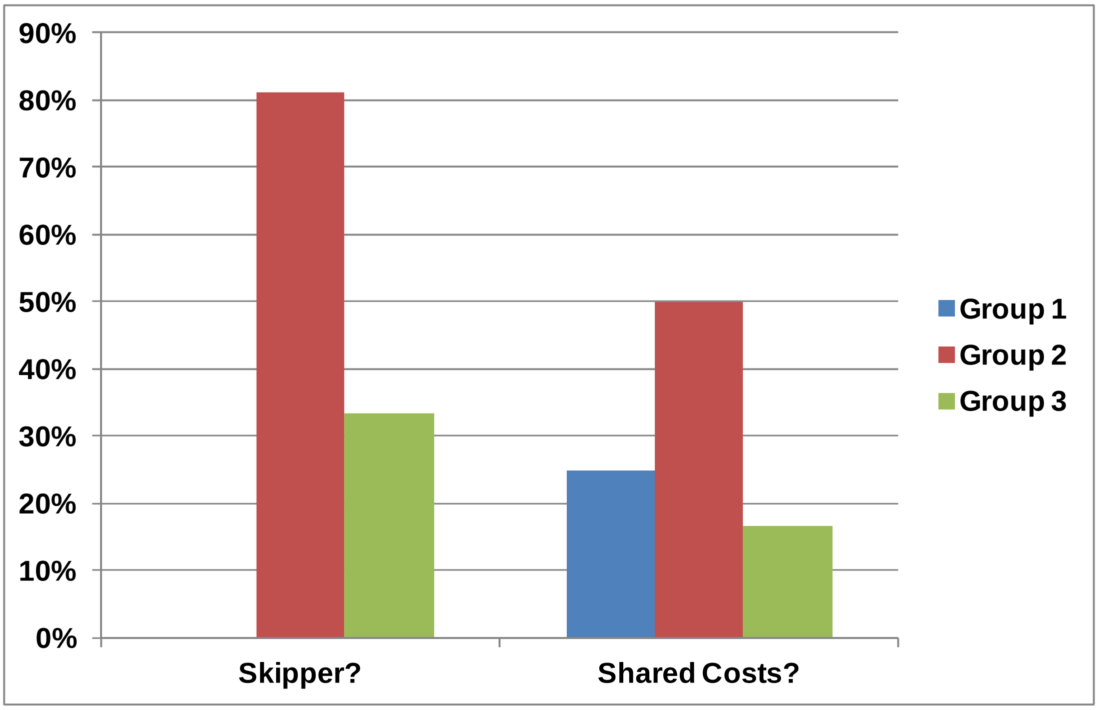


Figure 85 Proportion of operators hiring skippers (whole or part-time) and sharing some of the operating costs with crew

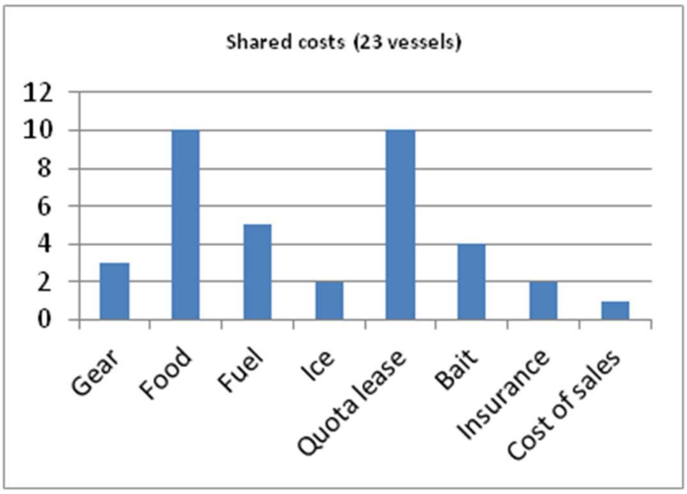


Figure 86 Nature of costs shared

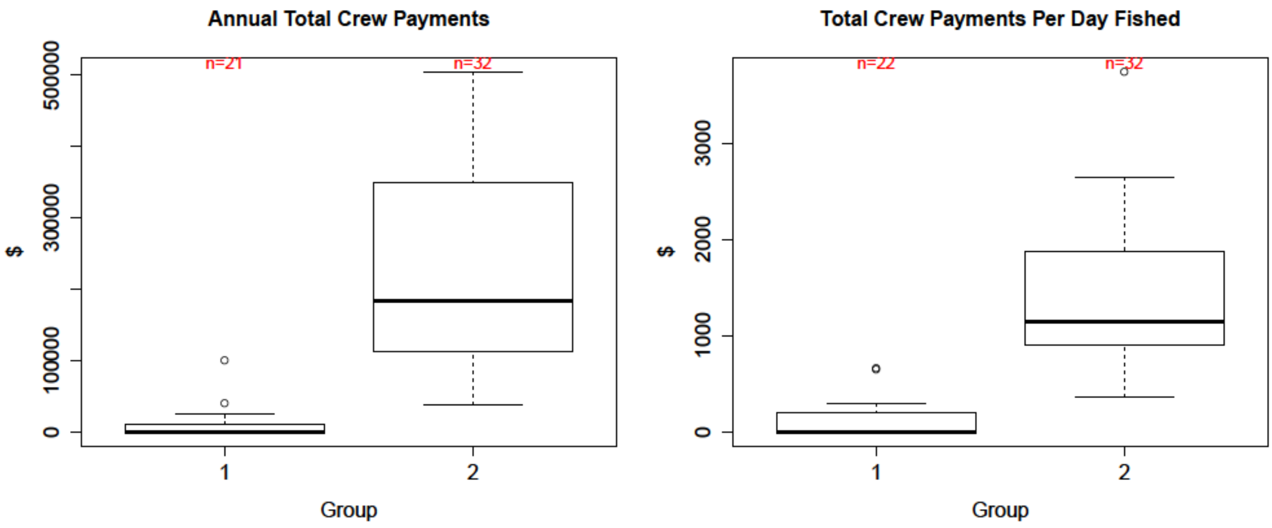


Figure 87 Annual crew costs

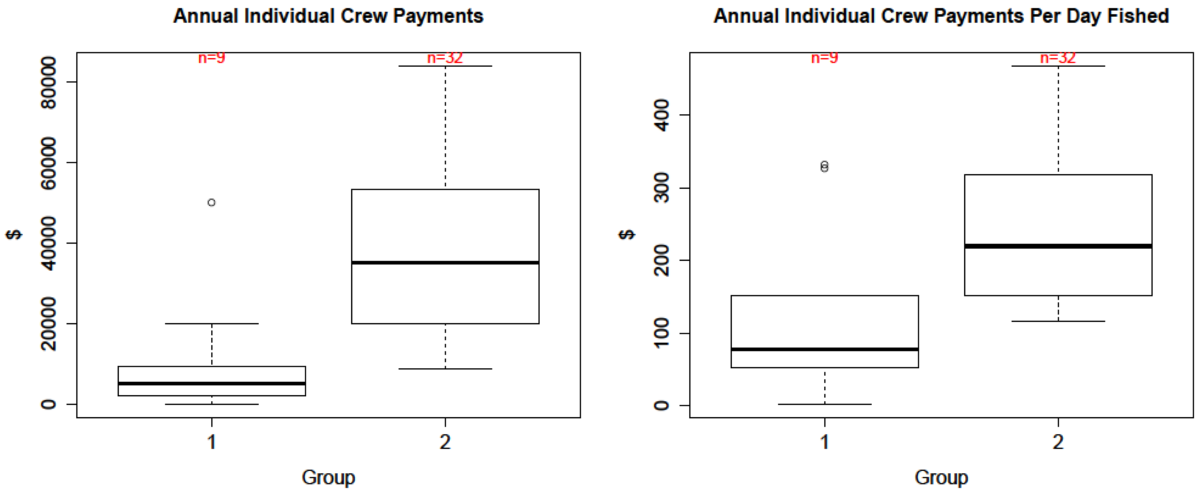


Figure 88 Individual crew payments

Catching costs

The following tables and figures present the information collected regarding the catching costs of fishing operations. Preliminary analysis of the repairs and maintenance costs is reported in the next section. Fuel and oil costs include all diesel and petrol as well as oil costs at the annual level, and are presented before the fuel rebate in the tables and figures below. This provides an indication of the magnitude of the fuel and oil costs which must be borne by operators upfront. Some information was also collected during the interviews regarding the total amount of rebate received, which determines the end-of-year final costs supported by operations in relation to fuel and oil. This information is still being analysed and will be included in the final results. Bait and tackle costs were aggregated as in a number of instances, these were also aggregated in the information collected in the interviews. Other catching costs included a range of items amongst which knives, ropes, anchor and chain, gaffs, lures, wet clothing, gas, etc.

Table 25 Annual catching costs per group of operators

	n	na	mean	sd	median	min	max	range	se
Group 1									
Fuel & Oil ($)	24	0	19,544	20,605	11,212	700	62,000	61,300	4,206
Bait & Tackle ($)	24	0	6,355	7,459	2,210	70	24,856	24,786	1,523
Quota Lease ($)	24	0	1,074	1,567	455	-	5,000	5,000	320
Food ($)	24	0	2,485	4,524	861	-	21,000	21,000	923
Ice ($)	24	0	2,392	3,680	508	-	13,750	13,750	751
Boxes & Bags ($)	24	0	921	3,334	-	-	15,840	15,840	680
Other Catching Costs ($)	24	0	178	522	-	-	2,300	2,300	107
Group 2									
Fuel & Oil ($)	31	1	85,868	55,568	67,500	16,058	262,642	246,584	9,980
Bait & Tackle ($)	31	1	41,573	21,636	39,528	6,671	93,345	86,674	3,886
Quota Lease ($)	31	1	29,582	30,096	18,700	-	86,029	86,029	5,405
Food ($)	31	1	15,717	14,759	14,382	-	81,773	81,773	2,651
Ice ($)	31	1	3,023	4,690	-	-	16,174	16,174	842
Boxes & Bags ($)	31	1	789	1,975	-	-	9,999	9,999	355
Other Catching Costs ($)	31	1	603	1,646	-	-	8,470	8,470	296
Group 3									
Fuel & Oil ($)	6	0	16,706	12,778	9,935	7,035	33,130	26,095	5,217
Bait & Tackle ($)	6	0	5,892	4,263	4,200	2,410	14,160	11,750	1,741
Quota Lease ($)	6	0	734	1,798	-	-	4,403	4,403	734
Food ($)	6	0	3,472	4,172	1,695	-	9,583	9,583	1,703
Ice ($)	6	0	4,316	2,916	4,720	167	7,666	7,499	1,190
Boxes & Bags ($)	6	0	1,074	1,584	300	-	3,930	3,930	647
Other Catching Costs ($)	6	0	785	1,384	-	-	3,400	3,400	565

Table 26 Catching costs per main fishing technique, by group of operators

		n	na	mean	sd	median	min	max	range	se
GROUP 1	**Line***									
	Bait and Tackle ($)	24	-	4,978	6,377	1,716	70	23,650	23,580	1,302
	Boxes & Bags ($)	24	-	896	3,339	-	-	15,840	15,840	681
	Food ($)	24	-	2,170	4,505	493	-	21,000	21,000	920
	Fuel and Oil ($)	24	-	13,840	17,655	7,027	400	59,400	59,000	3,604
	Ice ($)	24	-	1,987	3,705	214	-	13,750	13,750	756
	Quota Lease ($)	24	-	1,032	1,583	105	-	5,000	5,000	323
	Other Catching Costs ($)	24	-	170	487	-	-	2,100	2,100	99
	Other Fisheries									
	Bait and Tackle ($)	24	-	1,377	4,982	-	-	24,506	24,506	1,017
	Boxes & Bags ($)	24	-	24	113	-	-	552	552	23
	Food ($)	24	-	314	1,229	-	-	6,000	6,000	251
	Fuel and Oil ($)	24	-	5,704	14,312	-	-	59,520	59,520	2,922
	Ice ($)	24	-	405	1,191	-	-	4,703	4,703	243
	Quota Lease ($)	24	-	42	204	-	-	1,000	1,000	42
	Other Catching Costs ($)	24	-	8	41	-	-	200	200	8
GROUP 2	**Line***									
	Bait and Tackle ($)	31	1	41,573	21,636	39,528	6,671	93,345	86,674	3,886
	Boxes & Bags ($)	31	1	789	1,975	-	-	9,999	9,999	355
	Food ($)	31	1	15,717	14,759	14,382	-	81,773	81,773	2,651
	Fuel and Oil ($)	31	1	85,868	55,568	67,500	16,058	262,642	246,584	9,980
	Ice ($)	31	1	3,023	4,690	-	-	16,174	16,174	842
	Quota Lease ($)	31	1	29,582	30,096	18,700	-	86,029	86,029	5,405
	Other Catching Costs ($)	31	1	603	1,646	-	-	8,470	8,470	296
GROUP 3	**Line***									
	Bait and Tackle ($)	6	-	5,442	3,291	4,200	2,310	11,560	9,250	1,343
	Boxes & Bags ($)	6	-	1,074	1,584	300	-	3,930	3,930	647
	Food ($)	6	-	3,352	4,242	1,335	-	9,583	9,583	1,732
	Fuel and Oil ($)	6	-	13,171	10,696	7,850	4,950	30,130	25,180	4,366
	Ice ($)	6	-	3,266	2,773	2,985	167	7,666	7,499	1,132
	Quota Lease ($)	6	-	734	1,798	-	-	4,403	4,403	734
	Other Catching Costs ($)	6	-	785	1,384	-	-	3,400	3,400	565
	Other Fisheries									
	Bait and Tackle ($)	6	-	450	1,054	-	-	2,600	2,600	430
	Boxes & Bags ($)	6	-	-	-	-	-	-	-	-
	Food ($)	6	-	120	294	-	-	720	720	120
	Fuel and Oil ($)	6	-	3,534	3,402	3,060	-	10,000	10,000	1,389
	Ice ($)	6	-	1,050	1,388	350	-	3,000	3,000	567
	Quota Lease ($)	6	-	-	-	-	-	-	-	-
	Other Catching Costs ($)	6	-	-	-	-	-	-	-	-

*Includes RQ and non-RQ Line Fishing Costs

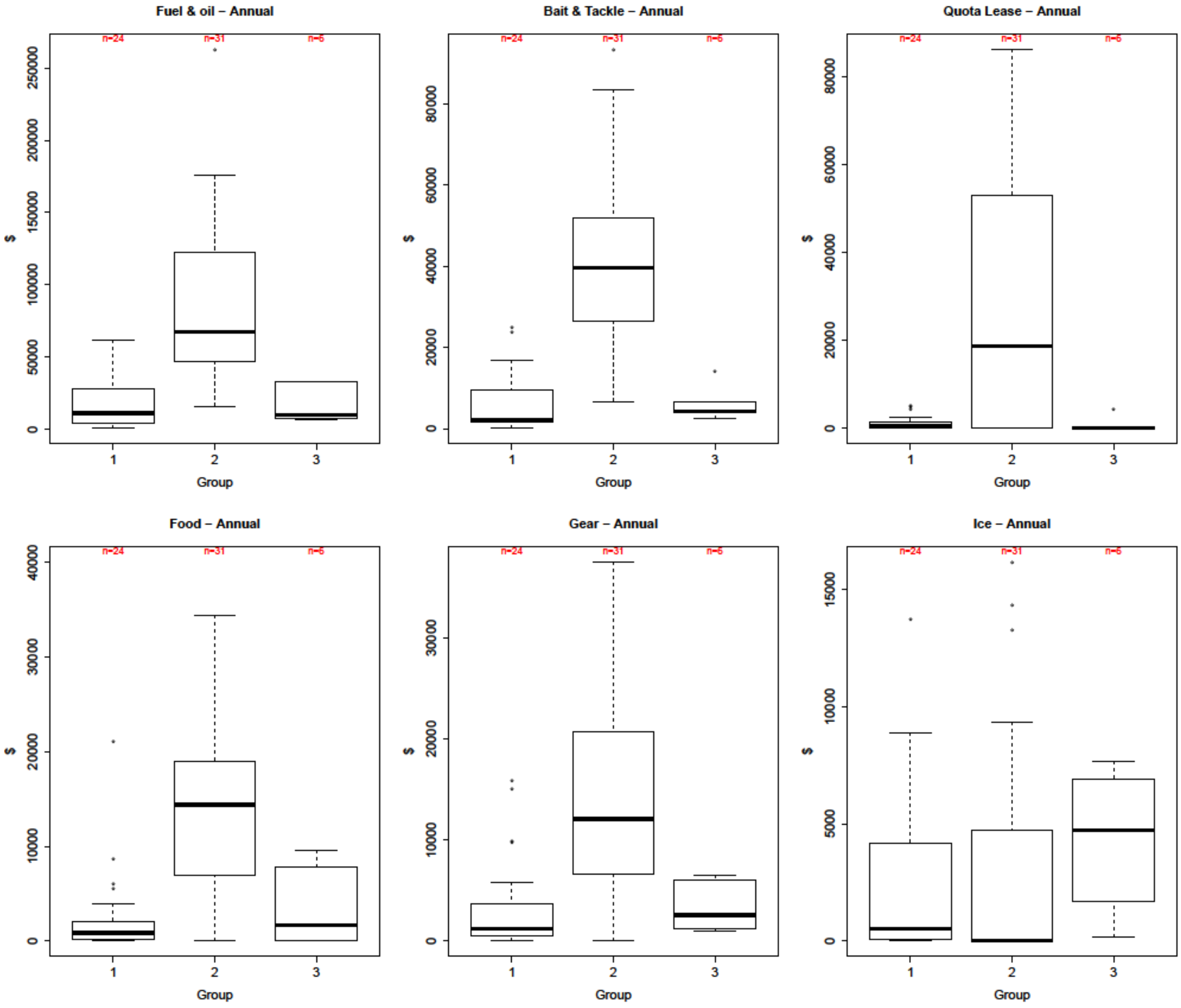


Figure 89 Annual Total Catching Costs per Operation, by Group of Operators

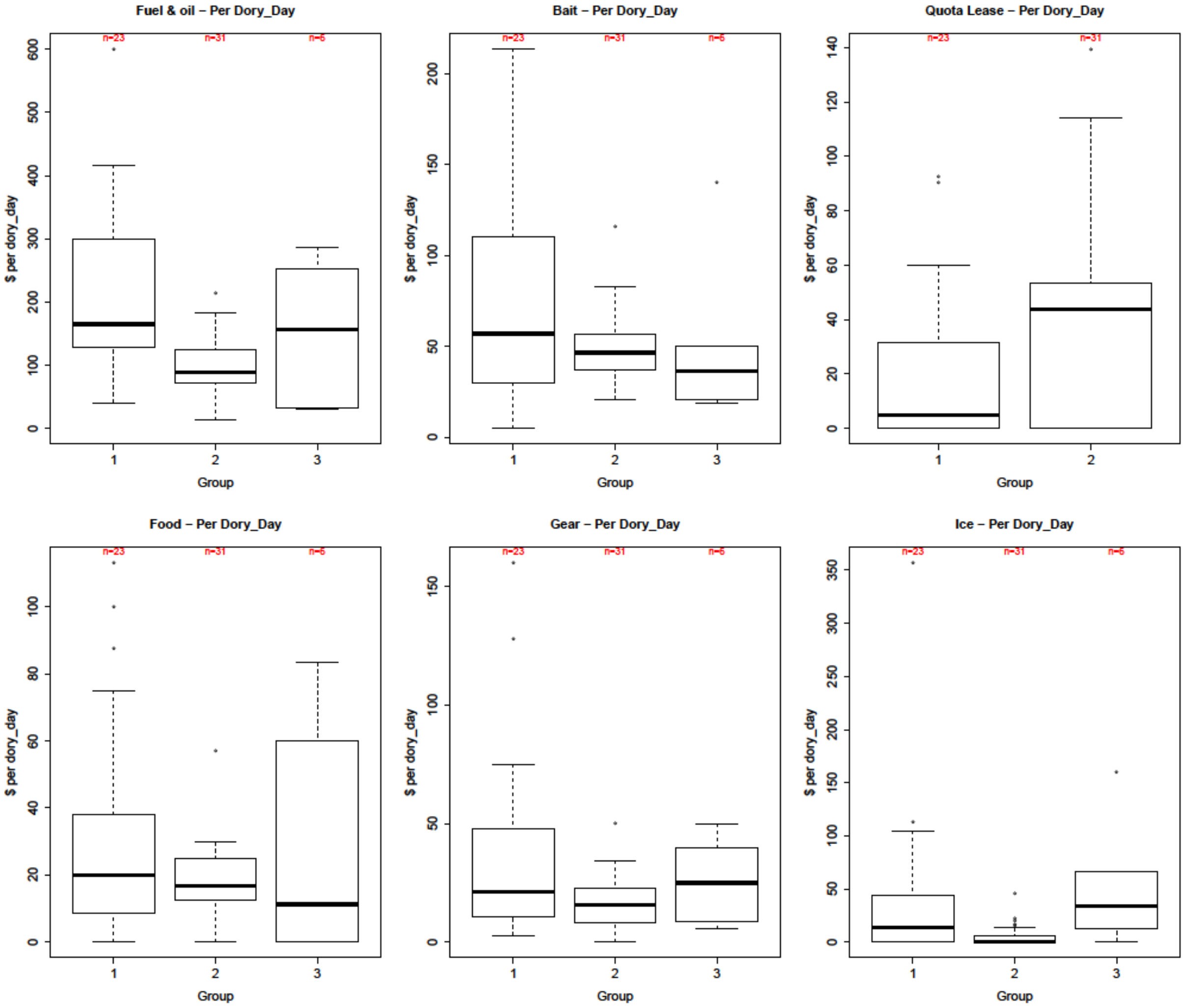
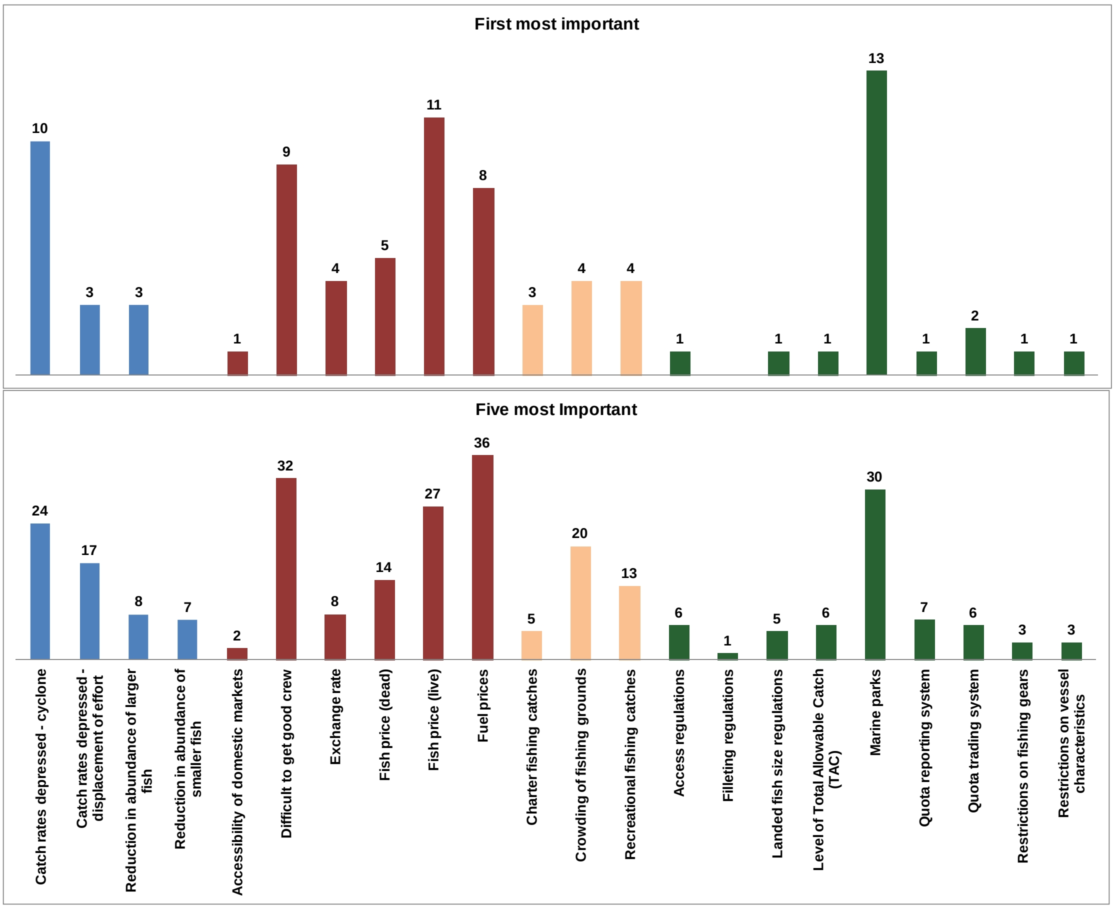


Figure 90 Line Catching Costs per Dory-Day, by Group of Operators

Perceptions


First most important

Five most Important

Figure 91 Most important factors perceived to currently affect profitability in the fishery

When considering the factors cited as one of the 5 most important factors affecting profitability in the fishery, factors belonging to the “Economic drivers” category were cited 43% of times, while factors belonging to the “Management” category were cited 24% of times, and factors belonging to the “Biological” category 20% of times. Individual factors within these categories were cited with variable frequency (see figure below): “fuel prices” were cited 13% of times, followed by “difficulty to get good crew” (11%), “marine parks” (11%), “live fish prices” (10%) and “catch rates depressed following cyclone damage” (8%). Factors relating to the crowding of fishing grounds were also cited a higher number of times, as well as interactions with recreational users and the prices of dead fish.

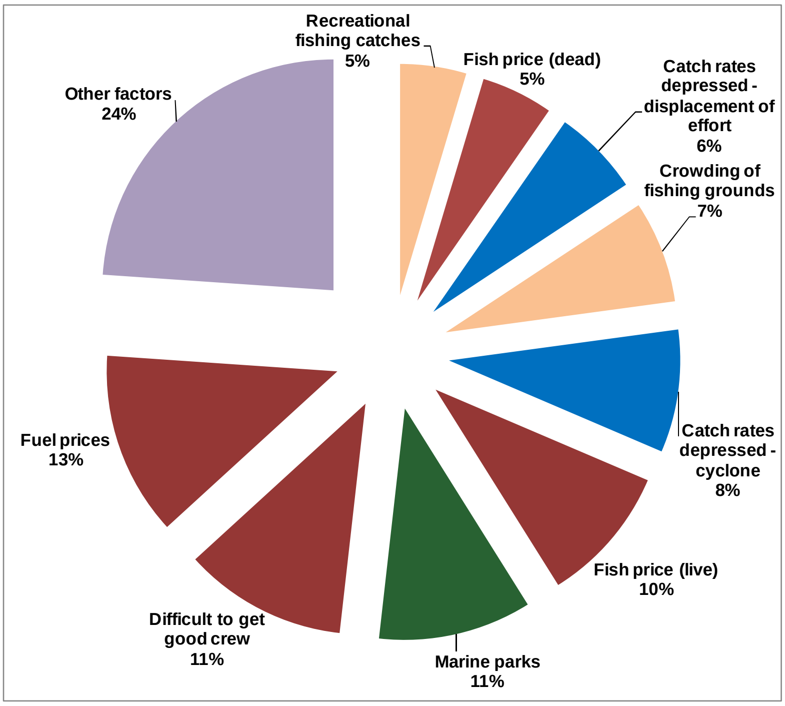


Figure 92 9 top individual factors perceived to affect profitability

Fish prices and price determinants

Figure 9393 presents the normalised nominal monthly ex-vessel prices from the two processors who provided us with time series data, as well as the Hong-Kong import prices for live coral trout for the period January 2004 to December 2011. At first sight, relative changes from one month to the next for the two ex-vessel price series is almost the same, suggesting that these are very similar between the two processors. In addition, relative changes between these ex-vessel prices and the Hong-Kong import prices also follow similar trends. The Hong Kong import price series is relatively smoother. This is likely to be because Hong-Kong imports live coral trout from several countries and handles large volumes of fish which is likely to smooth total supply, and hence average import prices. The strong monthly variations of the two ex-vessel price series highlight the existence of a significant level of price risk for operators in the fishery. In part, this variability has to do with a seasonality effect. Prices rise in December and January and drop in April and May. This seasonal pattern is however difficult to establish across years, suggesting that operators must deal with fairly high volatility in the prices they receive (see below). The ex-vessel price series appear to show a slightly positive long-term trend, although this appears to be quite limited.

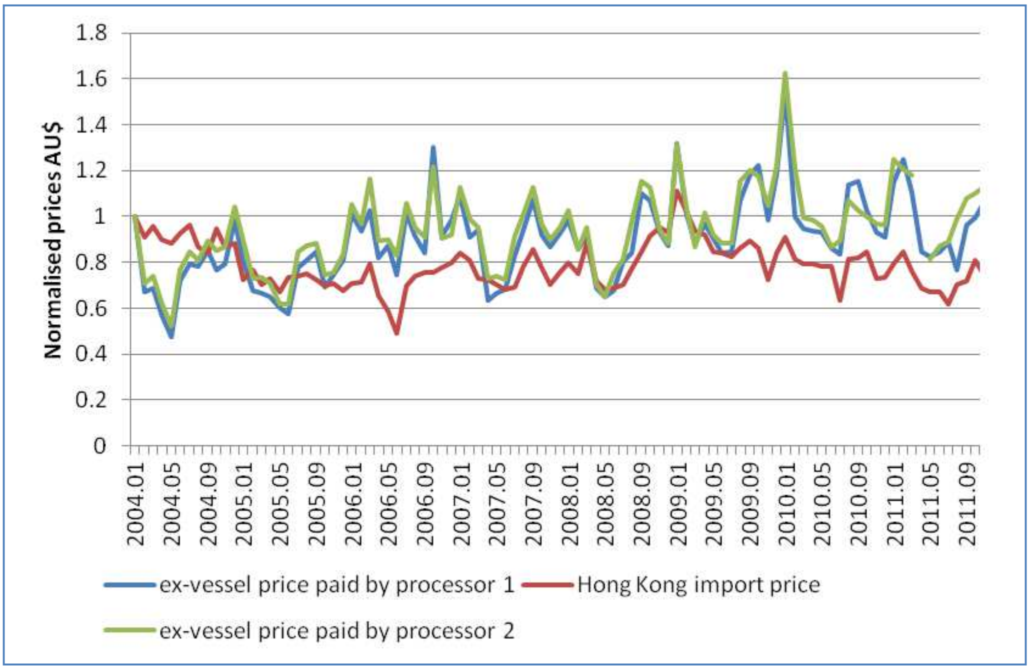
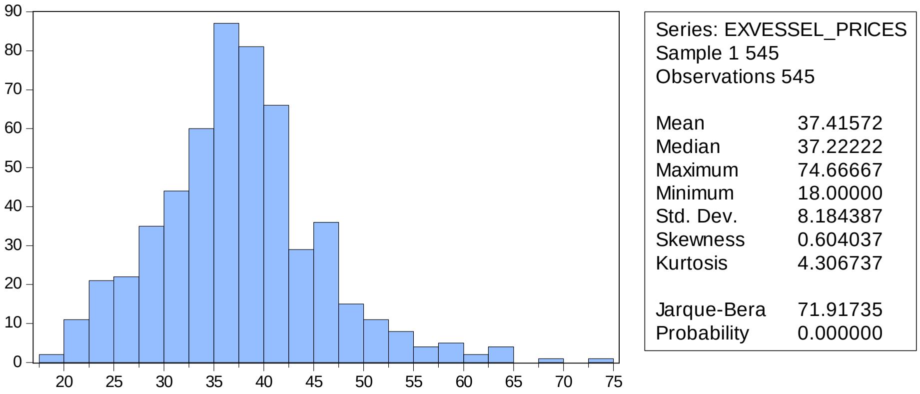


Figure 93 Normalised ex-vessel prices paid by two processors and import prices into Honk Kong, 2004-2011

Results of the co-integration analysis of these time series indicate that ex-vessel prices paid by the two processors, and import prices into Hong Kong, are related, confirming that the prices paid by Hong-Kong buyers have a direct impact on the prices paid to fishing operators by Australian exporters.

Price volatility

A histogram of weekly ex-vessel prices for live CT from 2002 to 2012, together with a range of descriptive statistics, are presented in Figure 9494. On average, weekly ex-vessel prices were AU$37 between 2002 and 2012, although as already indicated, prices displayed large variability over time. The maximum price obtained between 2002 and 2012 was AU$74 and the minimum price AU$18, with standard deviation equal to $8. The coefficient of variation (CV) of weekly prices is 22%, suggesting that weekly ex-vessel prices vary considerably with respect to their mean. Furthermore, the positive value of the skewness value (0.604) suggests that the distribution of weekly prices is slightly skewed to the right. The value of the kurtosis (4.3), larger than 3, implies that there are a large number of prices away from the average. The Jarque-Bera test rejects normality at the 1% significance level. The two latter results are further evidence that ex-vessel live CT prices have been subject to relatively high levels of volatility over the 2002-2012 period.



Series: EXVESSEL_PRICES
Sample 1 545
Observations 545

Mean	37.41572
Median	37.22222
Maximum	74.66667
Minimum	18.00000
Std. Dev.	8.184387
Skewness	0.604037
Kurtosis	4.306737
Jarque-Bera	71.91735
Probability	0.000000

Figure 94 Variability in ex-vessel prices observed over the 2002-2012 period

A more detailed picture of price volatility is given by plotting the divergence of prices from a 20 week moving average against the normalised ex-vessel weekly prices (Figure 95). As illustrated by the linear trend line in this figure, a positive trend exists in normalised ex-vessel weekly prices throughout the time period. However, weekly prices are highly variable between time periods with the highest spikes taking place around January, the largest being observed during years 2002, 2003 and 2010.

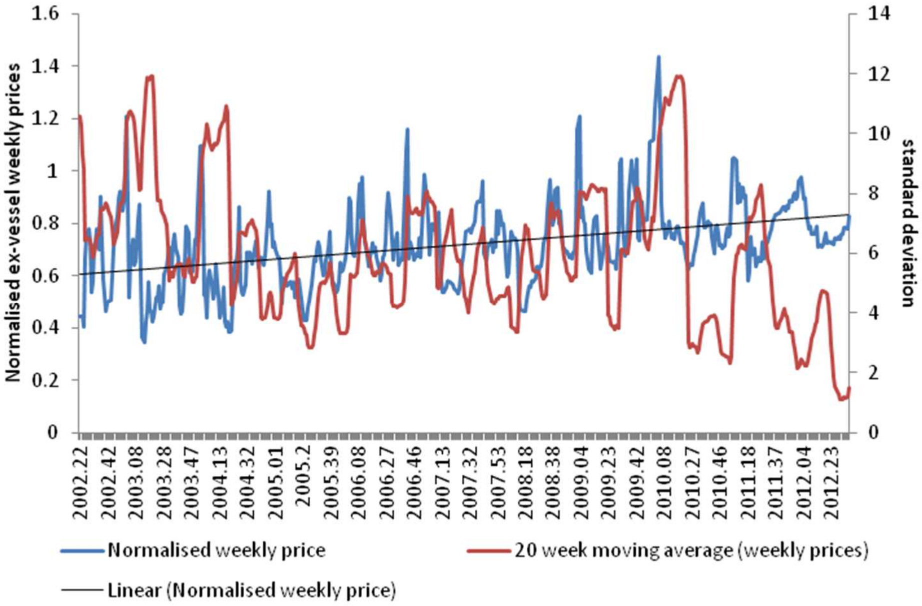


Figure 95 Normalized ex-vessel weekly prices and 20-week moving average of ex-vessel weekly prices (linear projection of normalized ex-vessel weekly prices added)

The 20 week moving average smooths out short term fluctuations and highlights longer term trends. Overall, the deviation between current weekly prices and their 20-week moving average indicates that variation of ex-vessel prices from their mean has declined over time. This decline in the variability of fish prices may be due to a consolidation in the number of processors buying live fish, which was pointed to us in a number of interviews as an important change in the industry over the last decade. Fishing operators would thus entertain more regular business relationships with single processors, rather than looking around for buyers paying higher prices, leading to more stable prices.

Figure 96 illustrates changes in the standard deviation from their mean of weekly ex-vessel prices for CT over the same period of time. This shows that price volatility itself has fluctuated quite significantly from year to year. In the period covered by the data, years 2002-2004 and 2010 were the years that seemed to exhibit the highest annual variability in prices, while the lowest levels of price variability were observed in 2004-06 and 2011-12.

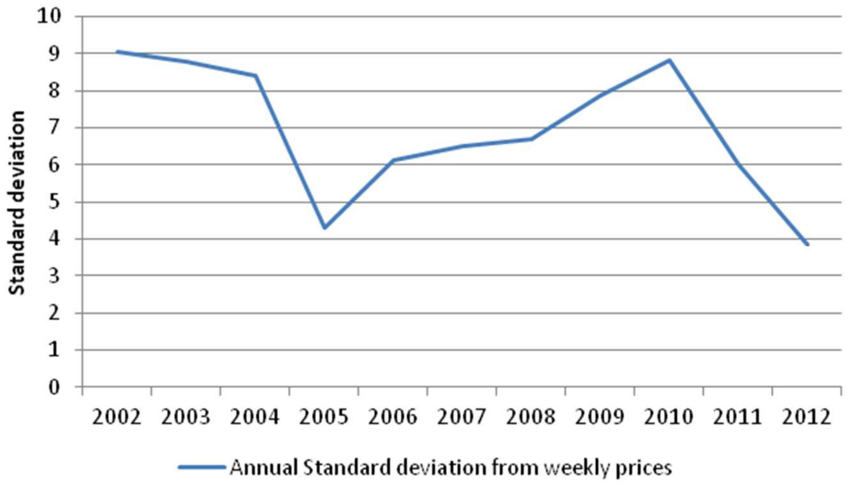


Figure 96 change in the standard deviation of weekly prices between years, 2002-2012

Analysis of the drivers of price fluctuations

Figure 97 illustrates index changes in the Australian Dollar (AUD) to Hong-Kong Dollar (HKD) exchange rate, as well as in live coral trout import prices into Hong Kong in HKD and AUD. The Australian dollar has become stronger over time against the Hong Kong dollar (with the exception of the end of 2008 and beginning of 2009, during the Global Financial Crisis). As a result, live coral trout import prices have become more expensive for buyers when converted in HKD (purple line), while from an Australian exporter perspective (AUD, red line), export prices have declined.

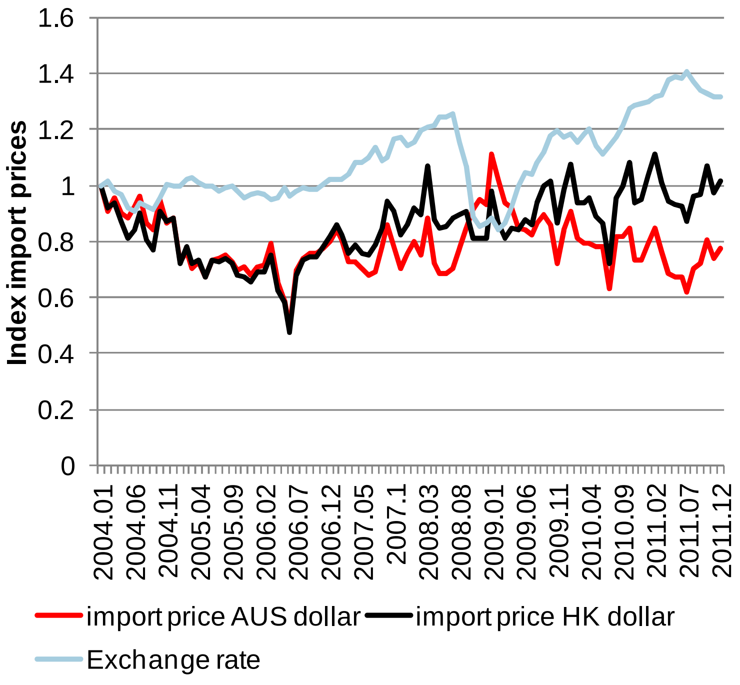


Figure 97 Hong-Kong import price indices for live CT: AUD, KD and AUD/HKD exchange rate, 2004-2011

Figure 98 98 presents the import price indices for live CT into the Hong-Kong market from the main exporting countries (Australia, Indonesia, Malaysia and the Philippines), over the 2004-2011 period. Prices paid for the

Australian product appear systematically higher, but also more volatile, compared to the prices obtained by exporters from the other three main countries.

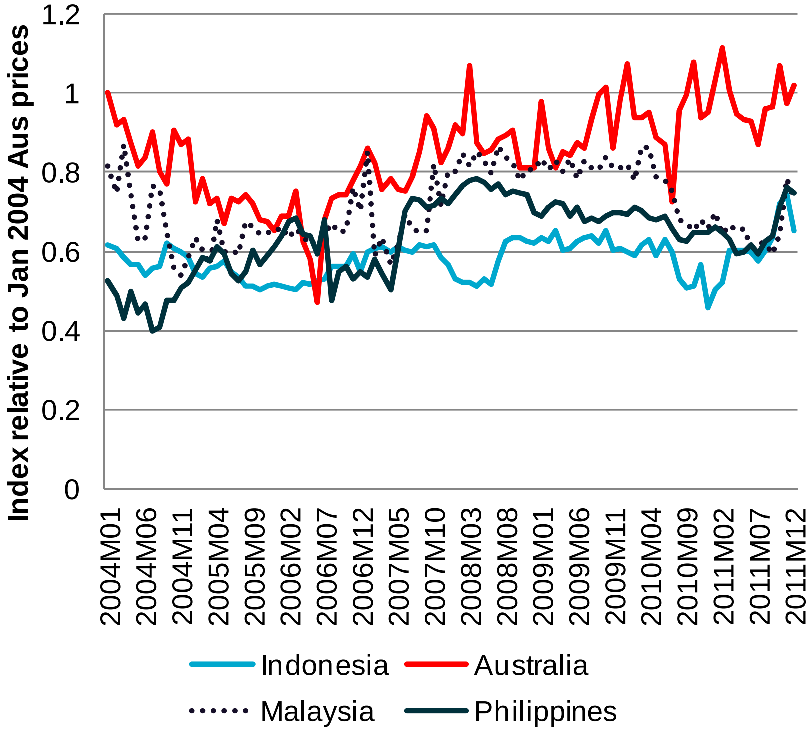


Figure 98 Import prices indices for imported CT live to Hong-Kong from different exporting countries

The results of the co-integration analysis carried out considering the import price series from these four countries seem to indicate that coral trout from Australia does not compete with coral trout exported from Indonesia, Philippines, and Malaysia. Therefore, changes in exports from these countries to Hong Kong should not directly impact the prices received by Australian producers, who receive the highest prices on the Hong Kong market. This suggests that Australian coral trout is sought by buyers that are prepared to pay higher prices, indicating a higher status of these fish as compared to live CT from other countries. On the other hand, analyses also indicated that Malaysia and the Philippines might be competing in the same coral trout market segment in Hong Kong, while Indonesian product, with the lowest price, does not compete with any other product.

Co-integration analysis of live coral trout price time series

The Johansen co-integration test requires the series analysed to be non-stationary. We used the Augmented Dickey Fuller test (ADF) to test for stationarity of the monthly price series for the two processors and for the Hong-Kong import prices from different countries, for the period from January 2004 to December 2011 (96 observations). The large degree of volatility in the price series caused high levels of variability between months; this resulted in the ADF test indicating that the price series were stationary. To deal with this problem, we aggregated the data to be bimonthly (49 observations). This allowed reducing the variability of the time series. The ADF test applied to this bimonthly data indicated that the prices of interest were non-stationary in levels and stationary in first differences at the 5% significance level (Table 27).

Table 27 Unit root tests (Augmented Dickey Fuller) of bimonthly logged nominal ex-vessel prices from two processors, and Hong Kong import prices for live coral trout from Australia, Malaysia, Indonesia and Philippines, Jan. 2004 to December 2011 (n=49 observations)

Prices	Level		First Differences	
	Constant	None	Constant	None
Ex-vessel Proc. 1 (AU$)	-1.375(5)	-1.723 (5)	-7.604* (4)	-7.461* (4)
Ex-vessel Proc. 2 (AU$)	-1.500 (5)	-1.092 (5)	-7.212* (4)	-7.094* (4)
Australian imports (AU$)	-2.714 (2)***	-0.500 (0)	-5.993* (1)	-6.044* (1)
Australian imports (HK$)	-2.302 (0)	0.122 (1)	-8.767* (0)	-8.860* (0)
Malaysian imports (HK$)	-2.518 (0)	-0.262 (0)	-8.116* (0)	-8.198* (0)
Indonesian imports (HK$)	-2.651*** (0)	0.079 (0)	-7.159* (0)	-7.231* (0)
Philippines imports (HK$)	-2.017 (0)	0.147 (0)	-7.504* (0)	-7.541* (0)

The values in parentheses indicate the number of lags; Prices are in Australian dollars per kg; *Indicates significance at the 1% significance level; ** 5% indicates significance at the 5% level, ***indicates significance at the 10% level.

Price relationships between ex-vessel prices paid by two Australian processors and Hong Kong import prices were investigated in two steps. First, the bi-variate Johansen co-integration test was used to investigate the relationship between two prices at a time. The results from all the bi-variate co-integration tests for the existence of relations between the ex-vessel prices paid by the two processors, and the Hong-Kong import prices (Table 28) reject the null hypothesis of lack of a co-integration vector with rank = 0, at the 5% significance level or more depending on the bi-variate relation considered. The hypothesis that there are two co-integrating vectors is rejected for all bi-variate relationships tested. For all the pairwise relationships tested, the results indicate that ex-vessel prices paid by the two processors, and import prices into Hong Kong, are related.

Second, a multivariate test was undertaken including the three price series of interest (Table 29). The results indicated at least two co-integration vectors in the multivariate system. The results suggest the ex-vessel prices paid by the two processors and import prices into Hong Kong are related, such that the prices paid by buyers in Hong Kong will have direct impact on the prices received by producers in Australia, concurring with the bivariate tests.

Table 28 Results of the bi-variate Johansen co-integration tests for the two processor price series and the Hong-Kong import price series

	Null Hypothesis[a]			
	Rank (ρ) = 0		Rank (ρ) ≤ 1	
Ln Nominal Prices	Max[b]	Trace[c]	Max[b]	Trace[c]
Proc. 1 / Proc. 2	26.21*	26.29*	0.09	0.09
Proc. 1 / Hong Kong	23.38*	29.63**	6.26	6.26
Proc. 2 / Hong Kong	23.60*	29.66*	6.06	6.06

Results from Akaike; a The null hypothesis is that the number of cointegration relationships is equal to ρ; b maximum eigenvalue test, c Trace test; * Indicates significance at the 1% level, ** indicates significance at the 5% level

Table 29 Results of the multivariate Johansen co-integration test for the two processor price series and the Hong-Kong import price series

Null Hypothesis[a]	Max[b]	95% critical value	Trace[c]	95% critical value
ρ = 0	28.89**	25.82	58.64*	42.92
ρ ≤ 1	23.54**	19.39	29.76**	25.87
ρ ≤ 2	6.22	12.52	6.22	12.52

Results from Akaike; a The null hypothesis is that the number of cointegration relationships is equal to ρ; b maximum eigenvalue test, c Trace test; * Indicates significance at the 1% level, ** indicates significance at the 5% level

Bivariate and multivariate co-integration tests were also used to investigate the potential competition between different countries exporting to the Hong Kong market. If this competition exists and can be detected through simultaneous variations in prices, then changes in supply from one exporter are susceptible of impacting not only the prices this exporter receives, but also the prices received by other exporters to the same market.

Only the bivariate co-integration test between prices for live CT from Malaysia and the Philippines rejected the null hypothesis of no co-integration with rank = 0, at least at the 5% significance level (Table 30). All the other bivariate co-integration relationships tested failed to reject the null hypothesis of no co-integration, even at the 10% significance level. Based on this result, it appears that coral trout from Australia does not compete with coral trout exported from Indonesia, Philippines, and Malaysia. Therefore, there may not be direct impacts on the prices received by Australian producers, of changes in the exports from these other countries to Hong Kong

A multivariate test was undertaken including all the Hong Kong price import series (Australia, Indonesia, Malaysia and Philippines) (Table 31). The results only partially confirmed those obtained from the bivariate co-integration tests. The Trace test indicated that one co-integration vector exists in the multivariate system, agreeing with the result obtained in the bivariate co-integration tests. On the other hand, the maximum eigenvalue test indicated no co-integration vectors in the multivariate system.

Table 30 Bivariate Johansen co-integration test for live CT import prices into the Hong-Kong market

	Null Hypothesis[a]			
	Rank (ρ) = 0		Rank (ρ) ≤ 1	
Ln Nominal Prices	Max[b]	Trace[c]	Max[b]	Trace[c]
Australia / Indonesia	7.991	7.990	0.078	0.078
Australia / Malaysia	3.945	3.962	0.018	0.018
Australia / Philippines	6.501	6.708	0.206	0.206
Indonesia / Malaysia	8.108	8.114	0.006	0.006
Indonesia / Philippines	7.589	7.910	0.321	0.321
Malaysia / Philippines	18.874*	19.028*	0.153	0.153

Results from Akaike; a The null hypothesis is that the number of cointegration relationships is equal to ρ; b maximum eigenvalue test, c Trace test; * Indicates significance at the 1% level, ** indicates significance at the 5% level

Table 31 Multivariate Johansen co-integration test for live CT import prices into the Hong-Kong market

Null Hypothesis[a]	Max[b]	95% critical value	Trace[c]	95% critical value
ρ = 0	29.097	32.118	63.950**	63.876
ρ ≤ 1	18.713	25.823	34.853	42.915
ρ ≤ 2	11.148	19.387	16.140	25.872
ρ ≤ 3	4.993	12.518	4.993	12.518

Results from Akaike; a The null hypothesis is that the number of cointegration relationships is equal to ρ; b maximum eigenvalue test, c Trace test; * Indicates significance at the 1% level, ** indicates significance at the 5% level

Quota trading patterns

RQ effort and landings fell sharply in 2004-05 (Figure 99) following the introduction of TACs and implementation of the GBRMPA Representative Areas Program. The latter increased the area of no-take zones in the GBRMP from <5% to >33% and was accompanied by a statewide fisheries buyback program. Landings have since remained low when compared to the pre-quota era and to-date, the TACs have not been met, so cannot currently be considered to actively constrain the RQ fishery's level of output. The only quota group to have come close is CT in the year 2008-09 when approximately 96% of the TAC was landed. In more recent years two significant cyclone events, Hamish in March 2009 and Yasi in February 2010, have also contributed to a decline in effort and landings across the whole fishery. Historic landings and the TAC (horizontal black dashed line) for each RQ group are shown in Figure 99.

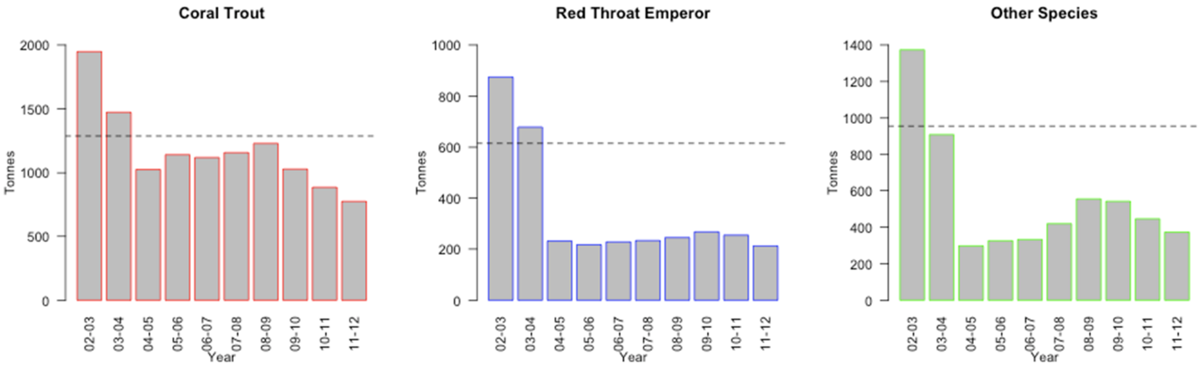


Figure 99 RQ landings over time for CT RTE OS with the TAC shown as a horizontal black line

Market dynamics

The greatest change in number of market participants was seen between 2004-05 and 2005-06 for all quota groups. CT, RTE and OS market participant numbers fell by 21%, 19%, and 13% respectively. This is believed to be mainly a result of license owners selling the entitlements they were awarded in the initial year, and is supported by the exceptionally high volume of permanent trades observed in this period. Permanent trades in the first year were seen to be in the region of 30-35% of the TAC whereas all subsequent years fall between 5-10% of TAC.

A summary of selected market characteristics and how these have evolved over time for the three quota types is set out in Table 32. Three years are reported, the year that ITQs were first introduced into the RQ fishery (2004-05), what is considered to be the 'peak' catch year since the introduction of ITQs (2008-09), and the last year for which complete records are available (2010-11).

Table 32 Summary of quota lease trade markets for each RQ group in the financial years 2004-05, 2008-09, and 2010-11

	Coral Trout			**Other Species**			**Red Throat Emperor**		
	2004-05	**2008-09**	**2010-11**	**2004-05**	**2008-09**	**2010-11**	**2004-05**	**2008-09**	**2010-11**
Account holders	367	322	320	359	375	374	358	351	**354**
Accounts landing fish	165	168	175	194	223	219	158	158	**160**
Number of lease trades	284	730	554	96	210	281	112	357	**377**
Lease Trades (LT) (000 units)	511.98	1,241.83	750.21	237.50	615.14	480.24	134.28	220.13	**244.42**
LT / TAC (%)	0.40	0.96	0.58	0.25	0.64	0.50	0.22	0.36	**0.40**
Permanent Trades (PT) (000 units)	373.97	70.08	95.39	312.90	49.55	49.83	199.62	28.38	**59.17**
PT / TAC (%)	0.29	0.05	0.07	0.33	0.05	0.05	0.32	0.05	**0.10**
% account holders with no LT	0.57	0.20	0.44	0.74	0.43	0.45	0.76	0.60	**0.54**
Gini Coefficient	**0.656**	**0.787**	**0.792**	**0.534**	**0.711**	**0.726**	**0.636**	**0.768**	**0.777**

The proportion of account holders participating in the lease market, the overall volume of quota leased, and the numbers of temporary trades undertaken were lowest in the first year of ITQs for all quota types. For CT these measures of participation and trade peak with landings in 2008-09 before falling to levels more similar to those seen in 2005-06. Measures of lease trade and participation for RTE and OS quota do not peak until a year later in 2009-10, when landings were also highest since the introduction of ITQs for RTE and amongst the highest for OS. These quota groups also differ from CT in the way that trades and levels of participation in their markets remain relatively flat after peaking, rather than falling. The proportion of account holders that participate in the associated lease trade markets are generally lower for OS and RTE categories when compared to CT for all years other than the most recent when CT participation fell close to that of OS (56%). Concentration of quota ownership was tested for by calculating the Gini index for each quota group in each year. The Gini index measures the level of inequality among values, the index is can have a value of between zero and one where zero is perfect equality and one perfect inequality (i.e. where one person owns all quota). The values of the Gini index calculated indicate that the market was relatively concentrated for all groups in 2004-05 and has become increasingly concentrated over time. The rate of concentration was greatest between the first year of ITQs and 2008-09.

Over the whole period observed, annual numbers of individual lease transactions increased by 95%, 193%, and 237% for CT, RTE and OS. The quantity of units leased also increased, by 47%, 82%, and 102% for CT, RTE and OS respectively. These are generally substantially larger increases than the 47% increase in number of trades and 60% increase in volume of trades seen over a comparable period of time in the Tasmanian rock lobster fishery (van Putten et al 2011b). As the total quantity of units leased (kg) increased proportionally less than the number of lease trades, the average size of these trades has fallen over time and by 2010-11 average CT lease trades were 25% smaller than in 2004-05, RTE 38%, and OS 40%.

Changes in the distribution of quota account types

Proportional ownership and use of CT quota by the alternative groups of quota accounts is illustrated in Figure 100. At the group level investors have consistently owned the greatest proportion of quota for the whole period observed (536,643 units in 2010-11), whilst lease dependent fishers have accounted for the greatest proportion of landings (606 tonnes in 2010-11). The role of investors as ‘owners’ and lease dependent fishers as ‘catchers’ has been consistently developing over time with investor holdings increasing from 10% of the CT TAC in 2004-05 to 42% in 2010-11, and proportion of landings CT taken by lease dependent fishers going from 40%

in 2004-05 to 69% in 2010-11. The role of quota redistributors that also land over one tonne of CT per year has diminished, both in terms of ownership and use, with the proportion of landings taken by this group falling sharply from 37% to 10%, almost exactly the same amount lease dependent landings have increased by. Ownership of quota by redistributors that landed less than one tonne of CT increased and then decreased as landings did the same.

Of the 367 businesses present in the first year of ITQs 176 of these were seen to still be present in some form by 2010-11. A significant proportion (38%) of businesses was inactive in 2004-05, meaning that quota owners neither leased nor caught any part of their quota during that year. This proportion was still 24% of the total in 2010-11, but decreased to 14% in 2008-09. Of the 139 inactive businesses seen in 2004-05, 103 left the system by 2010-11 (these businesses could be assumed to have sold out), 20 were still inactive, 3 had become independent (indicating that they had started fishing on their quota), 8 had become investors (so were now leasing their quota out), and 2 had become quota redistributors<1t (so were now leasing quota in and out, and catching CT). The 46 accounts classified as inactive in 2008-09 held a total of 33,787 CT quota units (~3% of TAC) (range of 0 to 12,292)

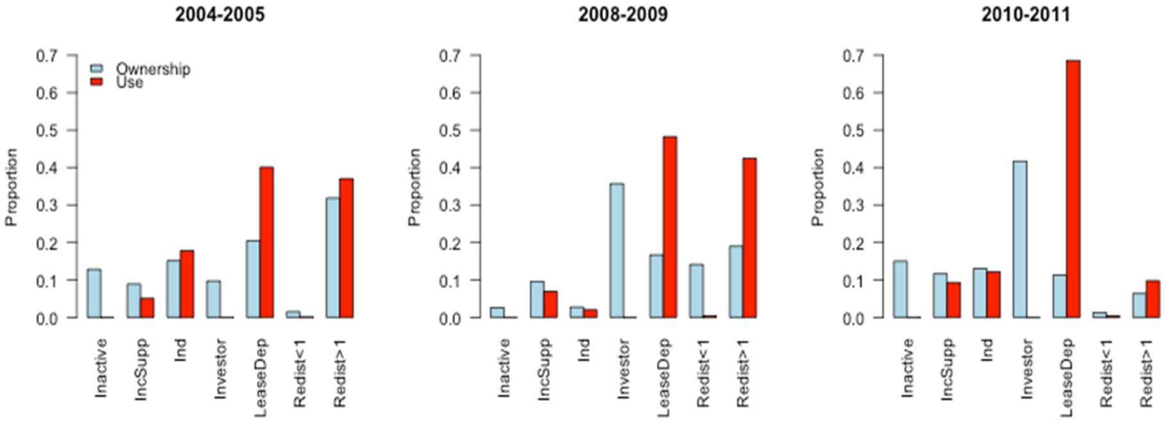


Figure 100 Evolution of CT quota ownership and use for alternative typologies as a proportion of the total (SEWPaC holdings excluded)

The number of independent operators fell as CT fishery conditions were such that the TAC was nearly taken in 2008-09, but once again increased as the gap between total fishery catches and the TAC increased. The quantity of account holders deemed to be inactive (use = 0, lease in/out = 0) almost doubled over the period observed from 46 in 2008-09 to 75 in 2010-11, however the volume of quota owned by this group increased sixfold from just under 33 tonnes in 2008-09 to almost 193 tonnes in 20010-11, such that in 2010-11 15% of the TAC for CT was not fished or traded.

Network analysis results

The plots in Figure 101 depict the CT lease trade market network in each financial year, and how it has changed over time. The circular nodes each represent an individual quota account that held or traded CT in that year. The lines joining nodes, edges, represent the existence of a direct lease trading relationship between those quota account holders in that financial year. The size of connected nodes reflects the total volume of trade it is involved in over the year in terms of number of quota units traded (both in and out). The completely unconnected nodes that sit at the bottom of each network are the quota holders that do not undertake any lease trade activity in that year, and as such their size is not related to level of trade. These businesses are a combination of those classified as either independent or inactive.

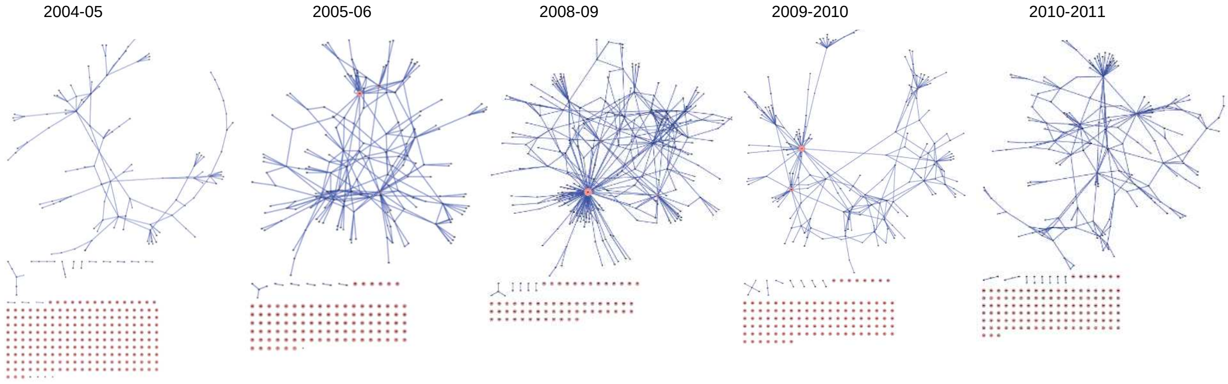


Figure 101 CT quota lease trade network maps

The network maps clearly demonstrate how CT lease market connections have evolved; with high numbers of unconnected non-traders in the first year (2004-05) the network then builds up, incorporating more and more participants, to a peak in 2008-09 before reverting to some extent by 2010-11.

Quota trading patterns analysis

Social network analysis (Scott 1991; Wasserman and Faust 1994; Haythornthwaite 1996) is the mapping and quantification of relationships between individual entities. Based upon the principals of network theory (Strogatz 2001; Barabási 2005), network maps and statistical measures are used to illustrate and mathematically assess a network’s properties and indicate how these may have changed over time. In context of the CRFFF, network analysis has been used to formally identify the existence and nature of trading relationships between anonymous account holders in the market for RQ quota, specifically short-term lease trades for CT. We used the open source platform Cytoscape (www.cytoscape.org/) to visualize and analyze the networks but a number of alternatives, such as the SNA package in R, are also available.

This methodology has been widely applied and used to analyze social networks such as the world wide web and citations in research (Barabási 2005). In a fisheries context the significance of social networks has been established with respect to compliance (Hatcher, Jaffry et al. 2000), viability during resource scarcity (Ramirez-Sanchez and Pinkerton 2009), and relationships between fish traders (Weisbuch, Kirman et al. 2000). To the best of our knowledge a study of the Tasmanian rock lobster ITQ market (van Putten, Hamon et al. 2011) is the only previous example of this technique being used to assess such markets in the context of fisheries. This provides some useful points of reference, allowing comparisons to be made between a number of key indicators.

The structure of networks, the associated descriptive statistics, and how these all change over time indicate how information is likely to pass through networks, the ability of one business entity to interact with another, and the relative degree of control each individual may exert over exchanges in the network. Individual entities within a network are typically referred to as nodes and connections between these nodes are called edges. From a theoretical perspective, the structural distribution of these edges, can range from being either purely random to completely regular. Early work in the area assumed random connectivity (Erdős and Rényi 1959) but more recently it has been shown that real life networks, especially those in the social / economic domain often display markedly non-random, so called “scale-free”, properties (Barabási and Albert 1999; Barabási 2009).

The number of other nodes any single node is directly connected with is its degree d. A network is said to be scale-free when its degree distribution, conforms to that of a power distribution (Barabási and Albert 1999).

$$P(d)=cd^{-\gamma}$$

where $P(d)$ is the probability P that a node has degree d, c is a normalizing constant, and γ is an unknown parameter. For $\gamma < 3$ the average degree distribution is considered not representative and the network is deemed to be scale-free (Barabási 2009). Under a power distribution the frequency of very high and very low degree distribution nodes is higher than would be expected had the network formed purely at random (Jackson 2009) and indicates the prominence of high degree nodes acting as hubs.

Several additional statistical measures are also used to assess the networks and are computed using the NetworkAnalyser component of Cytoscape (Assenov et al. 2008). The clustering coefficient is a measure of local cohesiveness and for directed networks

$$C_i = e_i / (d_i (d_i - 1))$$

where d_i is the number of neighbors of i and e_i is the number of connected pairs between all neighbors of i and $0 < C_i < 1$. The average clustering coefficient gives an overall indication of the level of clustering in the network as a whole and it has been shown that real world social networks can display high levels of clustering when compared to purely random networks (Watts and Strogatz 1998).

The network diameter indicates the maximum length of shortest paths between two nodes, in terms of the number of edges d between them. The characteristic path length of a network is the average shortest path length between nodes in the network, the shortest path length being $L(i,j)$, where i and j are two separate nodes. A high characteristic path length relative to the number of nodes in the network implies the network is becoming similar to a linear chain whereas a relatively low characteristic path length indicates the network is compact.

Characteristics of the nodes themselves are assessed using measures of closeness centrality and betweenness centrality. The closeness centrality of a node is a measure of how fast information can spread between connected nodes in the network (Newman 2003) and is calculated in Cytoscape as the reciprocal of its average shortest path length.

$$Cc(i) = 1 / avg(L(i,j))$$

where $L(i,j)$ is the length of the shortest path between two nodes i and j, and $0<Cc<1$ and zero indicates the node is isolated. The betweenness centrality of a node provides an indication of the amount of control exerted by this individual node on interactions in the network, Cytoscape uses the Brandes (2001) algorithm to calculate this:

$$Cb(i) = \sum j \neq I \neq k \, (\sigma jk(i) / \sigma jk)$$

where j and k are different nodes to i, σjk is the number of shortest paths from j to k, and $\sigma jk(i)$ the number of shortest paths from j to k that i lies on (Brandes 2001).

In the context of trade networks, properties such as those described in this section bear direct relation with the ability of information to spread between groups, and have implications for overall market efficiency.

Additional results from the network analysis

In a directed network such as the one considered here, where relationships are not necessarily symmetrical (i.e. trader A may lease to trader B but B does not lease to A), the degree distribution can be assessed in terms of either its inbound connections (in-degree) or its outbound connections (out-degree) as the numbers for each will vary. Degree distributions of both forms are plotted on a log scale in Figure 102 for the CT lease trade network and the parameter values for the power law (equation 1) are reported in Table 33.

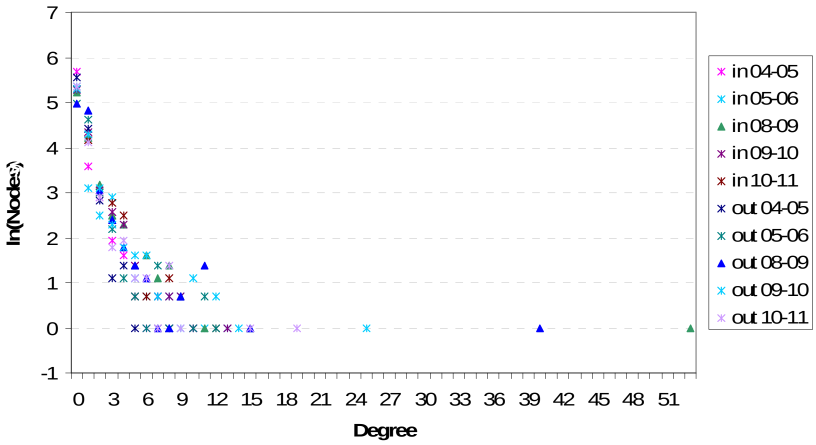


Figure 102 Annual level degree distributions (log scale, in- and out-) for the CT lease trade market

The general shape of the degree distributions in Figure 102 is similar across all years and relationship directions. This illustrates that the majority of market participants were connected to relatively few (one or less) other participants for the years observed. In 2004-05 80% of account holders had an in-degree of zero, implying no inbound connections, and 70% had out-degree measures of zero. In the same period 10% and 22% of account holder respectively had in- and out-degree measures of only one (indicating lease trading relationships with only one other account holder). Account holders with no lease trading relationships (i.e. degree distribution of zero) always formed the largest group in each year. The proportion of account holders with degree distributions of zero (for both in and out) were observed to be at their smallest in 08-09 when they accounted for 58% and 45% of account holders respectively, implying that nearly half the account holders leased quota in, while more than half the account holders leased quota out in that year.

All of the degree distributions satisfy the power-law (Table 33), indicating that all the networks have scale-free properties. The change in the network's nature can also be clearly seen in these indicators, with the γ coefficient being lowest in the high trade year indicating that hub type components play a greater role in that year (also visible in Figure 102102). Results for the initial year may be harder to interpret as the high levels of permanent trading that occurred concurrently in this and the following year is likely to have confounded the measure for these periods.

Table 33 Power law values for CT lease trade degree distributions

	Coefficient	2004-5	2008-9	2010-11
In-degree	*a*	43.572	41.968	70.603
	γ	-1.747	-1.211	-1.719
	correlation	0.979	0.994	0.989
	R^2	0.937	0.853	0.891
Out-degree	*a*	65.989	44.432	42.082
	γ	-2.224	-1.339	-1.453
	correlation	0.999	0.972	0.993
	R^2	0.932	0.762	0.870

The major differences between degree distributions in Figure 102 are seen in the size of the distribution's tail each year. In its initial years (2004-05 and 2005-06) the network has relatively short tails, with the maximum number of trading relationships any one market participant had being 10 in 2004-05 and 14 in 2005-06 (both out-degree). By 2008-09 (solid triangular points) the maximum had increased to 53 and 40 (for in- and out-degree respectively), the highest levels observed in any period, resulting in much fatter tails. In 2009-10 and 2010-11 the maximum number of inward oriented trading relationships dropped to 13 and 12 respectively. Outward oriented relationships dropped to 25 and 19 respectively.

The network clustering coefficient is consistently close to zero, as in the Tasmanian rock lobster (RL) case (van Putten et al. 2011b) and indicates low levels of clustering at the network level. This is to be expected in a market where agents trade to maximize profit, there is heterogeneity in preferences / utilities derived from owning / leasing quota and lack of concentration of ownership of quota in only a few agents. Measures of network diameter were generally lower in the CT market (from 3 to 8) when compared to values observed in Rock Lobster study (4 to 11). The peak of 8 occurs in 2008-09 and the value subsequently falls to 6 in 2010-11. This indicates a relatively less complex network and more direct routes between the furthest apart agents in the market. These differences with the Tasmanian rock lobster case are possibly related to the fact that rules regarding quota ownership and trade differ between the two fisheries, with QLD regulations allowing for broker-type activity to develop, as well as concentration of ownership. (The Tasmanian rock lobster fishery has restrictions on the ownership of quota.)

Not accounting for the initial year (2004-05), due to the relatively small number of nodes taking part in the market, the characteristic path length of the network has steadily fallen over time, from 3.37 in 2005-06 to 2.32 in 2010-11, indicating that the average trading connection between any two agents fell in this period. The initial increase from 1.45 to 3.37 between 2004-05 and 2005-06 is likely to be a result of the increase in the number of market participants over the same period, in the absence of broker type nodes that reduce the average path length between nodes. A similar magnitude increase in the characteristic path length was observed in the RL fishery and attributed to increasing numbers of quota owners having high number of connections.

Figure 103 plots the proportion of account holders with centrality values greater than zero over time. The proportion of individuals with a closeness centrality greater than zero in the CT market (Figure 103) is initially much higher than that observed for RL, but steadily decreases over time, which would indicate a fragmentation of the network into sub-components. This may be regionally defined, in relation to spatial constraints. The betweenness centrality for CT slightly increased in 2008-09 but then fell back close to its initial level, a level comparable to that observed in early years of RL quota trading.

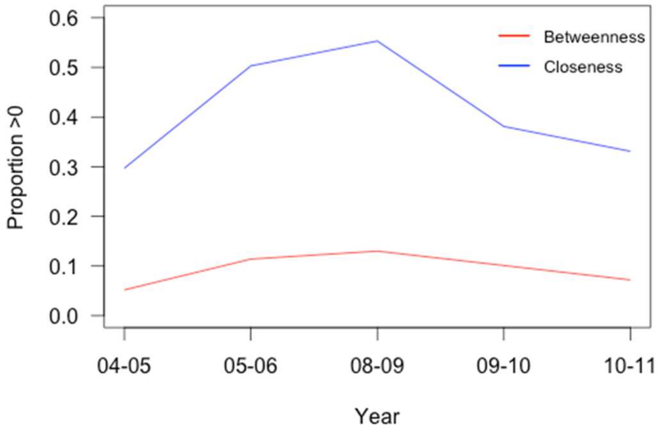


Figure 103 Proportion of nodes with betweenness and closeness centrality >0 for the CT lease market

From inception up to the 2008-09 peak in CT catch, network indicators for the CT ITQ component of the CRFFF fishery are generally consistent with those observed in the Tasmanian rock lobster fishery (van Putten et al. 2011b), and with those of a growing and maturing marketplace. As the fishery came closer to reaching its TAC temporary trade activity increased substantially and the role of well connected "hub" nodes grew. Yet, despite the networks all displaying scale-free properties, the typically assumed trend towards increasing scalefreeness as networks evolve (Barabási 2005) is not consistently observed in this case, with the opposite actually being observed to some degree as the gap between total landings and TAC subsequently grew between 2008-09 and 2010-11.

The observation that after the peak of 2008-09 the γ coefficient for in-degree distribution was seen to increase again, back to 2004-05 levels, also suggests a strong reduction in the role of well connected nodes as leasers in of quota from multiple other traders. Whilst the CT lease trade network has reverted to some degree since 2008-09, this has not occurred in a symmetrical manner as certain features of the peak period remain. However, and interestingly, the out-degree γ coefficient remained close to the level observed in 2008-09, suggesting that their role as a supplier of quota (with many outward connections) to the network has persisted. One possible explanation for this is that over time such account holders have undertaken permanent transfers to acquire sufficient quota that their need to lease quota in just to satisfy demand has diminished, especially as demand for CT quota is far lower in 2010-11. Concentration in the ownership of quota was observed for CT, lending weight to this explanation. This points to a need for permanent and temporary trades to be considered jointly in the analysis.

The other striking result is the proportion of nodes that are disconnected. The disconnected nodes seen in Figure 101 are a combination of businesses deemed either inactive or independent in Figure 100 and the pattern of disconnected nodes becoming less prevalent in better years is linked with the general increase in the level of lease market participation seen at that time (Table 32). For the independent component, when catches were higher, businesses whose quota holdings had previously been sufficient to cover their catches, and allow them to exist outside of the lease market, needed to source additional quota and consequently entered the market in order to lease it in (becoming ‘lease dependent’ in the process). This situation was also reflected in the inactive component whose numbers were substantially lower in the peak period (falling from 139 in 2004-05 to 13 in 2008-09) as they either sold out (99), began leasing their quota out (19 became investors), fished it themselves (4 became independent), fished it and leased it out (2 became income supplementers), fished it and leased in (1 became lease dependent), or leased in and leased out (1 became a quota redistributor<1t. These numbers were similar by 2010-11, the main exception being those that were investors falling by half with most of these having sold out.

The observation that some degree of inactivity persisted throughout the whole period (quota holders that did nothing with their quota) is an interesting and somewhat counterintuitive situation. In addition to the opportunity cost of not using it in some way (fish, lease out), the ownership of quota incurs annual fees that are levied independent of whether it is fished. Inactivity also results in the loss of associated catch history, potentially another cost to the account holder should management conditions change. Without more information logical explanations for this situation are that imperfect exchange of information is forming barriers to trade or that the transaction costs associated with leasing out are simply too great and exceed the benefits.

The CRFFF Economic Survey documents that were used in carrying out the surveys

Document	**File name**	**Version**
Interview tracking form	1 - CRFFFEconSurvey - Interview Tracking Form.pdf	16/11/2011
Questionnaire	2 - coral reef fin fish fishery economic questionnaire.pdf	16/11/2011
Interviewer guide	3 - Interviewer guide for CRFFF economic survey with activity tables.pdf	17/11/2011
Maps	4 - Map booklet.pdf	16/11/2011
Participant information form	5 - CRFFFEconSurvey - Participant_Information_Form.pdf	16/11/2011
Participant consent form	6 - CRFFFEconSurvey - Consent_Form.pdf	16/11/2011
Introduction to the survey	7 - Introduction to the survey (for phone contact).pdf	16/11/2011
Consent form for access to accounting data	8 - Accountant authority form.pdf	16/11/2011
Consent form to access DEEDI data summary	9 - Activity Summary Authority Form.pdf	16/11/2011
Agreement of confidentiality for surveyors	10 - Confidentiality agreement for surveyors.pdf	16/11/2011
DEEDI Letter	11 - letter to RQ holders re economic survey.pdf	16/11/2011
Project Flyer	12 - GBR flyer Sept 2011-final.pdf	16/11/2011
Templates of information received by respondents from DEEDI	13 - DEEDI Data Summary template.pdf	16/11/2011
CSIRO Social Science Human Research Ethics Committee Project Completion Ethics Report Form		

B. Operating Instructions for ELFSim 3.0

The code for ELFSim has been ported from VisualBasic to C++, and the MS Visual C++ 6.0 compiler. The code is housed in a publicly accessible Subversion code repository, and software versioning and revision control system maintained and supported by CSIRO. (Access can be obtained from Rich.Little@csiro.au.) The MS Visual C++ 6.0 compiler has been supplanted by the 2008 MS Visual Studio .Net framework, and although some of the project files for the Integrated Development Environment (IDE) (e.g. it uses a *.vcproj instead of a *.dsw) are different, and not backwards compatible, a move to this version is currently underway, with two branches to the repository currently active.

The code is written without a great reliance on MS specific classes, to support any movement of the model to other platforms. One of the only potential legacy issues of the model is the reliance on MS Access databases for input and output. A module called *easyodbc*.cpp is used to access the databases through an odbc connection. All calls to *easyodbc*.cpp in ELFSim are kept in the *readInput*.cpp module, which operates as the read/write interface.

Setting up the databases

The *easyodbc*.cpp connection, and thus model, access the databases through the Windows System DSN (Data Source Name). ELFSim databases are specified in the SystemDSN by accessing the menu:

Windows Control Panel: Administrative Tools: Data Sources (ODBC) or by starting

```
C:\WINDOWS\system32\odbcad32.exe
```

in 64 bit Windows operating system this command is

```
C:\WINDOWS\SysWOW64\odbcad32.exe
```

The ODBC link to ELFSim requires four system data sources as MS Access databases. The Windows data source name (DSN), and corresponding ELFSim MS Access names are:

	DSN	ELFSim MS Access database
1	elf	elf_input.mdb
2	elf_hist	CatchAndEffortR3c.mdb
3	results	elf_results.mdb
4	connect	Connectivity.mdb

Running ELFSim

ELFSim is run from a command line in the local sub-directory in which the executable *ELFSim*.exe resides. There are several arguments that can be passed in running the model, which can be queried by typing the help command:

```
*\ELFSim -help
```

Each simulation must specify which species to include, with at least one species needed to run the model. The flag *–s* is used to specify the species to use.

```
*\ELFSim –s CT
```

for simulations of common coral trout (*Plectropomus leaopardus*)

Or

```
*\ELFSim –s CT –s RTE
```

for simulations of both common coral trout and red throat emperor (*Lethrinus miniatus*).

Once the model is initialised so that all the reefs can support the catches historically taken from them (i.e. there are no extinct reefs) all the historical information needed to repeat a successful initialisation is saved in the elf_results.mdb database. This information consists of:

1. the initial fish density on each reef; and
2. the historical fishing mortalities on each reef.

Flags set at the command line are used to simply repeat a simulation that has already been initialised:

```
*\ELFSim –s CT –i 1 –Fs 1
```

These arguments indicate that the previously saved initial densities `–i 1` and fishing mortalities `–Fs 1` should be used. These data are found in the InitPopCT, InitPopRTE, FishingMortCT, FishingMortRTE tables of the elf_results.mdb database. The simulation will go through the historical period of the model only once starting the projection period if a saved initialisation is flagged for use. The *–run x* flag argument on the command line is used to save results to a new run with the same initialisation set up but potentially different conditions in the projection period.

```
*\ELFSim –s CT –i 1 –Fs 1 –run 2
```

Note that a run will need to have been set up in the elf_input.mdb database, which requires new entries in the tables: Runs, Run Parameters: *, VD_Parameters. There are default parameter values in the tables Defaults (for *Run Parameters* table), Biology (for *Run Parameters: Species Specific* table), AdultMigrationParameters (for *Run Parameters: Adult Migration* table), EffortAllocation (for *Run Parameters: Effort Allocation* table), and QuotaData (for *Run Parameters: QuotaData* table). The field Parameter_ID should link the tables.

Running a Stock Assessment model in ELFSim

The *–assess x* flag argument is used to run an assessment model in ELFSim. Two assessment models have been implemented in ELFSim. The CAB assessment is implemented in ELFSim in the *cabAssessment*.cpp module and the QDAF assessment is implemented in the *DAFAssessment.cpp* module. The interface for the assessment model is in the *ELFSim*.cpp module, which is the main control module for the model. The first call to the assessment model is to read the parameter data in the input database and initialise the data structures:

```
      printf("assessment model %d\n",g_runtimeParms.assessmentModel);
      switch (g_runtimeParms.assessmentModel) {
            case 0:
                  //nothing
                  break;
            case 1:
                  readAssessmentData(0);
                  initialiseCABassessment(0, false); //species 0 being assessed
                  break;
            case 2:
                  readDAFFAssessmentData(0);
```

```
                  initialiseDAFFassessment(0, false);
                  break;
      }
```

This code is called before the main loop for the historical period.

The Boolean argument in calling the assessment initialisation code (e.g `initialiseCABassessment(0, false);`) is used to indicate whether the global data structures used are to be re-initialised (`true`) or initialised (`false`). ELFSim can run through multiple projected replicates from a single initialisation and allocating memory in the data structures should only be done once on the first replicate. All subsequent replicates use the data structures with over-written memory already allocated. This occurs after the main loop for the historical period and requires many variables to be re-initialised.

Re-initialisations for the assessment models that do not require global data structure memory allocation are captured in the code snippet:

```
for (ns = 0; ns < g_runtimeParms.nsims; ns++) {

      if (ns > 0) {
            reinitialise();
            initialiseEAM(true);
            initialiseVDM(true);
            switch (g_runtimeParms.assessmentModel) {
            case 1:
                  initialiseCABassessment(0, true); //species 0 being assessed
                  break;
            case 2:
                  //initialise other assessment model;
                  initialiseDAFFassessment(0, true); //species 0 being assessed
                  break;
            }
      }.
.
.
```

The Boolean flag in

```
initialiseCABassessment(0, true);
```

indicates that the global data structure should be re-initialised, and not allocated with new memory to the data structures. This prevents memory leakage.

ELFSim deletes all previously created assessment files, collects data for catches and CPUE that have been collected historically, and samples the population age and size structure mid-way through each historical year before each projection starts.

The procedures:

```
compileAssessmentData(0, y-1,1);
```

and

```
compileDAFFAssessmentData(0, y-1,1)
```

collect catch and CPUE data that the operating model of ELFSim has generated. The procedures:

```
UVShist(0, y, m, 6); //CT by index 3 (green zone UVS survey)
```

and

```
DAFFUVShist(0, y, m, 6); //CT by index 3 (green zone UVS survey)
```

collect historical data from the historical UVS surveys, for the respective stock assessment models (see below), while the procedures

```
structureLineSurveyHist(0, y, m, 0, 4); //CT by index 3 (fleet 6)
```

and

```
structureDAFFLineSurveyHist(0, y, m, 0, 4);
```

collect historical data from the historical line surveys that operated from 1995-2002.

The assessment model is called at the start of the year once the projection period is entered:

```
switch (g_runtimeParms.assessmentModel) {
      case 1:
            doCABAssessment(0, y-1);
            printf(".... Assessment complete at start of %d\n",y);
            makeDecisionCABAssessment(0,y);
            break;
      case 2:

            doDAFFAssessment(0, y-1);
            printf(".... DAFF Assessment complete at start of %d\n",y);
            makeDecisionDAFFAssessment(0,y);

            break;
}
```

An initial run of the assessment model is performed prior to running the vessel dynamics model, thus using only data generated historically in the operating model.

At the end of the projection year, the catch and CPUE data derived from the vessel dynamics model for that year are compiled and standardised:

```
for (y = yend; y < yendProj; y++) {
      //this if to query to see where the model is when the window is not 
available.
      printf("projection year %d\n",y);
      state = fopen("state.txt","w");
      fprintf(state, "projection year %d\n",y);
      fclose(state);

      if (y > yend) {
            switch (g_runtimeParms.assessmentModel) {
                  case 1:
```

```
                   //requires the year y in which the file is written
                         doCPUEstandardisation(y);
                         //requires the year y-1 in which the data end
                         compileAssessmentData(0, y-1,1);
                         printf(".... Catches compiled until %d\n",y);
                         break;
                   case 2:
                         //requires the year y in which the file is written
                         doDAFFCPUEstandardisation(y);
                         //requires the year y-1 in which the data end
                         compileDAFFAssessmentData(0, y-1,1);
                         printf(".... DAFF Catches compiled until %d\n",y);
                         //initialiseVDM();
                   break;
             }
      }.
.
.
.
```

These are the main interfaces of the ELFSim model with the assessment model.

Assessment model details

The CAB and DAF assessment models have a global data structure that is defined in *globals*.h called `CABassessment_tag` and `DAFFassessment_tag.` The data structure is instantiated in *globals*.cpp as

```
CABassessment_tag g_CABassess;
```

and

```
DAFFassessment_tag g_DAFFassess;
```

These data structures have many properties as arrays and scalars that are initialised in `initialiseCABassessment`, and `initialiseDAFFassessment.` The procedures `_writePIN(sp, year)`, `_writeCTL(sp, year)`, `_writeDAT(sp, year)` all output the contents of the respective data structure in a formatted structure to the files needed by the assessment model.

The convention for function scope in ELFSim is that the underscore "_" indicates that a function has only local scope to the modules. Such functions are instantiated with the `static` keyword like:

```
static int _writeData2File(int sp, int year)
```

The `compileAssessmentData(0, y)` and `compileDAFFAssessmentData(0, y)` procedures collect data from the ELFSim operating model. The main operating model data structures that are used are those carrying the species and reef catches and effort:

`g_Populations[sp][r].ObsReefCatch[f][year][m]`

`g_reefs[r].ObsReefEffort[f][year][m]`

where `sp` is the species (0 CT, 1 RTE), `r` is the reef, `f` is the fleet, `year` and `m` are the year and month. Other data that may be used in the assessment model include length and ages of the catches.

C. Overview of the CAB assessment model implemented in ELFSim

A stock assessment model, called CAB, was implemented in ELFSim for evaluating management strategies. It is based on a multiple sub-population model in which all stocks share a common stock recruitment relationship. The model, which is fitted to data generated by ELFSim, thus attempts to estimate the underlying annual population sizes. The CPUE data used for assessment purposes is derived using a procedure that standardises CPUE across 1 degree spatial cells, vessels, years and months.

CPUE Standardisation

The CPUE standardisation model was written and compiled in the AD Model Builder (Fournier et al. 2012) to create an executable file, which was integrated into operating model, ELFSim. At the conclusion of each simulated calendar year, ELFSim writes an input file, calls the executable and waits for it to finish. Upon completion the output file is read and the years factors used in the CAB stock assessment.

Commercial fleet catch rates were standardised from one degree grid cell-, vessel-, year- and month-specific catch, $C_{y,m,g,v}$, and effort, $E_{y,m,g,v}$, data, by minimizing the objective function:

$$f = \left[\left(e^{\beta_y + \beta_m + \beta_g + \beta_v} E_{y,m,g,v} \right)^{\frac{1}{2}} - \left(C_{y,m,g,v} \right)^{\frac{1}{2}} \right]^2$$

Where β_y is a vector of parameters (one parameter for each year included in the data set), representing a year effect on CPUE, β_m is a vector of parameters (one parameter for each month included in the data set), representing a monthly effect on CPUE, β_g is a vector of parameters (one parameter for each one-degree grid for which a catch and record is available), representing the spatial effect on CPUE, and β_v is a vector of parameters (one parameter for each vessel included in the data set), representing the vessel effect on CPUE.

The year factors from CPUE standardisations of catch and effort data for commercial fleet generated using the fleet dynamics model over the course of an ELFSim projection shown in Figure 104 track the available biomass in the model.

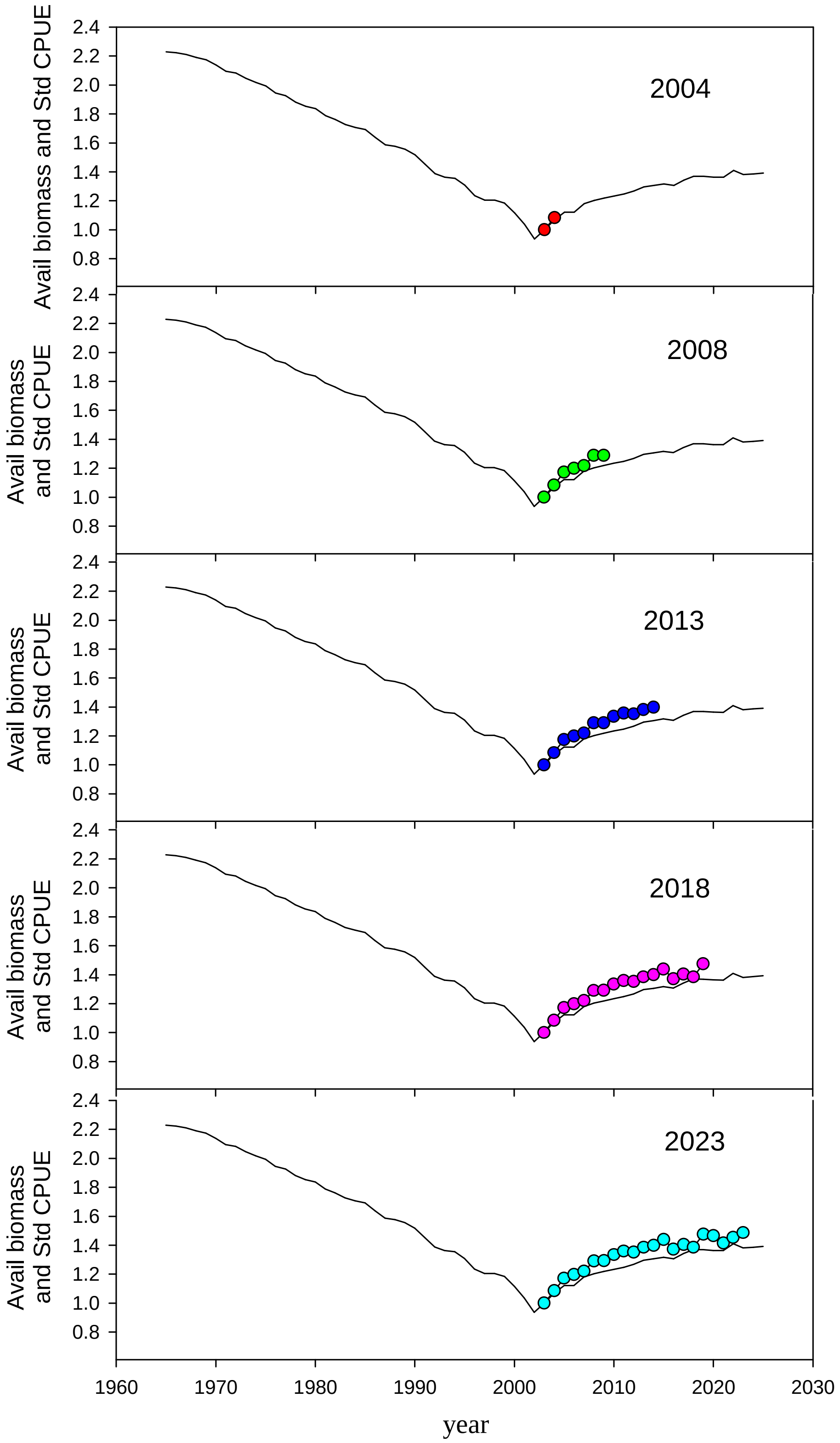


Figure 104 Year factors from CPUE standardisations, β_y (coloured circles) based on data generated for the commercial fleet for five projected years in ELFSim, compared to the available biomass in the ELFSim operating model (black line)

Implementing the CAB Stock Assessment in ELFSim

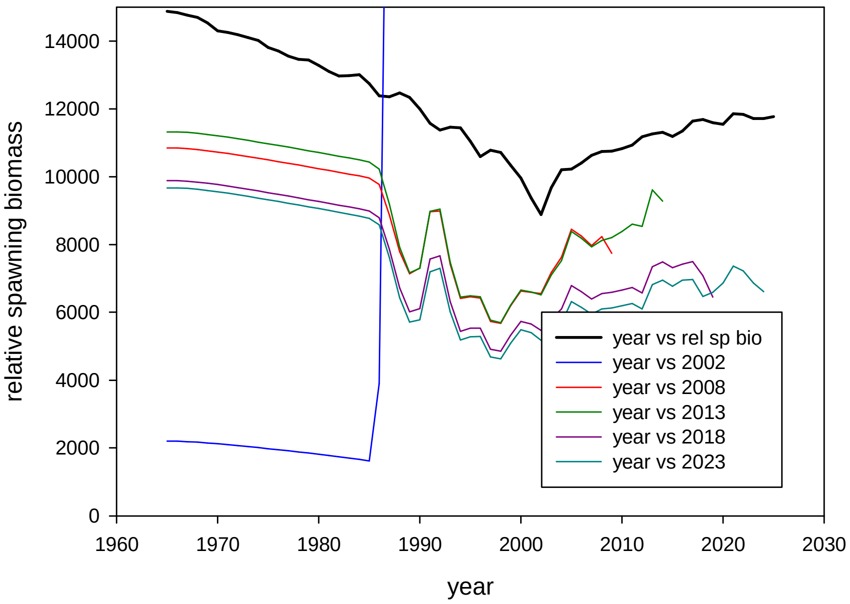
The CAB stock assessment model was also written and compiled in the AD Model Builder (Fournier et al. 2012) to create an executable file, which was integrated into operating model, ELFSim. At the conclusion of each simulated calendar year, after running the CPUE standardisation model ELFSim writes an input file based on sampled data (age, length and CPUE), and calls the executable. Upon completion the output file is read and spawning stock biomass is potentially used for a given decision procedure or harvest control rule.

Below we report the results of the stock assessment model in ELFSim performed annually from 2002 to 2025, and compared them to the operating model results which represent the underlying population the which the stock assessment model is trying to estimate. Age and length samples for the assessment model were taken from the underlying simulation model from 100 randomly chosen “blue” reefs (i.e. reefs currently open to fishing) in each year of the projection period. The operating model, ELFSim, was initialised in such a way that the “blue” and “green” reefs (reefs closed to fishing) were independent. The stock assessment therefore was attempting to measure only the stock state of the “blue” reefs.

Procedures in ELFSim were written to generate data from the operating model for use as input for the assessment model. This included a routine that collected spatially- explicit catch and effort data from the vessel dynamics model to derive a standardized CPUE measure.

Figure 105 (top) shows that the model does not appear to accurately estimate the actual underlying ELFSim biomass. Specifically, the underlying biomass in ELFSim is much higher than the estimated biomass estimated in any of the years reported (2002, 2008, 2013, 2023). When compared to in relative terms however, as spawning biomass relative to pre-exploitation levels (Figure 105, bottom), the assessment model more accurately estimates the underlying simulated biomass in ELFSim.

The fitted standardised CPUE for five projections years (Figure 106) show that the CAB assessment model fit the data from the underlying simulation model. The black dots represent CPUE data from the historical period of ELFSim, whereas the blue dots are the standardised CPUE data from the vessels in the vessel dynamics model in the projection period. The length and age distributions (Figure 107 and 108) sampled from 100 randomly selected “blue” reef showed that stock assessment model was able to fit the sampled data.



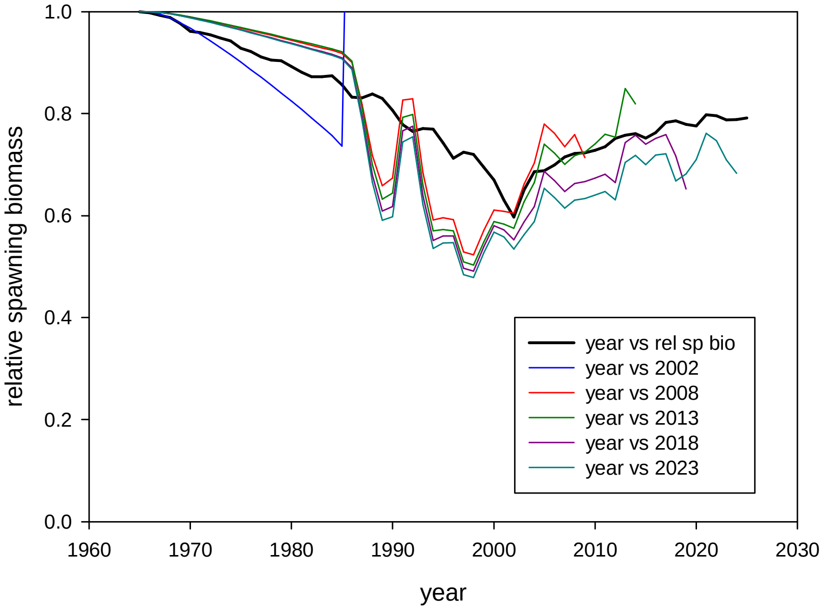


Figure 105 Estimated spawning biomass (top), and estimated spawning biomass relative to pre-exploitation values (bottom) through five projection years compared to the respective "actual" spawning biomass in the ELFSim operating model

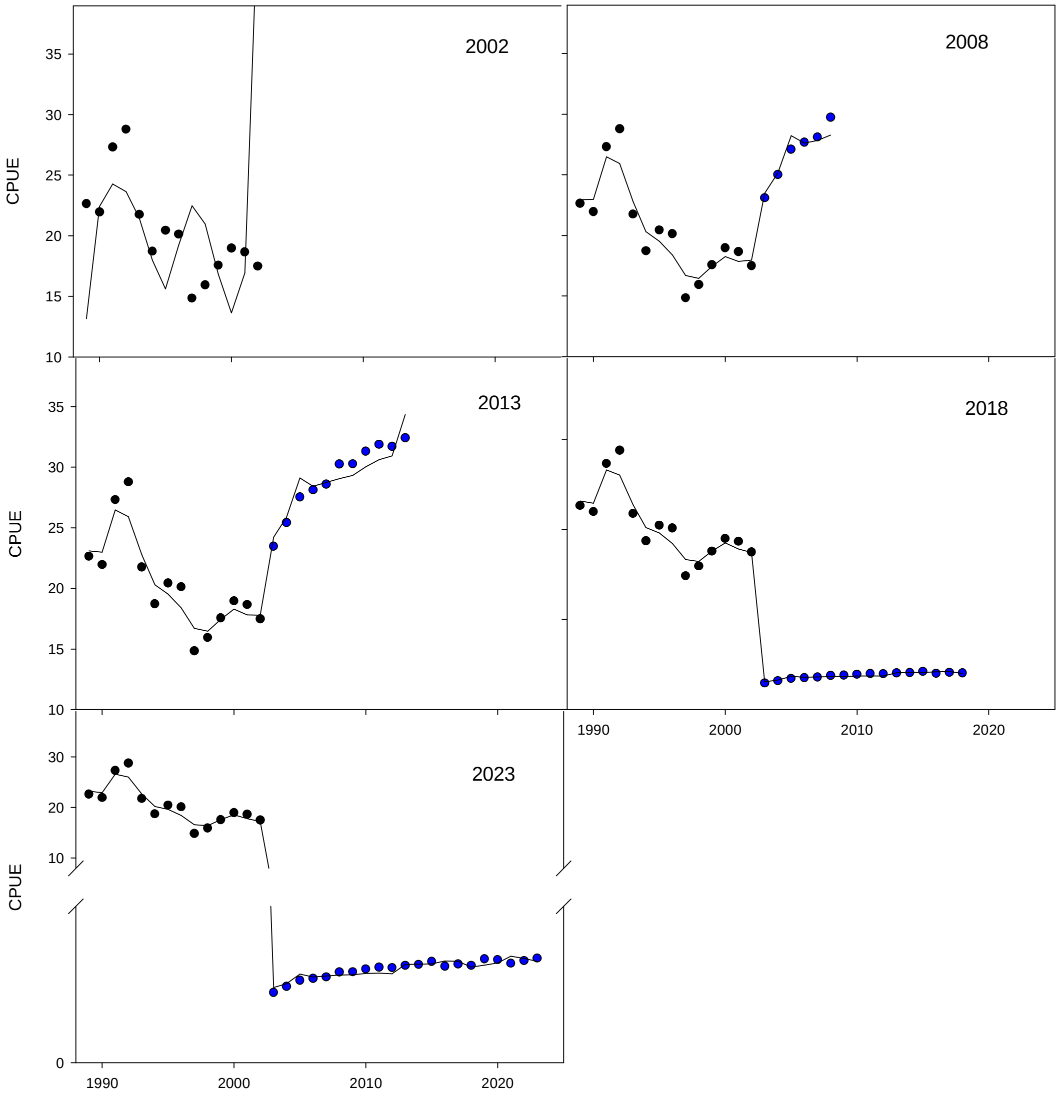


Figure 106 Model-predicted (black line) and observed (points) standardized CPUE derived for five projection years. Black points represent historical CPUE (kg/line/dory day). Blue points represent year factor values from the CPUE standardisation, with units not comparable to historical data

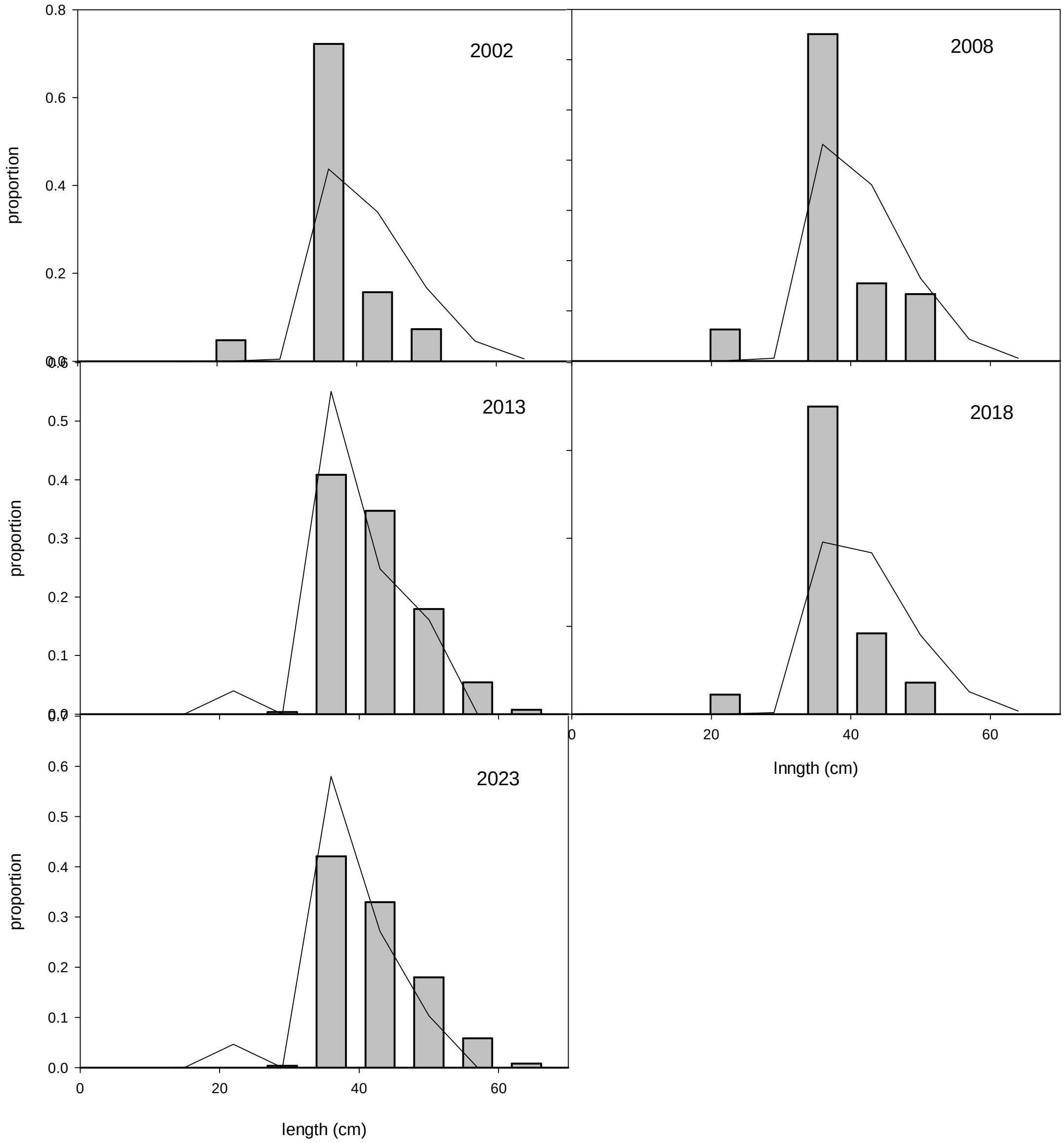


Figure 107 Model-predicted (black line) and observed (bars) length frequencies derived from an applications of the stock assessment conducted in 2023 of the simulated projection

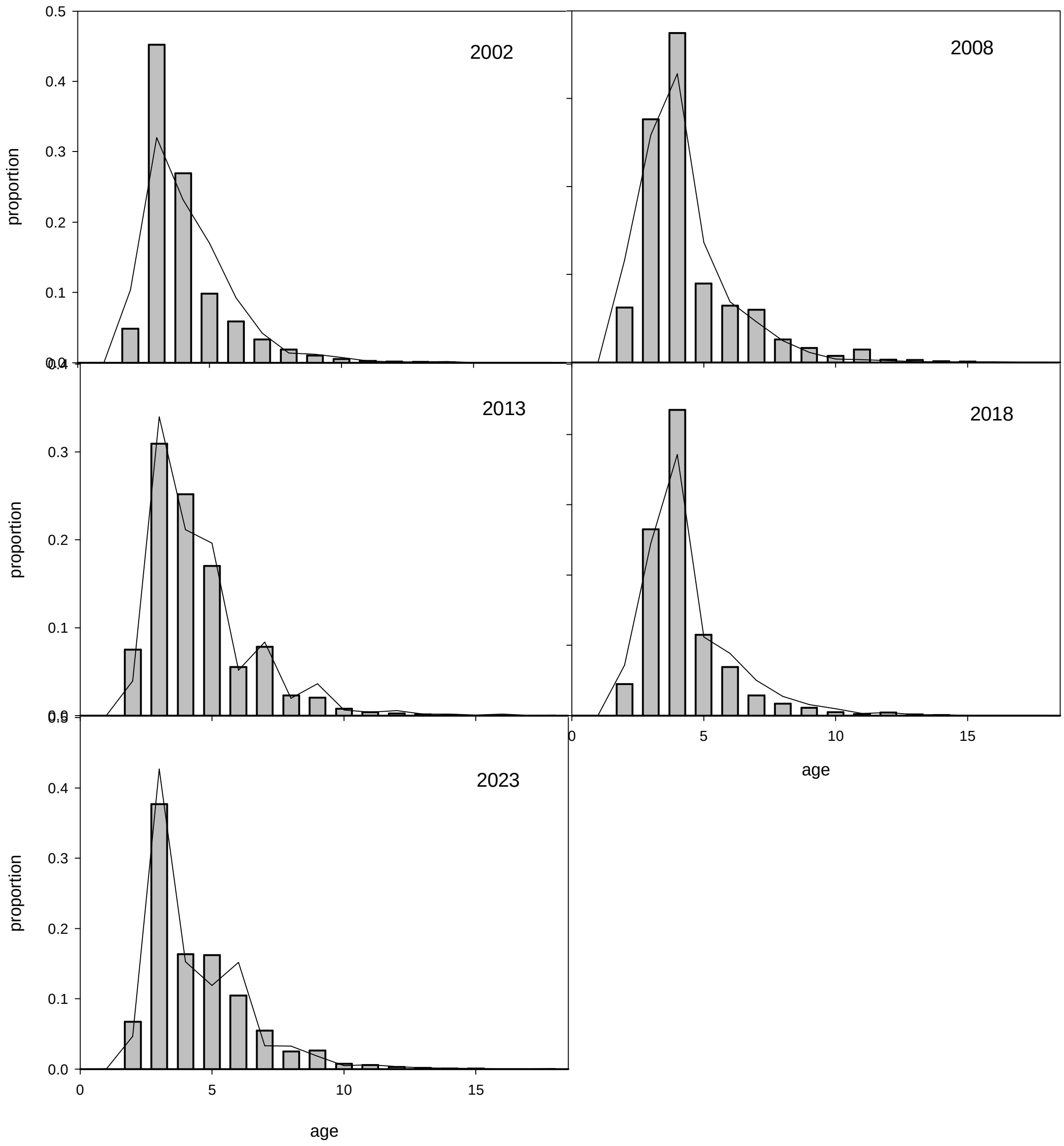


Figure 108 Model-predicted (black line) and observed (bars) age frequencies derived derived from an applications of the stock assessment conducted in 2023 of the simulated projection

D. DAF stock assessment model

Overview

The population dynamics model used in this assessment was a regional, age-structured, forward-prediction model. It was written in the software AD Model Builder (ADMB) (Fournier et al., 2012) and built on the general-purpose stock assessment model Cabezon (Cope et al., 2003), source code for which was kindly provided by Dr André Punt of CSIRO and the University of Washington. Cabezon is also the name of a fish on the west coast of North America, for which this model was used.

Cabezon calculates the number of fish of each age and sex in each year, and applies harvest rates (calculated from the recorded catch sizes) and the natural mortality rate to progress numbers-at-age forward from one year to the next. It includes calculations of length-at-age and weight-at-age. A particular strength of Cabezon is the capability to include multiple “fleets” which can be either fishing fleets or scientific research surveys, all of which may have different age- or length-dependent vulnerability functions. Fishing is assumed to take place as a short pulse in the middle of each year. This does not exactly match the coral trout fishery, in which fishing takes place all year round, but because the coral trout are relatively long-lived we did not believe that the errors would be significant.

Cabezon model projections can be matched against observed abundance indices, age-frequency data and length-frequency data.

The software ADMB estimates the model parameters by maximum likelihood, which is a long-standing and widely used statistical technique. Afterwards, ADMB can run simulations using Markov chain Monte Carlo (MCMC) to provide a random sample of potential parameter values, but that was not part of this project: decision rules used only the maximum likelihood estimates.

Building on the Cabezon population model, the following additional capabilities were incorporated for coral trout:

- Regional structure: This took into account the qualitatively different Regions, Subregions, Bioregions and Subbioregions of the GBR, and the green zones (zones closed to fishing).
- Green-zone fishing parameter: This parameter was the ratio of the fishing intensity in a green zone to that in blue zones in the same Subregion. It was impossible to estimate from the available data, and, based on advice from industry and government, was set to 0.2.
- Absolute abundance measures from underwater visual surveys (UVS): Generally, abundance measures in stock assessment are only *relative* abundance indices which compare one year against another and do not provide information on the actual numbers of fish present. An *absolute* abundance measure specifies the actual density of fish in a population, in this case as a number of fish per hectare.
- Habitat area: The area of habitat (in hectares) of each regional population of fish provided a way to scale up the fish density (number of fish per hectare) into an estimate of population size (an absolute number of fish in a Population).
- Changes in zoning: The appropriate numbers of fish were transferred between green and blue zones in years when the zoning changed, according to the area of the rezoned habitat.
- Size limits: A reduced fishing mortality rate (the post-release mortality rate) was assumed to operate on fish that were below the minimum legal size (MLS). The model assumed that fishers released all undersized fish, but not all of them survived.
- Social learning (hook shyness): A social-learning parameter was introduced to quantify a coral trout population’s ability to learn not to take bait when the population is fished. Population dynamics were still determined by the actual fishing mortality rate, but the model’s predicted fishery catch rates were those of a parallel population with the current year’s fishing intensity scaled up by the social-learning parameter.

The above concepts are expanded in the following sections.

Regional structure

The regional structure for the model was based on the Reef Bioregions defined by the GBRMPA expert committees (see Figure 109). The Bioregions grouped together reefs with common habitat features. The model assumed that the virgin population density (number of coral trout per hectare) was the same on all reefs (whether open or closed to fishing) within each Bioregion.

The Bioregions divided the GBR into six Regions from north to south: the Far Northern Region, the Cooktown Region, the Cairns–Townsville Region, the Mackay Region, the Swains Region and the Capricorn–Bunker Region (see Figure 110). Three Bioregions were not were not contained within a single Region: RA2 (Outer Barrier Reefs) was covered by both the Far Northern and the Cooktown Regions; RF1 (Northern Open Lagoon Reefs) was covered by the Cooktown Region and the Cairns Subregion; and RHC (High Continental Island Reefs) was covered by the Townsville Subregion and the Mackay Region.

Inspection of the commercial fishery logbook data showed that the intensity of fishing increased markedly from north to south. The far north of the GBR was relatively lightly fished, possibly because of the distance from port; Cairns was the nearest port from which live fish could be exported. Fishing intensity steadily increased from the far north south to Townsville, and thereafter was roughly constant from Townsville south to the Swains.

Therefore two of the northern Regions were divided into Subregions within which the fishing intensity could be considered constant. The Far Northern Region was divided into three Subregions: Cape York (to 11.7 °S), Lockhart River (11.7 °S to 13.0 °S), and Princess Charlotte Bay (from 13.0 °S); and the Cairns–Townsville Region was divided into two Subregions, Cairns and Townsville (split at 18.1 °S). This also necessitated splitting several of the Bioregions into Subbioregions along the Subregion boundaries. Finally, each Subbioregion was divided into two Populations, one containing fish in blue-zoned reefs (open to fishing), and the other containing fish in green-zoned reefs (closed to fishing). The different levels of the regional structure are illustrated in Figure 110.

Reefs zoned yellow, where fishing was restricted to one dory per primary commercial vessel and one hook per dory, were counted as blue. Commercial fishers use only one hook per dory in any case, so this restriction did not affect them in practice. The restriction of one dory per primary vessel was a problem when a yellow reef was surrounded by green reefs and thereby isolated from blue reefs; then it was not feasible for a primary vessel to drop one dory at the yellow reef and the others at blue reefs. The only reef where this was known to occur was Old Reef (number 19-048), and the commercial catch returned from that reef was indeed lower than from other blue and yellow reefs in the vicinity. This was an isolated instance where the zoning of a reef as yellow rather than blue made a big difference; due to the extra complexity of a model with a separate category for yellow reefs, we did not consider it worth incorporating.

When reefs within a Subbioregion were rezoned, the model transferred fish between blue and green populations according to the area of rezoned habitat. This allowed the model to cope with changes in catch rates caused by rezoning: if blue reefs were rezoned to green, fishers would have to operate within a smaller area which would be fished more intensively; hence catch rates would fall if either the total fishing effort or the total catch remained the same. The most notable example of this was the 2004 rezoning when the area of green zones increased from about 5% of the GBR to about 33%.

This model includes only Subbioregions where substantial commercial catches of coral trout have been taken. It omits Subbioregions in which targeted commercial fishing for *Plectropomus leopardus* was not economically viable, for example because they may have little suitable habitat or because a different species of coral trout such as *P. maculatus* or *P. laevis* may predominate. Commercial catch data was not always recorded to a fine enough spatial scale to allow accurate allocation into Subbioregions, but the records were adequate to decide which Subbioregions should be left in the model and which should be omitted. The catch data used as input to the model itself were spatially classified only to Sub-region level (see section “Basic population dynamics” below).

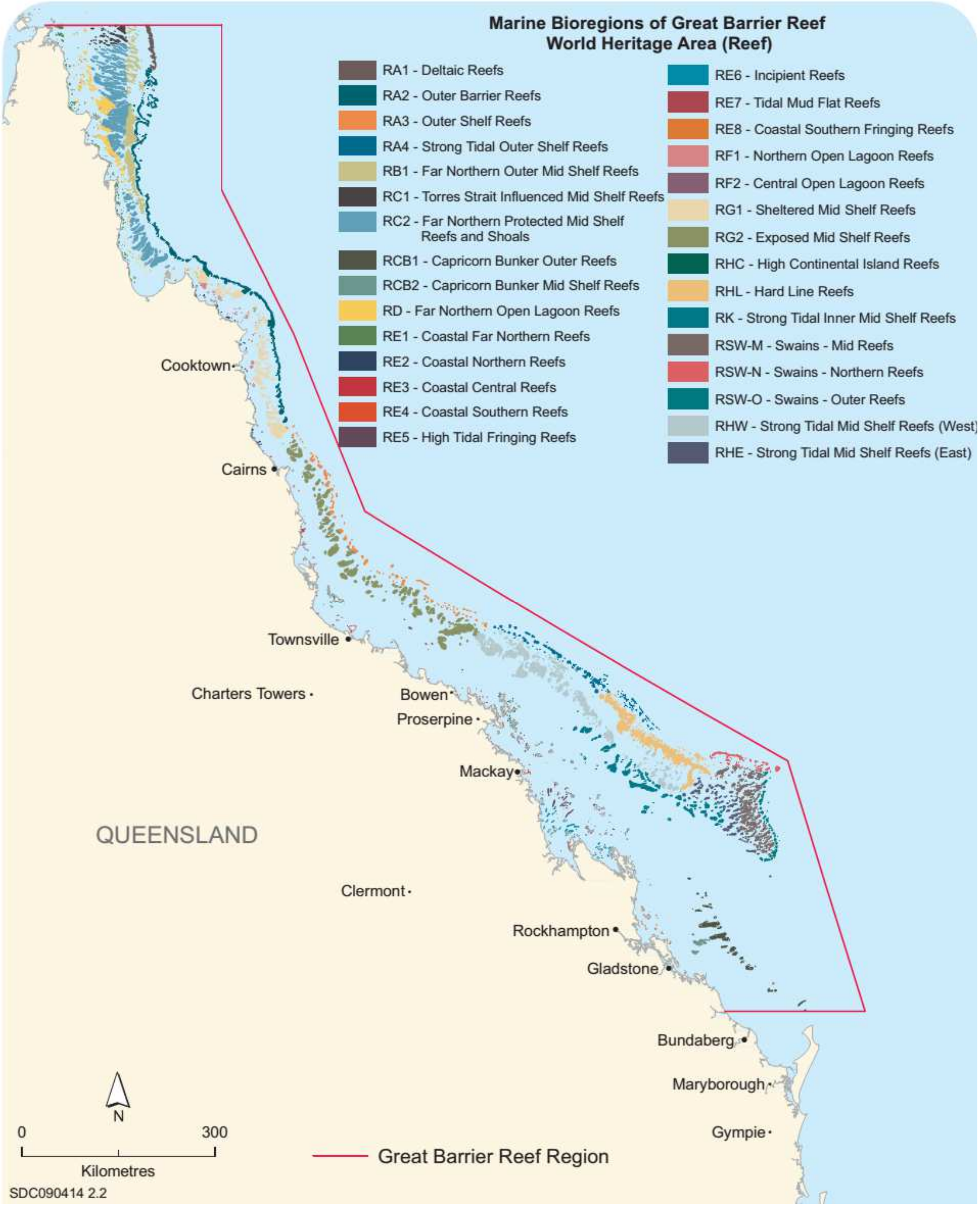


Figure 109 Map of GBRMPA Bioregions on which the DAF stock assessment was based. (Reproduced from GBRMPA, 2009)

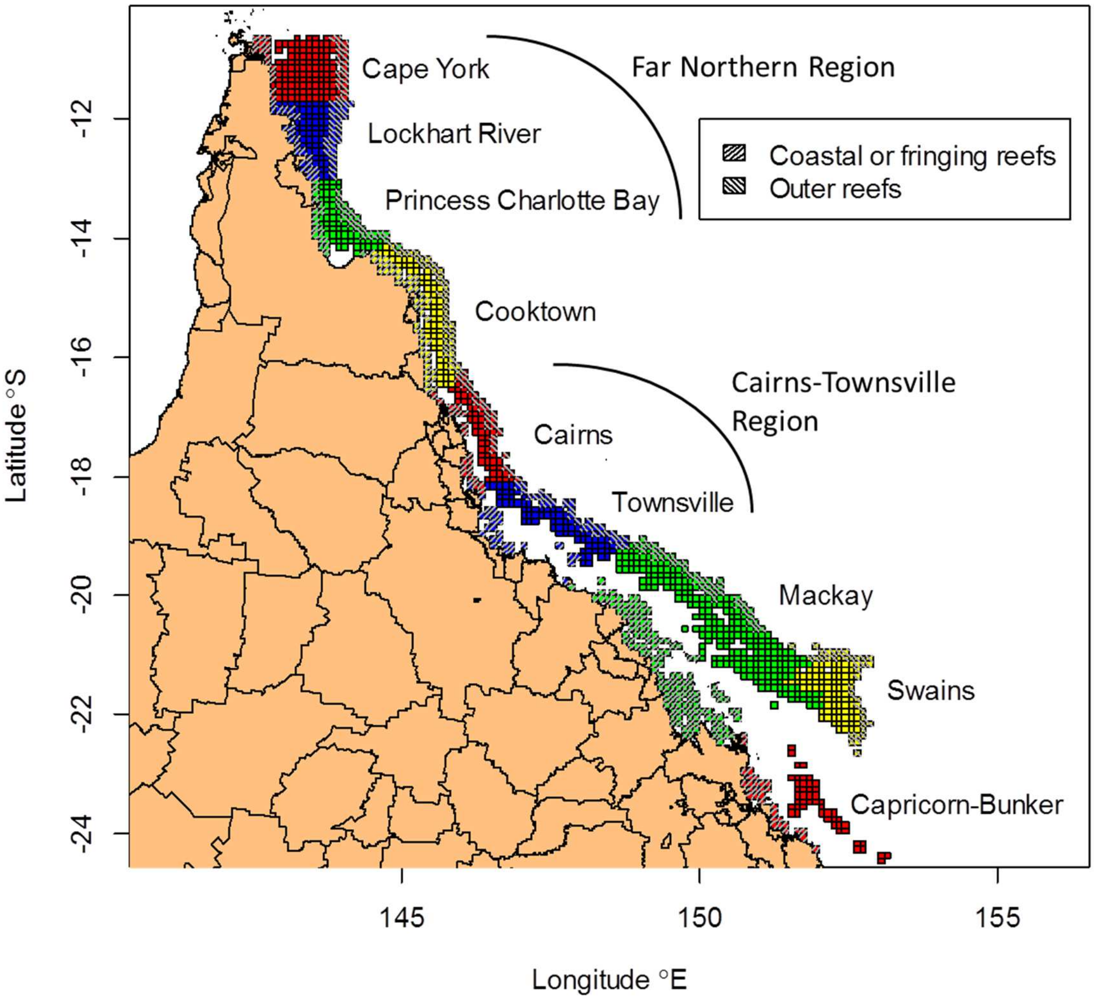


Figure 110 Regions and Subregions used in the stock assessment. Because the fishing intensity increases from north to south in the northern regions, the Far Northern Region is divided into three Subregions, and the Cairns–Townsville Region into two Subregions. The small squares are six-nautical-mile fishery logbook grid squares. Colours are chosen only to distinguish the Regions and Subregions, and have no other meaning. The Capricorn–Bunker Region was excluded from the stock assessment because fishers there did not strongly target coral trout, and underwater visual surveys showed dramatically different trends in coral trout abundance from the rest of the GBR

The entire Capricorn–Bunker Region was omitted because the catch of coral trout there was small, especially in recent years, and fishers there obviously did not strongly target coral trout. Also, underwater visual surveys conducted by the Australian Institute of Marine Science (AIMS) showed dramatically different trends in coral trout abundance in the Capricorn–Bunker Region from the rest of the GBR (Leigh et al., 2014, Figure 26, pp. 76–77). It appeared that the Capricorn–Bunker Region had quite different recruitment dynamics from the rest of the GBR, and modelling this region would require many more parameters (recruitment deviations specific to the Capricorn–Bunker Region) to be added to the population model. We note that the Capricorn Bunker Region is physically separated from the Swains reefs by the deep Capricorn Channel.

The model also omitted potential inter-reef habitat for coral trout, and indeed all habitat deeper than 30 m, because this habitat is currently impossible to quantify. It is certainly the case that some coral trout live deeper than 30 m, and some live in areas not attached to particular coral reefs, but underwater video surveys show that most of the area between reefs is not suitable habitat for coral trout (Michael Cappo, AIMS, personal communication).

The Regions, Subregions, Bioregions and Subbioregions used in the model are listed in full in Table 34. Habitat areas of the Subbioregions are listed in Table 35.

Table 34 Regions, Subregions, Bioregions and Subbioregions used in the model. Regions and Subregions used in the assessment model are shown also in Figure 111. Subregions are listed from north to south, and Subbioregions are listed from west to east (inner shelf to outer shelf) within each Subregion (except in the Cape York Subregion where they both have the same shelf position and are listed from north to south)

Subbioregion	Bioregion & description		Subregion	Region
RC1	RC1	Mid shelf	Cape York	Far Northern
RC2 North	RC2	Protected mid shelf	Cape York	Far Northern
RD Central	RD	Open lagoon reefs	Lockhart River	Far Northern
RC2 Central	RC2	Protected mid shelf	Lockhart River	Far Northern
RB1 Central	RB1	Outer mid shelf	Lockhart River	Far Northern
RC2 South	RC2	Protected mid shelf	Pr. Charlotte Bay	Far Northern
RF1 North	RF1	Open lagoon reefs	Cooktown	Cooktown
RG1	RG1	Sheltered mid shelf	Cooktown	Cooktown
RA2 South	RA2	Outer barrier reefs	Cooktown	Cooktown
RG2 North	RG2	Exposed mid shelf	Cairns	Cairns–Townsville
RA3 North	RA3	Outer shelf	Cairns	Cairns–Townsville
RG2 South	RG2	Exposed mid shelf	Townsville	Cairns–Townsville
RA3 South	RA3	Outer shelf	Townsville	Cairns–Townsville
RK	RK	Strong tidal inner shelf	Mackay	Mackay
RHW	RHW	Strong tidal mid shelf	Mackay	Mackay
RHL	RHL	Hard Line	Mackay	Mackay
RA4	RA4	Strong tidal outer shelf	Mackay	Mackay
RHE	RHE	Strong tidal mid shelf	Swains	Swains
RSW-M	RSW-M	Swains mid	Swains	Swains
RSW-O	RSW-O	Swains outer	Swains	Swains

Table 35: Habitat areas for each Subbioregion, scaled to equivalent reef-slope area. Zoning is current from 1 July 2004

Subbioregion	Blue-zone habitat (ha)	Green-zone habitat (ha)
RC1	3065	1195
RC2 North	8036	15210
RD Central	14702	4203
RC2 Central	15580	4115
RB1 Central	19440	2138
RC2 South	13446	8050
RF1 North	2656	1819
RG1	24680	7518
RA2 South	8699	7318
RG2 North	19919	5884
RA3 North	2550	2209
RG2 South	31850	8377
RA3 South	1691	1932
RK	18877	4880
RHW	41011	14294
RHL	35119	9864
RA4	6004	2286
RHE	7282	2987
RSW-M	14865	5918
RSW-O	3229	2029

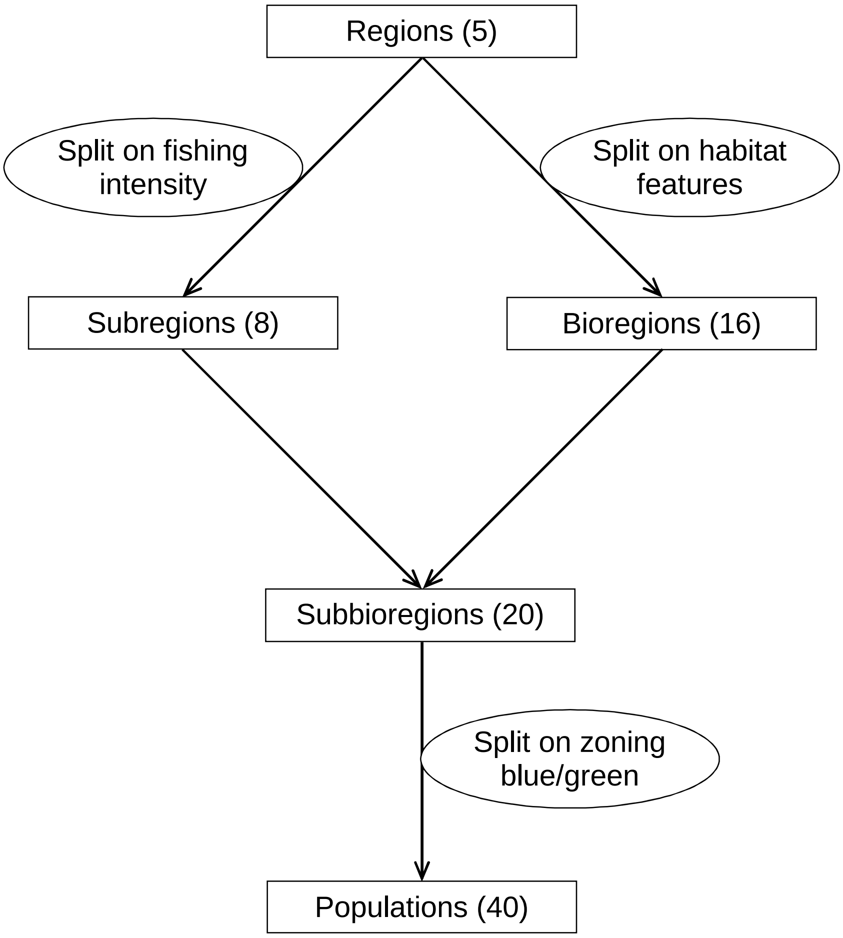


Figure 111 Regional structure of the coral trout population model, showing separate splits of Regions into Subregions and Bioregions, both of which then split into Subbioregions. Each Subbioregion contains two populations of coral trout, one in blue zones (open to fishing) and one in green zones (closed to fishing). The total number of each type of structural element is shown in parentheses. The model included only Subbioregions with substantial commercial catches of coral trout

Basic population dynamics

The model operated on calendar years, which were thought to better suit the biology of coral trout which spawns late in the year. Calendar years also matched the ELFSim software (Little et al., 2007a). Fishery quota, on the other hand, operates on Australian financial years, July to June.

Numbers of fish N present in the model at the beginning of a year were indexed by Population (k), year (t) and age (a). Sexes were not distinguished. Each Subbioregion contained two Populations, one zoned blue (open to fishing) and the other green (closed to fishing). The number of fish of age zero was set equal to the recruitment $R_{k\,t}$ to Population k in year t:

$$N_{k\,t\,0} = R_{k\,t}\,. \tag{D1}$$

Recruitment is discussed in the next section (“Recruitment”).

For ages one year and upwards, population numbers are derived from those for the same year-class in the previous year (year $t-1$ and age $a-1$): for $1 \le a < a_{\max}$,

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\, e^{-M} (1 - V_{a-1} U_{k\;t-1}), \tag{D2}$$

where $a_{\max}$ is the age of the oldest age-class in the model, M is the instantaneous natural mortality rate, V_a is the vulnerability to fishing at age a, and $U_{k\,t}$ is the harvest rate of population k in year t. The quantities $a_{\max}$,

V_a and $U_{k\,t}$ are discussed below. The oldest age-class $a_{\max}$ was a “plus group”, holding all fish of age $a_{\max}$ or older. The formula for it was slightly different to (C2): for $a = a_{\max}$,

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\, e^{-M} (1 - V_{a-1} U_{k\,t-1}) + N_{k\,t-1\,a}\, e^{-M} (1 - V_a U_{k\,t-1}). \tag{D3}$$

$a_{\max}$ was chosen to be one year older than the oldest observed fish, i.e., $a_{\max} = 20$ yr, so that all observed age frequencies were zero at age $a_{\max}$. This approach used all the information present in the age frequency data, so that no information was lost in truncating the age distribution at $a_{\max}$.

The fishery was assumed to start from the virgin (never fished) state in year 1, which was calendar year 1962, the first year in which the Queensland Fish Board recorded catch of coral trout. The level of fishing before then was assumed to be zero. The population structure in year 1 was given by, for $1 \le a < a_{\max}$,

$$N_{k\,1\,a} = R_{k\,0}\, e^{-aM},$$

where $R_{k\,0}$ is the deterministic number of recruits to population k in the virgin state (see “Recruitment” section below). For the plus group the formula took account of older fish: for $a = a_{\max}$,

$$N_{k\,1\,a} = R_{k\,0}\, e^{-aM} \big/ (1 - e^{-M}).$$

The vulnerability V_a is estimated in the model and represents the relative chance that a fish of age a that is present in the population will be caught by fishing or other sampling. Very small fish will not be caught even if they are in the vicinity, so have low vulnerability. Young fish will also be assigned low vulnerability if they are not in the vicinity, for example if they have a life cycle whereby young fish inhabit only very deep water that is not fished. This latter feature distinguishes the term “vulnerability” from the equipment-specific term “selectivity”, which refers only to the capability of the fishing gear to catch fish that are at the location being fished. Young coral trout are not thought to inhabit different localities to older fish, except that they may be more inclined to take cover inside coral, so for coral trout it makes no difference whether the term “vulnerability” or “selectivity” is used. Other reef fish such as red-throat emperor (*Lethrinus miniatus*) may reside elsewhere when young, so the term “vulnerability” is preferred for them (Leigh et al., 2006). The model used a logistic function for vulnerability as a function of length. This function gradually increases from very low vulnerability for small fish, to approach 1 for large fish:

$$V_L^* = 1 \big/ \left[1 + \exp\left\{ -(\log 19)\,(L - L_{50}) / (L_{95} - L_{50}) \right\} \right], \tag{D4}$$

where L_{50} is the fork length at 50% vulnerability and L_{95} is the fork length at 95% vulnerability (see Haddon, 2001, p. 353); both L_{50} and the parameter $L_{95\,\mathrm{diff}} = L_{95} - L_{50}$ were estimated in the model. The asterisk distinguishes length-dependent vulnerability V_L^* from age-dependent vulnerability V_a. The conversion factor of 0.9409 was used to convert total length to fork length.

Length-dependent vulnerability was converted to age-dependent vulnerability using the distribution of length at age in the middle of the year. This distribution was assumed to be normal, with mean given by the growth curve and standard deviation by the estimated coefficient of variation: at a given age a, it produced the proportion of fish $p(L\,|\,a)$ in each length-class L, such that $\sum_L p(L\,|\,a) = 1$. Then the age-dependent vulnerability was given by

$$V_a = \sum_L p(L\,|\,a)\, V_L^*. \tag{D5}$$

The model used 1 cm length categories with midpoints ranging from 1 cm to 70 cm, and calculated the vulnerability in the middle of the year, at exact age $a + \frac{1}{2}$.

The harvest rate $U_{k\,t}$ is the proportion of vulnerable fish in Population k that are caught in year t. In fact, catch sizes were specified only to Subregion level, so it depended only on the Subregion g that contained Population k:

$$U_{k\,t} = U^{*}_{g\,t} ,$$

and the Subregion harvest rate $U^{*}_{g\,t}$ was calculated as the ratio of catch weight from Subregion *g* in year *t*, to the mid-year vulnerable biomass in Subregion *g* just before the start of the fishing pulse:

$$U^{*}_{g\,t} = C_{g\,t} \Big/ \sum_{k \in K(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a , \qquad \text{(D6)}$$

where W_a is the average mid-year weight of a fish of age *a*, and *K*(*g*) is the set of Populations that make up Subregion *g*. Treatment of green-zoned Populations is described below in section “Green zone fishing parameters”. Formulae (C2) and (C3) were used unchanged from Cabezon, and are appropriate when either the fishing intensity is low to moderate, or the non-vulnerable fish are absent from the fishing grounds. If the fishing intensity is very high then the vulnerability should more properly be applied to the fishing mortality rate than the harvest rate, which leads to a power relationship: (C2) and (C3) become

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\, e^{-M} (1 - U_{k\;t-1})^{V_{a-1}}$$

and

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\, e^{-M} (1 - U_{k\;t-1})^{V_{a-1}} + N_{k\,t-1\,a}\, e^{-M} (1 - U_{k\;t-1})^{V_a} .$$

The equation relating harvest rate to catch size also becomes much more complicated than (D6). The fishing intensity on the GBR was not thought to be high enough to require this change. Therefore we used equations (D2) and (D3). A case of a fishery that would need the power relationship, together with the methodology for post-release mortality discussed in ”Size limits” below, is that of a heavily fished catch-and-release fishery in which a typical fish may be caught and released several times in a single year; in Queensland, dusky flathead (*Platycephalus fuscus*) may be such a case. Adjustments to the harvest rates to take account of green zones and minimum legal size limits are described in dedicated sections below.

This model does not use Cabezon’s multiple-fleet capability, whereby vulnerability can depend on both age and fleet in equations (D2) and (D3), and a separate harvest rate is defined for each fleet in a given year. In principle it may be desirable to allow different vulnerability functions for the commercial and recreational fleets, because commercial fishers target fish up to 1.5 kg, although they retain larger fish if they catch them, whereas recreational fishers especially value large fish but still value and retain legal-sized smaller fish. In practice, however, the only data from which to estimate vulnerability functions came from scientific surveys and were not specific to either the commercial or recreational fleet. Therefore it was not possible to distinguish fleet-specific vulnerability functions.

The capability for different vulnerability functions was, however, used for the underwater visual survey (UVS) data, which recorded the estimated length of each fish sighted by the divers. UVS did not involve fishing gear so was expected to have a different vulnerability (visibility) function to samples collected by fishing.

Targeting of medium-sized fish by commercial fishers provides some incentive to use what is known as a “dome-shaped” vulnerability function. Such a function peaks at a moderate size and then decreases for large fish, instead of continuing to increase like the logistic function. We did not use dome-shaped vulnerability because there was insufficient evidence for it. Fishers retain large fish when they catch them, and it is unknown whether commercial fishers are able to choose fishing locations that are frequented by dinner-plate sized fish but not by large fish. Also, dome-shaped vulnerability can be dangerous because it postulates a large bank of spawning fish that are never observed. It is not known definitely whether these unobserved fish actually exist; if not, the spawning stock size could be grossly overestimated.

Recruitment

Spawning and recruitment were assumed to take place simultaneously at the start of each calendar year. The model allowed no time lag between spawning and subsequent recruitment. This formulation matched that used by both Cabezon and ELFSim, and involved adding one year to the age of fish that were aged during a year.

There is debate over the distance that coral trout larvae migrate from the location where they were spawned, but current evidence favours short distances that are still sufficient for green zones (marine protected areas) to seed recruits into blue zones. Harrison et al. (2012) conducted a genetic parentage analysis of potential bar-cheek coral trout *P. maculatus* parents in green zones and offspring in green and blue zones within 30 km. They found that about 30% of juveniles with assigned parents were collected within 2 km of the parents; one juvenile was 28 km from the parents, and the average was 8.6 km. Therefore the model summed egg production over Subbioregions, not large-scale elements such as Subregions or Regions, or very small-scale ones such as Populations.

In Population k, the recruitment $R_{k\,t}$ in year t followed a Beverton-Holt stock-recruitment relationship (Beverton and Holt, 1957) with random, annual lognormal deviations:

$$R_{k\,t} \big/ R_{k\,0} = e^{d_t} \, \frac{r\, S_{k\,t} \big/ S_{k\,0}}{1 + (r-1)\, S_{k\,t} \big/ S_{k\,0}},$$

where $S_{k\,t}$ is the egg production in year t in the Subbioregion containing Population k (blue zones and green zones combined), $R_{k\,0}$ and $S_{k\,0}$ are the deterministic values of $R_{k\,t}$ and $S_{k\,t}$ in a virgin (never fished) population, $r > 1$ is the recruitment compensation ratio, and d_t is the log-recruitment deviation. The recruitment compensation ratio (Goodyear, 1977) is the average number of offspring of each adult fish that survive to spawning age, when the population size is very low. The equivalent parameter known as “steepness”, denoted h, came into use later than r and is defined as $h = r \big/ (4 + r)$; it lies in the range $0.2 < h \leq 1$, and is the ratio of recruitment to virgin recruitment when stock size is reduced to 20% of the virgin size.

The egg production in a Subbioregion comprising Populations k (zoned blue) and k^* (zoned green) is

$$S_{k\,t} = \sum_{a=1}^{a_{\max}} x_a \, (N_{k\,t\,a} + N_{k^*\,t\,a}),$$

where x_a is the product of the maturity proportion and the fecundity at age a. The recruitment compensation ratio r was estimated in the model and was common to all Regions.

Within each Subbioregion, the parameters $R_{k\,0}$ were made proportional to the habitat areas H_k of the Populations. A value of the recruitment density $R_{k\,0} \big/ H_k$, as a number of recruits per hectare, was estimated within the model for each Subbioregion; the same density value $R_{k\,0} \big/ H_k$ was used for both blue zones and green zones. This approach is the same as the standard approach which estimates virgin recruitment size; it simply takes account of the ratio of habitat areas for the different populations.

The log-recruitment deviations d_t were estimated within the model and followed a normal distribution with mean zero. A lower bound of 0.1 was applied to the standard deviation to prevent the likelihood from becoming infinite. Cabezon applies a bias-correction factor so that the expected value of e^{d_t} is equal to 1. We did not apply this, as we set the median equal to 1 rather than the arithmetic mean equal to 1.

There was only one recruitment deviation per year, covering all Regions, because Region-specific deviations could not be estimated reliably from the available data. We note that, judging from the UVS data collected by AIMS, GBR-wide recruitment deviations would not have fitted the Capricorn–Bunker Region and, if the catch sizes from this Region had been large enough to justify including it in the model, an extra sequence of recruitment deviations would have been needed just for this Region (see section ”Regional structure” above).

Green zone fishing parameter

Fishing in green zones was handled by a parameter f_{green} which acted as a scaling factor on the vulnerable biomass: only a proportion f_{green} of the vulnerable biomass in equation (D6) was actually considered vulnerable if the Population was zoned green, where $0 \leq f_{\text{green}} \leq 1$.

For a Subregion g comprising a set of Populations $K(g)$, we split $K(g)$ into a set of blue-zoned Populations $K_{\text{blue}}(g)$ and a set of green-zoned Populations $K_{\text{green}}(g)$. Then the vulnerable biomass in Population k is equal to

$$\begin{cases} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a\,, & \text{if } k \in K_{\text{blue}}(g) \\ f_{\text{green}} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a\,, & \text{if } k \in K_{\text{green}}(g) \end{cases}$$

and equation (C6) becomes

$$U^*_{g\,t} = C_{g\,t} \Bigg/ \left\{ \sum_{k \in K_{\text{blue}}(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a + f_{\text{green}} \sum_{k \in K_{\text{green}}(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a \right\}. \tag{D7}$$

When Population k is zoned green, the population dynamic equations (D2) and (D3) become respectively

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\, e^{-M} (1 - f_{\text{green}} V_{a-1} U_{k\;t-1}),$$

and

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\, e^{-M} (1 - f_{\text{green}} V_{a-1} U_{k\;t-1}) + N_{k\,t-1\,a}\, e^{-M} (1 - f_{\text{green}} V_a U_{k\;t-1}).$$

There were no data from which f_{green} could be estimated reliably. Therefore it was fixed to the value 0.2; i.e., the harvest rate in green zones was assumed to be 20% of that in neighbouring blue zones, based on advice from industry and government. It was clear that there was substantial fishing in green zones, but many fishers did not indulge in it, and those that did would have had to put time into avoiding being caught, which must have made their fishing less effective. We regarded the figure of 20% as reasonable.

The vulnerable biomass in subregion g at the start of year t is equal to the denominator in equation (D7). To use vulnerable biomass as an abundance index to compare to catch rates, we adjust it to the middle of the fishing pulse:

$$B_{gt} = \sqrt{1 - U^*_{gt}} \left\{ \sum_{k \in K_{\text{blue}}(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a + f_{\text{green}} \sum_{k \in K_{\text{green}}(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_a \right\}, \tag{D8}$$

This is different to, and slightly more accurate than, the equation used in Cabezon, which uses $1 - \tfrac{1}{2} U^*_{gt}$ in place of the square-root factor. The difference was expected to be negligible, but equation (C8) is more logical when the social learning parameter is applied (see “Social learning parameter” below).

Changes in zoning

Zoning of reefs changed from time to time. The biggest change in zoning came in July 2004 when the proportion of the GBR that was closed to fishing increased from about 5% to 33%. This change meant that fishers had a smaller area in which to legally fish, and had to fish it more intensively, which would have resulted in a decrease in catch rates. It was considered desirable for the model to capture this effect. Habitat area, denoted H_k (see “Recruitment” above) is now indexed also by year (t), and denoted $H_{k\,t}$. Formally, $H_{k\,t}$ denotes the average habitat area of Population k in year t.

Suppose that zoning changed in year t in a Subbioregion comprising Populations k (zoned blue) and k^* (zoned green). It is assumed that all the rezoning in the Subbioregion in year t is in the same direction, either all from blue to green or all from green to blue. The projected population numbers under the previous year’s zoning are given by the right-hand sides of equations (D1), (D2) and (D3), and are denoted N^{proj}_{kta}. If the zoning change is from blue to green (the more common case), then $H_{k\,t} < H_{k\,t-1}$ and $H_{k^*\,t} > H_{k^*\,t-1}$. The total habitat in the

Subbioregion is still the same, i.e., $H_{k\,t} + H_{k^*\,t} = H_{k\,t-1} + H_{k^*\,t-1}$. The population numbers are adjusted by the formulae

$$N_{kta} = \left(H_{kt} \big/ H_{k\,t-1}\right) N_{kta}^{\text{proj}}$$

and

$$N_{k^*ta} = N_{k^*ta}^{\text{proj}} + \left\{\left(H_{k\,t-1} - H_{kt}\right) \big/ H_{k\,t-1}\right\} N_{kta}^{\text{proj}}.$$

If the zoning change is from green to blue (the rarer case), the formulae are

$$N_{kta} = N_{kta}^{\text{proj}} + \left\{\left(H_{kt} - H_{k\,t-1}\right) \big/ H_{k^*\,t-1}\right\} N_{k^*ta}^{\text{proj}}$$

and

$$N_{k^*ta} = \left(H_{k^*t} \big/ H_{k^*\,t-1}\right) N_{kta}^{\text{proj}}.$$

Accounting for zoning changes in this way also means that vulnerable biomasses can no longer be used on their own as abundance indices, because they change with zoning in ways that are unrelated to abundance. Therefore the vulnerable biomass $B_{g\,t}$ in (D8) has to be scaled by the "vulnerable habitat area"

$$\tilde{H}_{g\,t} = \sum_{k \in K_{\text{blue}}(g)} H_{k\,t} + f_{\text{green}} \sum_{k \in K_{\text{green}}(g)} H_{k\,t} \qquad \text{(D9)}$$

to produce an abundance index

$$B_{gt} \big/ \tilde{H}_{gt}$$

that is comparable from year to year.

Size limits

Minimum legal sizes (MLS), which could change over time, were handled by adjusting the vulnerability function in equation (D5), and specifying a post-release mortality rate *u*. Let the MLS be L_{MLS}. Then (D5) is altered to

$$V_a = u \sum_{L < L_{\text{MLS}}} p(L \mid a)\, V_L^* + \sum_{L \geq L_{\text{MLS}}} p(L \mid a)\, V_L^*,$$

which is used in the population dynamic equations (D2) and (D3). The post-release mortality rate was fixed at 0.25 on the basis of a recent FRDC funded study by Brown et al. (2008). Since the ELFSim operating model assumes a post-release mortality rate of 0.15, this value was used when the assessment model was used to estimate ELFSim stock status.

For the harvest-rates and abundance indices defined by equations (D6) and (D8), the catch and catch-rate are assumed to comprise only legal-sized fish. Therefore we define a separate vulnerability function for fish that the fishers keep,

$$V_{a\,\text{keep}} = \sum_{L \geq L_{\text{MLS}}} p(L \mid a)\, V_L^*,$$

and (D6) becomes

$$U_{g\,t}^* = C_{g\,t} \Bigg/ \sum_{k \in K(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_{a\,\text{keep}}.$$

For green-zone fishing and social learning (see below), V_a is also replaced by $V_{a\,\mathrm{keep}}$ in (D7) and (D10).

An ideal treatment of a MLS would also involve increasing the weight-at-age of fish that were caught, and decreasing the weight-at-age of the remaining fish that were not caught. This would have imposed a programming and computational overhead for little perceived benefit, and was not pursued.

Social learning parameter

Social learning (hook shyness) by coral trout was handled by including a parallel or "shadow" population of fish with a higher fishing mortality rate than the actual population, which is intended to depress the catch rates when the population learns not to take bait as a result of being fished.

In the presence of social learning, the square-root term in (D8) is raised to the power γ, the social learning parameter, to produce the shadow vulnerable biomass

$$\tilde{B}_{gt} = \left(1-U^*_{gt}\right)^{\gamma/2} \left\{ \sum_{k\in K_{\mathrm{blue}}(g)} \sum_{a=0}^{a_{\max}} N_{kta}\, e^{-M/2}\, W_a\, V_a + f_{\mathrm{green}} \sum_{k\in K_{\mathrm{green}}(g)} \sum_{a=0}^{a_{\max}} N_{kta}\, e^{-M/2}\, W_a\, V_a \right\}. \qquad \text{(D10)}$$

The shadow biomass $\tilde{B}_{gt}$ was used in abundance indices, in place of the true vulnerable biomass B_{gt}, to match to the standardised commercial catch rates. The formulation that avoids the power relationship in (D10) uses a factor of $1-(\gamma/2)U^*_{gt}$ instead of the factor involving the power $\gamma/2$. This is undesirable because it can easily produce negative values (equivalent to taking a catch greater than the available biomass). Admittedly, square-roots and power relationships can cause trouble in the automatic differentiation routines used in ADMB, because the derivative becomes infinite when the argument is zero and the power is less than 1. They were judged to be necessary here, despite the potential problems.

The social learning parameter γ can be estimated in the model, with the restriction only that it had to be greater than zero. In the absence of social learning it would have the value 1. If social learning is present its value should be greater than 1. For the current application of the model this parameter was set to 1.

List of model parameters

The parameters used in the model are listed in Table 36. The recruitment deviations d_t are constrained to sum to zero so that their mean was not confounded with the recruitment-density parameters $R_{k\,0\,\mathrm{dens}}$. There were no age-frequency data from which to estimate any recruitment deviations before the 1981 year class or after the 2007 year class; the most recent sample was from spring 2009. Therefore the recruitment deviations were fixed at zero (deterministic recruitment) for year classes outside the range 1981–2007. Catch rates and abundance are not well correlated for coral trout, so catch rates were not considered adequate for estimation of recruitment deviations from catch-rate data alone.

Table 36: Parameters used in the model. The Length column is the number of degrees of freedom in the parameter. The Value is listed when it is fixed, and left blank when estimated

Name	Length	Value	Description
$R_{k\,0\,\mathrm{dens}}$	16		Virgin density of recruits, R_{k0}/H_k (number of recruits of age 0 per hectare), by Bioregion (k = 1, …, 16)
r	1		Recruitment compensation ratio
d_t	26		Recruitment deviations (years 1981, …, 2007), constrained to sum to zero; lower bound of 0.1 on standard deviation
M	1		Instantaneous natural mortality rate
L_{50}	1		Fork length at 50% vulnerability to fishing
$L_{95\,\mathrm{diff}}$	1		Fork length at 95% vulnerability to fishing, minus L_{50}
L_{50}^{UVS}	1		Fork length at 50% vulnerability to UVS
$L_{95\,\mathrm{diff}}^{\mathrm{UVS}}$	1		Fork length at 95% vulnerability to fishing, minus L_{50}^{UVS}
f_{green}	1	0.20	Intensity of fishing in green zones, as a fraction of that in neighbouring blue zones
u	1	0.25	Discard mortality rate
γ	1		Social learning parameter

Data and likelihoods

The data used in the model are listed in Table 37: these data were largely not raw data but had been derived from raw data by methods such as catch-rate standardisations.

Table 37: Data used in the model. The data listed above the bold line were used in the model's internal calculations, while those below the line were used to match the model's predictions

Name	Description
L_∞, K, t_0	Von Bertalanffy growth curve parameters
$\mathrm{CVL_{min}}$	Coefficient of variation of length about the mean at age 1
$\mathrm{CVL_{max}}$	Coefficient of variation of length about the mean at age $a_{\max}-1$
W_a	Average mid-year weight of a fish of age a
x_a	Product of maturity proportion and fecundity at age a
MLS_t	Minimum legal size (fork length) by year
$H_{k\,t}$	Habitat area (hectares) by Subbioregion and year
$C_{g\,t}$	Catch size by Subregion and year, sum of commercial and recreational catches, interpolated and extrapolated backwards in time were necessary.
$Y_{g\,t}$	Relative abundances from standardised commercial catch rates by Subregion and year
$\mathrm{CVY}_{g\,t}$	Coefficients of variation of the experimental error in $Y_{g\,t}$, which the model used as lower bounds for the overall coefficients of variation including process error
$A_{k\,t}$	Absolute abundances (number of fish per hectare of reef slope) from underwater visual surveys (UVS) contracted by GBRMPA and the ELF Project, by Subbioregion and year
$\mathrm{CVA}_{g\,t}$	Coefficients of variation of the experimental error in $A_{g\,t}$, which the model used as lower bounds for the overall coefficients of variation including process error
$Y_{k\,t}^{\mathrm{UVS}}$	Relative abundances from UVS conducted by AIMS and Fisheries Queensland, by Subbioregion and year
$\mathrm{CVY}_{k\,t}^{\mathrm{UVS}}$	Coefficients of variation of the experimental error in $Y_{k\,t}^{\mathrm{UVS}}$, which the model used as lower bounds for the overall coefficients of variation including process error
$y_{k\,t\,a}$	Age frequencies by Subbioregion, year and age
$y_{k\,t\,\ell}^{\mathrm{UVS}}$	Length frequencies from UVS by Subbioregion, year and length class (the same surveys that produced $A_{k\,t}$)

The data listed above the bold line in Table 37 were used in the model's internal calculations. The data below the line were used to match the model's predictions, as described in the following sections. The coefficients of variation (CVs, ratios of standard error to the mean value) of the abundance data were the standard errors of log-transformed parameters in generalised linear models. These CVs included only observation error (error that can be made arbitrarily small by collecting more data) and not process error (error caused by lack of fit of the model, which generally is not reduced by collecting more data). Therefore, to account for possible process error, they were used in the model only as lower bounds for the CVs.

Likelihood for relative abundance measures

A relative abundance index $Y_{g\,t}$ follows a lognormal distribution. The abundance from standardised catch rates is assumed to be proportional to the social-learning-adjusted vulnerable biomass $\tilde{B}_{gt}$ from equation (D10), scaled by the corresponding habitat area $\tilde{H}_{gt}$ from equation (D9). The constant of proportionality is captured in the parameter μ below: it accounts for the fact that catch rates (numbers of fish caught by a line fisher per dory-day of fishing) measure only the relative abundance of fish, and do not directly measure the number of fish per hectare of habitat. This parameter is not used when the number of fish per hectare is measured directly, as in underwater visual surveys (see "Likelihood for absolute abundance measures" below).

When the mean μ and standard deviation $\sigma_{g\,t}$ of $\log Y_{gt} - \log\left(\tilde{B}_{gt} \big/ \tilde{H}_{gt}\right)$ are specified, the likelihood is

$$\prod_{g}\prod_{t}\left(\left\{1\big/\left(\sqrt{2\pi}\,\sigma_{gt}\right)\right\}\exp\left[-\tfrac{1}{2}\left\{\log Y_{gt}-\log\left(\tilde{B}_{gt}\big/\tilde{H}_{gt}\right)-\mu\right\}^{2}\big/{\sigma_{gt}}^{2}\right]\right),$$

where subscripts g and t denote Subregions and years respectively. It is convenient to use the negative log-likelihood (NLL), which, omitting the constant factors of $\sqrt{2\pi}$ above, is

$$\ell = \sum_g \sum_t \left[\log \sigma_{gt} + \tfrac{1}{2} \left\{ \log Y_{gt} - \log\left(\tilde{B}_{gt} \big/ \tilde{H}_{gt} \right) - \mu \right\}^2 \big/ \sigma_{gt}{}^2 \right].$$

The standard deviation σ_{gt} is set to CVY_{gt} (see Table 37) multiplied by a scale factor $\sigma \geq 1$ which is intended to account for process error (see ”Data” above). Then the NLL, omitting constant terms, is

$$\ell = \sum_g \sum_t \left[\log \sigma - \tfrac{1}{2} \log w_{gt} + \tfrac{1}{2} w_{gt} \left\{ \log Y_{gt} - \log\left(\tilde{B}_{gt} \big/ \tilde{H}_{gt} \right) - \mu \right\}^2 \big/ \sigma^2 \right], \tag{D11}$$

where $w_{gt} = 1 \big/ \mathrm{CVY}_{gt}^2$.

Standard estimators of μ and σ^2 are:

$$\hat{\mu}_Y = \sum_g \sum_t w_{gt} \left\{ \log Y_{gt} - \log\left(\tilde{B}_{gt} \big/ \tilde{H}_{gt} \right) \right\} \Big/ \sum_g \sum_t w_{gt}$$

and

$$\hat{\sigma}_Y^2 = \sum_g \sum_t \left[w_{gt} \left\{ \log Y_{gt} - \log\left(\tilde{B}_{gt} \big/ \tilde{H}_{gt} \right) - \hat{\mu}_Y \right\}^2 \right] \Big/ (n_Y - 1).$$

Substituting these expressions into (D11) provides a likelihood that depends only on data (Y_{gt}, w_{gt} and $\tilde{H}_{gt}$) and model predictions ($\tilde{B}_{gt}$):

$$\ell = (n_Y - 1) \log \tilde{\sigma}_Y + \tfrac{1}{2} (n_Y - 1) \hat{\sigma}_Y^2 \big/ \tilde{\sigma}_Y^2, \tag{D12}$$

where n_Y is the total number of Subregion–year combinations in the index series, and $\tilde{\sigma}_Y$ is the estimate of σ taking account of its lower bound $\sigma_{Y\,\mathrm{min}} = 1$:

$$\tilde{\sigma}_Y = \max(\hat{\sigma}_Y, \sigma_{Y\,\mathrm{min}}). \tag{D13}$$

Formula (D12) is similar to the negative log-likelihood derived by Haddon (2001, p. 89) but includes the adjustment term for the lower bound on σ. The “max” function is not suitable for ADMB because its derivative is discontinuous. The following expression for $\tilde{\sigma}_Y$ was used instead:

$$\tilde{\sigma} = \tfrac{1}{2}(\hat{\sigma}_Y + \sigma_{Y\,\mathrm{min}}) + \sqrt{\tfrac{1}{4}(\hat{\sigma}_Y - \sigma_{Y\,\mathrm{min}})^2 + \delta^2 \sigma_{Y\,\mathrm{min}}^2}, \tag{D14}$$

where $\delta > 0$ is a smoothness parameter that took the value 0.1. The value $\delta = 0$ makes (D14) the same as (D13), which is the formula that has to be avoided. The smoothing has the side effect of shifting the value of $\tilde{\sigma}_Y$ at $\sigma_{Y\,\mathrm{min}} = \hat{\sigma}_Y$ up to $(1 + \delta)\, \sigma_{Y\,\mathrm{min}}$ instead of setting it at $\sigma_{Y\,\mathrm{min}}$. The value $\delta = 0.1$ shifted it up 10%, which was held to be a reasonable compromise.

For UVS data, the relative abundance index Y_{kt}^{UVS} uses numbers instead of biomass, and does not have to be adjusted for social learning. Also UVS data are defined on Populations instead of Bioregions, because the reefs on which the UVS data were collected are known. Instead of the adjusted biomass $\tilde{B}_{gt}$ in a Subregion g, UVS uses the total number of fish vulnerable (i.e., visible) to UVS in Population k:

$$\tilde{N}_{kt} = \sum_{a=0}^{a_{\max}} V_a^{\mathrm{UVS}} N_{kta},$$

where V_a^{UVS} is the age-dependent vulnerability to UVS, which is defined in the same way as V_a (see equations (D4) and (D5)), but with different parameters (see Table 36). Instead of $\tilde{B}_{g\,t} \big/ \tilde{H}_{g\,t}$, the model's abundance index is now $\tilde{N}_{k\,t} \big/ H_{k\,t}$. The negative log-likelihood is the same as (D12) but with a different value n_Y^{UVS} for n_Y, and different expressions $\hat{\sigma}_Y^{\text{UVS}}$ for $\hat{\sigma}_Y$ and $\tilde{\sigma}_Y^{\text{UVS}}$ for $\tilde{\sigma}_Y$. The lower bound $\sigma_{Y\min}^{\text{UVS}}$ still takes the value 1.

Likelihood for absolute abundance measures

A discussed above, the likelihoods for absolute abundance measures $A_{k\,t}$ do not contain the mean-offset parameter μ in (D11), as it is set equal to zero. Then (D11) becomes

$$\ell = \sum_k \sum_t \left[\log\sigma - \tfrac{1}{2}\log w_{k\,t} + \tfrac{1}{2} w_{k\,t} \left\{ \log A_{k\,t} - \log\left(\tilde{N}_{k\,t} \big/ H_{k\,t} \right) \right\}^2 \big/ \sigma^2 \right],$$

where k denotes a Subbioregion and t a year; the standard deviation parameter σ and weighting factors $w_{k\,t}$ are different to those in (D11). The final negative log-likelihood (D12) becomes

$$\ell = n_A \log \tilde{\sigma}_A + \tfrac{1}{2} n_A \, \hat{\sigma}_A^2 \big/ \tilde{\sigma}_A^2 \,, \qquad \text{(C15)}$$

where n_A is the total number of Subbioregion–year combinations in the index series,

$$\hat{\sigma}_A^2 = \sum_k \sum_t \left[w_{k\,t} \left\{ \log A_{k\,t} - \log\left(\tilde{N}_{k\,t} \big/ H_{k\,t} \right) \right\}^2 \right] \Big/ n_A \,,$$

$$\tilde{\sigma}_A = \max(\hat{\sigma}_A \,, \sigma_{A\,\min}) \qquad \text{(C16)}$$

and $\sigma_{A\,\min} = 1$. The number of degrees of freedom is n_A, not $n_A - 1$, because the mean μ is no longer estimated. The max function in (D16) was also made into a smooth function in the same way as in equation (D14).

Likelihood for age frequencies and length frequencies

An age frequency consists of a number of fish y_a measured in each age class $a = 0, \ldots, a_{\max}$. When each fish is considered to be independent of all other fish, the likelihood of a single age frequency is multinomial:

$$\binom{y_{\text{tot}}}{y_0 \,, \ldots, \, y_{a_{\max}}} \prod_{a=0}^{a_{\max}} p_a^{\;y_a} \,, \qquad \text{(C17)}$$

where y_{tot} is the total number of fish whose ages are measured (sum of the y_a), p_a is the model's predicted proportion of fish in age-class a, the multinomial coefficient is defined as

$$\binom{y_{\text{tot}}}{y_0 \,, \ldots, \, y_{a_{\max}}} = y_{\text{tot}}! \Big/ \prod_{a=0}^{a_{\max}} y_a! \,,$$

and the factorial function is defined as

$$y! = \prod_{i=1}^{y} i \,.$$

In practice, sampled fish are not independent, and instead of the total number y_{tot} the sample has an "effective sample size" that is usually much less than y_{tot} (Pennington and Vølstad, 1994; McAllister and Ianelli, 1997; Francis, 2011). We deal with the problem of effective sample size by adjusting the multinomial likelihood. The approach estimates the effective sample size from the "raggedness" of the age-frequency distribution: a smooth distribution gives a high effective sample size, and a very ragged one gives a low effective sample size. It does not use the actual sample size y_{tot}.

We accept the point made by Francis (2011) that this approach will overestimate the effective sample size if the sample distribution is smooth but biased towards either old fish or young fish. We believe that this is not a major problem in fishery-independent sampling of Queensland fish populations, in which the sample age distributions tend to be ragged and show little sign of smoothness. The mathematical form proposed by Francis is complex, which makes it difficult to visualise how his method works. We put substantial resources into trying to derive sensible answers from it in the eastern king prawn fishery on the Australian east coast, but without success. That project eventually used the same approach documented here (O'Neill et al., 2014).

We believe that the method we use, although not perfect, is the best method currently available for adjusting age-frequency likelihoods for effective sample size. It differs from the one used by Cabezon which abandoned the multinomial likelihood and replaced it by a sum of squares analogous to a chi-square statistic. We retain the multinomial likelihood as far as possible.

Firstly, we note that zero values of y_a in (D17) make no contribution to the likelihood. Hence we restrict the likelihood to ages a for which $y_a > 0$. We let q denote the number of such ages and Q denote the set of these ages. Then the likelihood (D17) becomes

$$\left\{ y_{\text{tot}}! \Big/ \prod_{a\in Q} y_a! \right\} \prod_{a\in Q} p_a{}^{y_a} . \tag{D18}$$

We introduce the effective sample size, denoted T, so that an observation of y_a fish of age a in the sample of size y_{tot} is transformed to an effective observation of $(T/y_{\text{tot}})y_a$ fish from a sample of size T. We also treat the likelihood (D18) like a probability density function (p.d.f.) of the y_a in $q-1$ dimensions; the number of dimensions is $q-1$ rather than q because the y_a are not independent but are constrained to sum to y_{tot}. The transformed likelihood has to remain a p.d.f. of y_a, not of $(T/y_{\text{tot}})y_a$, which necessitates multiplying by the factor $(T/y_{\text{tot}})^{q-1}$. Therefore the likelihood (C18) is transformed to

$$(T/y_{\text{tot}})^{q-1} \left\{ T! \Big/ \prod_{a\in Q} (Ty_a/y_{\text{tot}})! \right\} \prod_{a\in Q} p_a{}^{Ty_a/y_{\text{tot}}} . \tag{D19}$$

When Ty_a/y_{tot} is not an integer, the factorial function can be replaced by the gamma function. e approximate the factorial function by Stirling’s formula which is a well-known formula in mathematics:

$$x! \sim \sqrt{2\pi x}\, x^x e^{-x} .$$

This approximation becomes extremely close as $x \rightarrow \infty$, but for practical purposes is also close for small x, e.g., $x \geq 1$. Then, omitting constant factors and factors involving only the data y_a, the likelihood (D19) becomes

$$T^{q-1} \left\{ T^{T+\frac{1}{2}} e^{-T} \Big/ \left[T^{q/2} \prod_{a\in Q} \left\{ (Ty_a/y_{\text{tot}})^{Ty_a/y_{\text{tot}}} e^{-Ty_a/y_{\text{tot}}} \right\} \right] \right\} \prod_{a\in Q} p_a{}^{Ty_a/y_{\text{tot}}} ,$$

which, with some algebraic manipulation, can be simplified to

$$T^{(q-1)/2} \prod_{a\in Q} (p_a/\hat{p}_a)^{T\hat{p}_a} ,$$

where $\hat{p}_a = y_a/y_{\text{tot}}$ is the observed proportion of fish of age a in the sample. This produces the negative log-likelihood

$$\ell = -\tfrac{1}{2}(q-1)\log T + T\sum_{a\in Q} \hat{p}_a \log(\hat{p}_a/p_a) . \tag{D20}$$

(Note that $p_a/\hat{p}_a$ has been replaced by $\hat{p}_a/p_a$ to reverse the sign of the log factor.)

The effective sample size T is estimated by maximum likelihood, by minimising the negative log-likelihood (D20):

$$\hat{T} = \tfrac{1}{2}(q-1) \Big/ \sum_{a \in Q} \hat{p}_a \log(\hat{p}_a / p_a) . \qquad \text{(D21)}$$

In the theory of generalised linear models (see McCullagh and Nelder, 1989, p. 197), this is also the estimate produced by equating the deviance of the multinomial model, $2T \sum \hat{p}_a \log(\hat{p}_a / p_a)$ to its asymptotic, large-sample expectation, $q-1$. Substituting the estimate (D21) into the negative log-likelihood (C20), and ignoring the resulting constant term, yields the final negative log-likelihood for the age-frequency sample:

$$\ell = -\tfrac{1}{2}(q-1)\log \hat{T} . \qquad \text{(D22)}$$

For every available age-frequency sample, the negative log-likelihood given by (D22) and (D21) is added into the overall negative log-likelihood for the model. Using this formulation it would be easy to impose a lower bound $T_{\min}$ on the effective sample size T for each sample, e.g., to force $T \geq 1$ or $T \geq 2$, but we did not consider it necessary to do that. The negative log-likelihood for such a case would be

$$-\tfrac{1}{2}(q-1)\log \tilde{T} + \tfrac{1}{2}(q-1)\tilde{T} \big/ \hat{T} ,$$

where $\tilde{T} = \max(\hat{T}, T_{\min})$.

We note that, in the fishery-independent sampling programs that provided age-frequency data for this fishery, nearly all fish sampled were aged. Therefore we did not need to deal with the additional complexity of age-length keys to combine length frequencies with ageing data on some of the fish to produce overall age-frequencies.

Length-frequency samples were handled in exactly the same way as age-frequency samples. Each age-frequency or length-frequency produced a term of the form (D22) that was added into overall negative log-likelihood for the model.

Because the age-frequency and length-frequency samples were collected scientifically and were not subject to minimum legal size limits, the size-limit adjustments to the vulnerability functions (see “Size limits” above) were not employed in calculating the predicted age- and length-frequencies.

Likelihood for recruitment deviations

The recruitment deviations d_t were assumed to follow a lognormal distribution and were treated identically to the relative abundance indices (“Likelihood for relative abundance measures” above). This produced a single term to add into the overall negative log-likelihood.

E. References

Adams, S. A., Mapstone, B. D., Russ, G. R. and Davies, C. R. (2000). Geographic variation in the sex ratio, sex specific size, and age structure of *Plectropomus leopardus* (Serranidae) between reefs open and closed to fishing on the Great Barrier Reef. *Canadian Journal of Fisheries and Aquatic Sciences* **57**, 1448–1458.

Assenov, Y., et al. (2008). Computing topological parameters of biological networks. Bioinformatics **24**(2): 282-284.

Atema, J., Kingsford, M. J. and Gerlach, G. (2002). Larval reef fish could use odour for detection, retention and orientation to reefs. *Marine Ecology Progress Series* **241**, 151–160.

Ayling, A. M. and Ayling, A. L. (1986). *Coral Trout Survey Data*. Daintree, Qld, Australia: Sea Research. Downloaded 20130308.

Ayling, A. M. and Ayling, A. L. (2000). Where are All the Coral Trout? http://www.searesearch.com.au/reports/wheretrt/wheretrt.html. Downloaded 20131218.

Barabási, A.-L. (2005). Network Theory--the Emergence of the Creative Enterprise. Science **308**(5722): 639-641.

Barabási, A.-L. (2009). Scale-Free Networks: A Decade and Beyond. Science **325**(5939): 412-413.

Barabási, A.-L. and Albert R. (1999). Emergence of Scaling in Random Networks. Science **286**(5439): 509-512.

Beinssen, K. (1989). *Results of the Boult Reef Replenishment Area Study*. Brisbane: Queensland Department of Environment and Conservation.

Beverton, R. J. H. and Holt, S. J. (1957). *On the Dynamics of Exploited Fish Populations*. London: Chapman and Hall.

Brandes, U. (2001). A faster algorithm for betweenness centrality. The Journal of Mathematical Sociology 25(2): 163-177.

Brown, I. W., Doherty, P., Ferreira, B. P., Keenan, C. P., McPherson, G. R., Russ, G. R., Samoilys, M. and Sumpton, W. D. (1994). *Growth, Reproduction and Recruitment of Great Barrier Reef Food Fish Stocks*. Brisbane: Queensland Department of Primary Industries. Downloaded 20130311.

Brown, I. W., Sumpton, W. D., McLennan, M. F., Welch, D. J., Kirkwood, J. M., Butcher, A. R., Mapleston, A., Mayer, D. G., Begg, G. A., Campbell, M. D., Halliday, I. and Sawynok, W. (2008). *National Strategy for the Survival of Released Line-caught Fish: Tropical Reef Species*. Brisbane: Queensland Department of Primary Industries and Fisheries. http://frdc.com.au/research/Documents/Final_reports/2003-019-DLD.pdf. Downloaded 20130311.

Carter, A., Williams, A. J., Russ, G. R. and Tobin, A. (2009a). The effects of no-take zoning, region and year on reproductive output of the common coral trout, *Plectropomus leopardus*. *International Marine Conservation Congress Annual Convention*, Washington, DC, 17–24 May 2009.

Carter, A. B., Williams, A. J. and Russ, G. R. (2009b). Increased accuracy of batch fecundity estimates using oocyte stage ratios in *Plectropomus leopardus*. *Journal of Fish Biology* **75**, 716–722.

Coleman, F. C., Koenig, C. C. and Collins, L. A. (1996). Reproductive styles of shallow-water groupers (Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. *Environmental Biology of Fishes* **47**, 129–141.

Cope, J. M., Piner, K., Minte-Vera, C. V. and Punt, A. E. (2003). *Status and Future Prospects for the Cabezon (Scorpaenichthys marmoratus) as Assessed in 2003* Portland, OR: Pacific Fishery Management Council. http://www.pcouncil.org/wp-content/uploads/Cabezon_2003_Assessment.pdf. Downloaded 20140221.

Craig, M. T., Sadovy de Mitcheson, Y. J. and Heemstra, P. C. (2011). *Groupers of the World: A Field and Market Guide*. Grahamstown, South Africa: National Inquiry Services Centre.

Davies, C. R. (2000). *Inter-reef movement of the common coral trout, Plectropomus leopardus*. Townsville: Great Barrier Reef Marine Park Authority, Research Publication No. 61. http://hdl.handle.net/11017/344. Downloaded 20140122.

Erdős, P. and Rényi A. (1959). On random graphs. Publicationes Mathematicae Debrecen **6**: 290-297.

Evans, R. D., van Herwerden, L., Russ, G. R. and Frisch, A. J. (2010). Strong genetic but not spatial subdivision of two reef fish species targeted by fishers on the Great Barrier Reef. *Fisheries Research* **102**, 16–25.

Fernandes, L., et al. (2005). Establishing Representative No-Take Areas in the Great Barrier Reef: Large-Scale Implementation of Theory on Marine Protected Areas. Conservation Biology **19,** 1733-1744.

Ferreira, B. P. (1993). Reproduction of the inshore coral trout *Plectropomus maculates* (Perciformes: Serranidae) from the Central Great Barrier Reef, Australia. *Journal of Fish Biology* **42**, 831–844.

Ferreira, B. P. (1995). Reproduction of the common coral trout *Plectropomus leopardus* (Serranidae: Epinephelinae) from the central and northern Great Barrier Reef, Australia. *Bulletin of Marine Science* **56**, 653–669.

Ferreira, B. P. and Russ, G. R. (1992). Age, growth and mortality of the Inshore Coral Trout *Plectropomus maculatus* (Pisces: Serranidae) from the Central Great Barrier Reef, Australia. *Australian Journal of Marine and Freshwater Research* **43**, 1301–1312.

Ferreira, B. P. and Russ, G. R. (1994). Age validation and estimation of growth rate of the coral trout, *Plectropomus leopardus*, (Lacepede 1802) from Lizard Island, northern Great Barrier Reef. *Fishery Bulletin* **92**, 46–57.

Fisher, R. (2005). Swimming speeds of larval coral reef fishes: Impacts on self-recruitment and dispersal. *Marine Ecology Progress Series* **285**, 223–232.

Fournier, D. A., Skaug, H. J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M. N., Nielsen, A. and Sibert, J. (2012). AD Model Builder: Using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optimization Methods and Software* **27**, DOI: 10.1080/10556788.2011.597854.

Francis, R. I. C. C. (2011). Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* **68**, 1124–1138.

Fulton, E. A., Smith, A.D.M, and Smith D.C. (2011). Human behaviour: the key source of uncertainty in fisheries management. Fish and Fisheries **12**, 2-17.

GBRMPA (2009). *Great Barrier Reef Outlook Report 2009*. Townsville: Great Barrier Reef Marine Park Authority. http://www.gbrmpa.gov.au/__data/assets/pdf_file/0018/3843/OutlookReport_Full.pdf. Downloaded 20131217.

Gerlach, G., Atema, J., Kingsford, M. J., Black, K. P. and Miller-Sims, V. (2007). Smelling home can prevent dispersal of reef fish larvae. *Proceedings of the National Academy of Sciences* **104**, 858–863.

Goeden, G. B. (1978). *A Monograph of the Coral Trout, Plectropomus leopardus (Lacepédè)*. Brisbane: Queensland Fisheries Service. Downloaded 20120516.

Goeden, G. B. (1979). Is the Great Barrier Reef being Overfished? *Australian Fisheries*, September 1979, 18–20.

Goodyear, C. P. (1977). Assessing the impact of power plant mortality on the compensatory reserve of fish populations. *Conference on Assessing the Effects of Power Plant Induced Mortality on Fish populations*, Gatlinburg, TN, 3–6 May 1977, 186–195. Pergamon Press.

Haddon, M. (2001). *Modelling and Quantitative Methods in Fisheries*. Boca Raton, FL: CRC Press.

Harrison, H. B., Williamson, D. H., Evans, R. D., Almany, G. R., Thorrold, S. R., Russ, G. R., Feldheim, K. A., van Herwerden, L., Planes, S., Srinivasan, M., Berumen, M. L. and Jones, G. P. (2012). Larval export from marine reserves and the recruitment benefit for fish and fisheries. *Current Biology* **22**, 1023–1028.

Hatcher, A., et al. (2000). Normative and Social Influences Affecting Compliance with Fishery Regulations. Land Economics **76**(3): 448-461.

Haythornthwaite, C. (1996). Social network analysis: An approach and technique for the study of information exchange. Library & Information Science Research **18**(4): 323-342.

Henry, G. W. and Lyle, J. M. (2003). *The National Recreational and Indigenous Fishing Survey*. Canberra: Australian Government Department of Agriculture, Fisheries and Forestry. http://eprints.utas.edu.au/2526/1/Henry_Lyle_Nationalsurvey.pdf. Downloaded 20100216.

Heupel, M. R., Williams, A. J., Welch, D. J., Davies, C. R., Adams, S. A., Carlos, G. and Mapstone, B. D. (2010). Demography of a large exploited grouper, Plectropomus laevis: Implications for fisheries management. *Marine and Freshwater Research* **61**, 184–195.

Higgs, J. (1999). *RFISH Technical Report No. 2: Results from the 1997 Diary Round*. Brisbane: Queensland Department of Primary Industries. Downloaded 20100514.

Higgs, J. (2001). *Recreational Catch Estimates for Queensland Residents. RFISH Technical Report No. 3*. Brisbane: Queensland Department of Primary Industries. Downloaded 20100514.

Higgs, J., Olyott, L. and McInnes, K. (2007). *Experimental Results from the Third Statewide Recreational Fishing Information System Diary Program (2002)*. Brisbane: Queensland Department of Primary Industries and Fisheries. Downloaded 20100514.

Higgs, J. B. (1995). Fishing club activities on the Great Barrier Reef. *State of the Great Barrier Reef World Heritage Area Workshop*, Townsville, 27–29 November 1995, 335–345. Great Barrier Reef Marine Park Authority.

Hopley, D., Smithers, S. G. and Parnell, K. E. (2007). *The Geomorphology of the Great Barrier Reef: Development, Diversity, and Change*. Cambridge, UK: Cambridge University Press.

Jackson, M. O. (2009). An Overview of Social Networks and Economic Applications. The Handbook of Social Economics., ed. Jess Benhabib, Alberto Bisin and Matthew O. Jackson. Elsevier Press. forthcoming.

Kingsford, M. J. (1992). Spatial and temporal variation in predation on reef fishes by coral trout (*Plectropomus leopardus*, Serranidae). *Coral Reefs* **11**, 193–198.

Lambeck, K., Esat, T. M. and Potter, E.-K. (2002). Links between climate and sea levels for the past three million years. *Nature* **419**, 199–206.

Leigh, G. M., Williams, A. J., Begg, G. A., Gribble, N. A. and Whybird, O. J. (2006). *Stock Assessment of the Queensland East Coast Red Throat Emperor (Lethrinus miniatus) fishery*. Brisbane: Queensland Department of Primary Industries and Fisheries. http://www.dpi.qld.gov.au/28_11074.htm. Downloaded 20140210.

Leight, G.L., Campbell, A.B., Lunow, C.P., and O'Neill, M.F. (2014). *Stock assessment of the Queensland east coast common coral trout (Plectropomus leopardus) fishery.* Technical Report. Queensland Department of Agriculture, Fisheries and Forestry.

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

Little, L. R., Punt, A. E., Mapstone, B. D., Begg, G.A., Goldman, B. and Williams, A.J. (2009). An agent-based model for simulating trading of multi-species fisheries quota. *Ecological Modelling* **220**, 3404–3412.

Loubens, G. (1978). Biologie de quelques espèces de poisson du lagon néo-calédonien : 1. Détermination de l'âge (otolithométrie). *Cahiers ORSTOM, Série Océanographie* **16**, 263–283.

Loubens, G. (1980). Biologie de quelques espèces de poissons du lagon néo-calédonien : 2. Sexualité et reproduction. *Cahiers de l'Indo-Pacifique* **2**, 41–72.

Mackie, M. C. (2003). Socially controlled sex-change in the half-moon grouper, *Epinephelus rivulatus*, at Ningaloo Reef, Western Australia. *Coral Reefs* **22**, 133–142.

Madin, E. M. P., Madin, J. S. and Booth, D. J. (2011). Landscape of fear visible from space. *Nature Scientific Reports* **1**, article no. 14.

Mapstone, B. D., Carlos, G., Lunow, C. P. and Reid, A. E. (2004a). *Uncertainty in Length Measurements of Live Coral Trout: Implications for Compliance to and Enforcement of Minimum Legal Size Limits*. Townsville: CRC Reef Research Centre, Technical Report No. 54. http://www.reef.crc.org.au/publications/techreport/pdf/Technical%20Report%2054.pdf. Downloaded 20140203.

Mapstone, B. D., Davies, C. R., Little, L. R., Punt, A. E., Smith, A. D. M., Pantus, F., Lou, D. C., Williams, A. J., Jones, A., Ayling, A. M., Russ, G. R. and McDonald, A. D. (2004b). *The Effects of Line Fishing on the Great Barrier Reef and Evaluations of Alternative Potential Management Strategies*. Townsville: CRC Reef Research Centre. Downloaded 20111012.

McAllister, M. K. and Ianelli, J. N. (1997). Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 284–300.

McCullagh, P. and Nelder, J. A. (1989). *Generalized Linear Models*. Second ed. Springer.

McPherson, G. R., Squire, L., O'Brien, J. and Goeden, G. B. (1985). Great Barrier Reef Demersal Fish Research. *Seventeenth Regional Technical Meeting on Fisheries*, Noumea, 5–9 August 1985. South Pacific Commission.

Newman, M. E. J. (2003). A measure of betweenness centrality based on random walks. eprint arXiv:cond-mat/0309045.

NOAA (2006a). *Gulf of Mexico Red Grouper: SEDAR 12 Stock Assessment Report 1*. National Oceanic and Atmospheric Administration. http://www.sefsc.noaa.gov/sedar/download/S12SAR1%20Gulf%20Red%20Grouper%20Completev2.pdf?id=DOCUMENT. Downloaded 20131118.

NOAA (2006b). *SEDAR 10 Stock Assessment Report: Gulf of Mexico Gag Grouper*. National Oceanic and Atmospheric Administration. http://www.sefsc.noaa.gov/sedar/download/S10SAR2%20GOM%20Gag%20Assessment%20Report.pdf?id=DOCUMENT. Downloaded 20131118.

NOAA (2011). *SEDAR 23 Stock Assessment Report: South Atlantic and Gulf of Mexico Goliath Grouper*. National Oceanic and Atmospheric Administration. http://www.sefsc.noaa.gov/sedar/download/S23_SAR_complete_and_final.pdf?id=DOCUMENT. Downloaded 20131118.

O'Neill, M. F., Leigh, G. M., Wang, Y.-G., Braccini, J. M. and Ives, M. C. (2014). Linking spatial stock dynamics and economics: Evaluation of indicators and fishery management for the travelling eastern king prawn (*Melicertus plebejus*). *ICES Journal of Marine Science*.

Pennington, M. and Vølstad, J. H. (1994). Assessing the effect of intra-haul correlation and variable density on estimates of population characteristics from marine surveys. *Biometrics* **50**, 725–732.

Ramirez-Sanchez, S. and Pinkerton E. (2009). The impact of resource scarcity on bonding and bridging social capital: the case of fishers’ information-sharing networks in Loreto, BCS, Mexico. Ecology and Society **14**(1): 22.

Randall, J. E. (1997). *Randall's Underwater Photos: Collection of Almost 2000 Underwater Photos*: Unpublished. Creative Commons by Attribution Licence for non-commercial use. http://www.fishbase.org. Downloaded December 2013.

Randall, J. E. and Hoese, D. F. (1986). *Revision of the Groupers of the Indo-Pacific Genus Plectropomus (Perciformes: Serranidae)*. Honolulu: Bishop Museum.

Russ, G. R. (1984). A review of coral reef fisheries. *Productivity and Processes in Island Marine Ecosystems: Recommendations and Scientific Papers from the Unesco/IOC Sessions on Marine Science Co-operation in the Pacific at the XVth Pacific Science Congress, Dunedin, New Zealand, February 1983*, pp. 74–92. UNESCO Report in Marine Science No. 27.

Russ, G. R., Lou, D. C. and Ferreira, B. P. (1995). *A Long-term Study on Population Structure of the Coral Trout Plectropomus leopardus on Reefs Open and Closed to Fishing in the Central Great Barrier Reef*. Townsville: CRC Reef Research Centre, Technical Report No. 3. Downloaded 20120608.

Russ, G. R., Lou, D. C. and Ferreira, B. P. (1996). Temporal tracking of a strong cohort in the population of a coral reef fish, the coral trout, *Plectropomus leopardus* (Serranidae: Epinephelinae), in the central Great Barrier Reef, Australia. *Canadian Journal of Fisheries and Aquatic Sciences* **53**, 2745–2751.

Russ, G. R., Lou, D. C., Higgs, J. B. and Ferreira, B. P. (1998). Mortality rate of a cohort of the coral trout, *Plectropomus leopardus*, in zones of the Great Barrier Reef Marine Park closed to fishing. *Marine and Freshwater Research* **49**, 507–511.

Samoilys, M. A. (1997). Movement in a large predatory fish: Coral trout, *Plectropomus leopardus* (Pisces: Serranidae), on Heron Reef, Australia. *Coral Reefs* **16**, 151–158.

Samoilys, M. A. (2000). *Reproductive Dynamics of an Exploited Serranid on the Great Barrier Reef*. PhD thesis, School of Marine Biology and Aquaculture, James Cook University.

Scott, J. (1991). Social network analysis: A handbook. London: Saga

Sriver, R. L. and Huber, M. (2007). Reply to comment by R. N. Maue and R. E. Hart on “Low frequency variability in globally integrated tropical cyclone power dissipation”. *Geophysical Research Letters* **34**, L11704.

St John, J., Russ, G. R., Brown, I. W. and Squire, L. C. (2001). The diet of the large coral reef serranid *Plectropomus leopardus* in two fishing zones on the Great Barrier Reef, Australia. *Fishery Bulletin* **99**, 180–192.

Starck, W. (2005). "Threats" to the Great Barrier Reef. *IPA Backgrounder* **17**, 1–21.

Stobutzki, I. C. and Bellwood, D. R. (1997). Sustained swimming abilities of the late pelagic stages of coral reef fishes. *Marine Ecology Progress Series* **149**, 35–41.

Strogatz, S. H. (2001). Exploring complex networks. Nature **410**(6825): 268-276.

Sumpton, W. D., Brown, I. W., Mayer, D. G., McLennan, M. F., Mapleston, A., Butcher, A. R., Welch, D. J., Kirkwood, J. M., Sawynok, B. and Begg, G. A. (2010). Assessing the effects of line capture and barotrauma relief procedures on post-release survival of key tropical reef fish species in Australia using recreational tagging clubs. *Fisheries Management and Ecology* **17**, 77–88.

Taylor, S., Webley, J. and McInnes, K. (2012). *2010 Statewide Recreational Fishing Survey*. Brisbane: Department of Agriculture, Fisheries and Forestry. http://www.daff.qld.gov.au/fisheries/monitoring-our-fisheries/statewide-and-regional-recreational-fishing-survey/queenslands-2010-statewide-recreational-fishing-survey. Downloaded 20131218.

Thébaud O, Innes J, Norman A, Tickell S, Cameron D, Cannard T, Slade S, Kung J, Kerrigan B, Little L, Williams L (2012) Economic Survey of the Queensland Commercial Coral Reef Fin-Fish Fishery. CSIRO Marine and Atmospheric Research, Brisbane, Australia.

Thébaud, O., Innes, J., Norman-López, A., Slade, S., Cameron, D., Cannard, T., Tickell, S., Kung, J., Kerrigan, B., Williams, L. and Little, L. R. (2014). Micro-economic drivers of profitability in an ITQ-managed fishery: An analysis of the Queensland Coral Reef Fin-Fish Fishery. *Marine Policy* **43**, 200–207.

van Putten, I. and Gardner, C. (2010). Lease quota fishing in a changing rock lobster industry. Marine Policy **34,** 859-867.

van Putten, I. E., Kulmala, S, Thebaud, O., Dowling, N., Hamon, K.G., Hutton, T. and Pascoe, S. (2011). Theories and behavioural drivers underlying fleet dynamics models. Fish and Fisheries **13**, 216-235.

van Putten, I., Hamon, K.G., and Gardner, C. (2011b) Network analysis of a rock lobster quota lease market. Fisheries Research **107**, 122-130.

von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II). *Human biology* **10**, 181–213.

Wasserman, S. and Faust, K. (1994). Social Network Analysis: Methods And Applications (Structural Analysis In The Social Sciences. Cambridge University Press.

Watts, D. J. and Strogatz, S.H. (1998). Collective dynamics of ‘small-world’networks. Nature **393**(6684): 440-442.

Weisbuch, G., et al. (2000). Market Organisation and Trading Relationships. The Economic Journal **110**(463): 411-436.

Williams, D. M. and Russ, G. R. (1994). *Review of Data on Fishes of Commercial and Recreational Fishing Interest in the Great Barrier Reef.* Townsville: Great Barrier Reef Marine Park Authority, Research Publication No. 33. Downloaded 20130402.

Williams, D. M., Wolanski, E. and Andrews, J. C. (1984). Transport mechanisms and the potential movement of planktonic larvae in the central region of the Great Barrier Reef. *Coral Reefs* **3**, 229–236.

Zeller, D. C., Stoute, S. L. and Russ, G. R. (2003). Movements of reef fishes across marine reserve boundaries: Effects of manipulating a density gradient. *Marine Ecology Progress Series* **254**, 269–280.

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