Setting economic target reference points for multiple species in mixed fisheries

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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Science
AFMA	Australian Fisheries Management Authority
BBN	Bayesian Belief Network
BN	Bayesian Network
B_{MEY}	Biomass at maximum economic yield
B_{MSY}	Biomass at maximum sustainable yield
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
GAB	Great Australian Bight (fishery)
HSP	(Commonwealth) Harvest Strategy Policy
LRP	Limit reference point
MEY	Maximum economic yield
MSY	Maximum sustainable yield
NER	Net economic returns
NPF	Northern Prawn Fishery
SESSF	Southern and Eastern Shark and Scalefish Fishery
TRP	Target reference point

Executive Summary

What the report is about

Improving the economic performance of Australian fisheries requires identifying appropriate target reference points, which are often measured in terms of the biomass level for each species. Within multispecies fisheries, identifying the level of biomass that is associated with maximum economic yield (MEY) requires detailed bioeconomic models of the fisheries. For many fisheries, such models are unavailable, so some form of cost effective proxy measure is required to estimate approximate target reference points based on, in some cases, limited information.

In this study, we develop a framework for estimating appropriate economic target reference points for species within mixed fisheries. We test the framework against a case study fishery, and find that the framework, while not perfect, is able to perform better than current default assumptions about the target reference points.

Background

The Commonwealth Fisheries Harvest Strategy Policy (HSP) and Guidelines (DAFF 2007) state that "fisheries harvest strategies for key commercial stocks should be designed to pursue maximising the economic yield from the fishery, and ensure stocks remain above the levels at which the risk to the stock is unacceptably high". With these objectives in mind, the target biomass is that which produces MEY, or B_{MEY}. In fisheries where B_{MEY} is unknown, a proxy of $1.2B_{MSY}$ is to be used instead, where B_{MSY} is the biomass at maximum sustainable yield. In fisheries that target or catch multiple species, the guidelines propose to apply MEY "across all species in the fishery", implying that secondary (lower valued) species may be fished at levels that result in biomass levels lower than their individual B_{MEY} but above their limit reference point . In such cases, the biomass of some species at the fishery-wide MEY may be lower than the biomass at which MEY would be reached if each species was caught independently of the others, while for other species it may be higher.

However, identifying an appropriate target reference point for species within a multispecies fishery is complex. There is currently no standard framework to determine target reference points for individual stocks within a multispecies fishery to generate MEY for the fishery as a whole. Simple single species indicators such as the 1.2 B_{MSY} proxy for B_{MEY} is unlikely to be appropriate, especially for species that make up a small proportion of the catch.

Aims/objectives

The aim of this project is to develop a framework that will assist managers in developing target reference points consistent with the HSP in multispecies and mixed fisheries. The project specifically aims to address the problem of determining appropriate target reference points for both target and byproduct species, as these are dependent not only on their own biological (e.g. growth, reproductive and mortality parameters) and economic (e.g. prices and costs of harvest) characteristics, but also the biological and economic characteristics of their associated species. The specific objectives were to:

1. Develop a framework to cost effectively determine target reference points for target and non-target stocks in multispecies fisheries, pursuant with the Commonwealth Harvest Strategy Policy (HSP) objectives of maximum economic yield; and

2. Demonstrate the applicability of the framework developed using a case study fishery

Methodology

The analytical part of the project involved three main stages, summarised in Figure 1. Prior to developing the models, a comprehensive review of existing literature on estimate MEY in multispecies fisheries was undertaken.

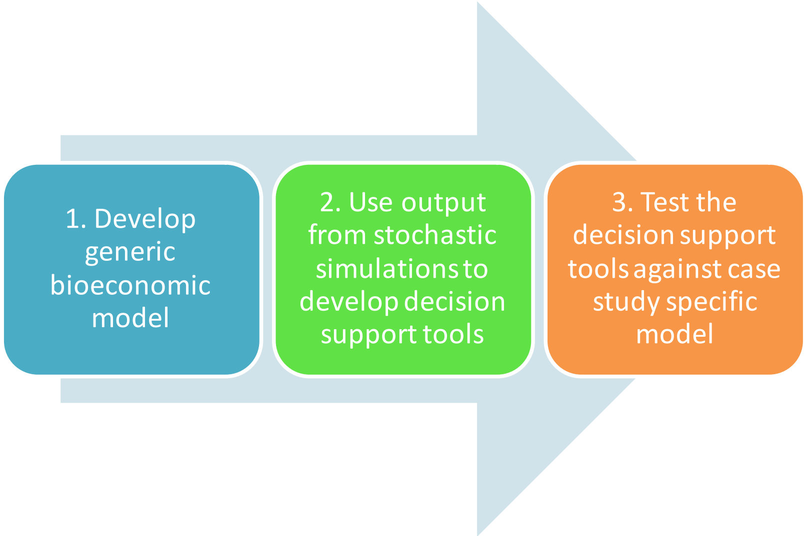

Figure 1. Outline of the methods employed

First, a "generic" multispecies bioeconomic model of a mixed fishery was developed. The model was run stochastically, varying the number of species and their individual biological and economic characteristics. The model was an optimisation model with the objective of maximising total fishery profits across all species, and the resultant optimal biomass of each species (B_{MEY}) was compared with the biomass that would produce its maximum sustainable yield (B_{MSY}) to produce a target reference point consistent with the current management framework. From this, a wide range of biological and economic conditions were considered.

The output from the model was used to develop the generic decision support framework. Two approaches were used to develop this framework: (1) the use of a regression tree to provide a simple set of "rules of thumb" for determining an appropriate target reference point; and (2) a Bayesian network to provide an estimate of the likely probability of a target reference point given the information known about the fishery and species. The models were also used to assess the impact on profits of imposing the estimated proxy reference point on the dominant species only and also the impact of imposing the default target reference point of $B_{MEY}=1.2B_{MSY}$.

A separate model of a specific multispecies multi-fleet fishery was developed, based on the trawl component of the Southern and Eastern Scalefish and Shark Fishery (SESSF). Two forms of the model were developed – a dynamic model that takes into account the current state of the fishery and the discount rate, and an equilibrium model that considers only the long run outcomes. Maximum economic yield was estimated in both models (i.e. dynamic and static maximum economic yield) and the target reference points identified. The generic framework was also used to estimate the proxy target reference points, and these were compared with the more fishery specific estimates.

Results

The results from the generic models suggest the key determinants of the target reference point of individual species in multispecies mixed fisheries are catchability, growth rates and share of total fishery revenue. Other variables, such as costs of fishing, prices and number of species in the fishery are also influential but to a lesser degree. Imposing the outcomes from the decision support frameworks on the fishery resulted in profit levels close to those from the "true" optimisation, and substantially closer than by using the default target reference point proxy (i.e. B_{MEY}=1.2B_{MSY}).

The outcomes from the decision support framework were also generally consistent with the target reference points derived from the fishery-specific model. Again, imposing these targets on the fishery specific model resulted in similar levels of profits, and higher levels of profits than when imposing the current default proxy. In the case of the latter, it was impossible to simultaneously achieve the target reference point for all species.

An incidental result from the study is that attempting to impose a target reference point on all species may not be necessary (nor feasible) in multispecies fisheries. Instead, imposing a target on the dominant species (in terms of revenue share) for each sub-fleet results in outcomes close to optimal, and reduces conflicts in catches where target reference points are not perfectly aligned.

A further result from the study is that dynamic maximum economic yield for individual species in a multispecies fishery, with the exception of dominant species in terms of revenue share, is close to the static estimate of the target.

Implications for relevant stakeholders

The key implications of the study are that

1. reasonable appropriate estimates of proxy target reference points can be obtained based on limited biological and economic information on the fishery;
2. the use of the current proxy target reference point (i.e. B_{MEY}=1.2B_{MSY}) for all key commercial species is both inappropriate and infeasible in multispecies fisheries; and
3. imposition of target reference points may be best limited to a subset of the key commercial species (based on revenue share) species rather than all key species

Recommendations

- From the results of the study, the designation of a simple default proxy target reference point as BMEY=1.2BMSY needs to be reconsidered, particularly in the case of multispecies fisheries. The results in this study provide an alternative approach for deriving more appropriate target reference points. This approach should be considered by RAGs and MACs in setting future targets.
- Determining an appropriate set of criteria for establishing how many and which species should be controlled is an area for further research. The benefits of this research may be substantial as it is likely to result in lower costs and discarding, and potentially higher profits due to fewer constraints on activities.

Keywords

Target reference points, multispecies fisheries, bioeconomic model, Bayesian networks, regression trees

Introduction

The Commonwealth HSP requires that key commercial stocks be maintained, on average, at a biomass level that produces maximum economic yield (B_{MEY}). In multispecies fisheries, this has been interpreted to be the combination of species biomasses that maximise economic profits for the fishery overall, which may differ substantially from what may be derived in a single species assessment. The HSP requires a set of target reference points for key commercial species consistent with the principle of maximising economic returns from the fishery as a whole to be established. The existence of non-target by-product species affects the optimal yield of the target species (and vice versa), and subsequently their appropriate reference points. There is currently no standard framework to determine target reference points for individual stocks within a multispecies fishery to generate MEY for the fishery as a whole. Simple single species indicators such as the 1.2 B_{MSY} proxy for B_{MEY} may not always be accurate. Similarly, use of reference CPUE rates in cases where data on species are poor is also inappropriate, and is proving problematic. For example, in the SESSF, problems have recently arisen regarding the proposed quotas for Ocean Perch (a by-product species) being incompatible with those for their associated target species (Pink Ling).

The aim of this project is to develop a framework that will assist managers in developing target reference points consistent with the HSP in multispecies and mixed fisheries. The project specifically aims to address the problem of determining appropriate target reference points for both target and byproduct species, as these are dependent not only on their own biological (e.g. growth, reproductive and mortality parameters) and economic (e.g. prices and costs of harvest) characteristics, but also the biological and economic characteristics of their associated species. The project also notes that in some cases there is more than one “target” species during a single fishing effort (tow, pot set, hook set etc). Further, the optimal harvest rates for these target species also depends on the profits associated with the byproduct species (Punt *et al.* 2011).

The setting of appropriate and precise reference points consistent with the Commonwealth Harvest Strategy (i.e. maximum economic yield, MEY) would require a detailed bioeconomic model of the fishery that includes all species that are commercially harvested. Examples of such models are those developed for the Northern Prawn fishery (e.g. Punt et al. 2011) and the Great Australian Bight Trawl fishery (Kompas *et al.* 2012). However, a common problem in Australian fisheries (and internationally) is that the quality and quantity of data for different species varies considerably. For some of the byproduct species, data are very limited. Similarly, for relatively small fisheries, data on the main target species may also be limited. There is a general need, therefore, to develop a harvest strategy framework that could be used to provide appropriate reference points for a wide variety of species with different quantities and quality of data.

The applicability of the frameworks developed is demonstrated using a case study fishery. Discussions with AFMA during early stages of the development of the project suggested that the key fishery that would benefit from such analysis would be the Commonwealth Trawl Sector (formerly South-East Trawl) within the SESSF, which is a multispecies fishery. Early discussions with the South-East MAC also confirmed the need for such work, particularly given that total allowable catches are being set for a wide range of species, many of which are primarily by-product species. Further, the SESSF is also relatively data poor for many species (e.g. there is limited biological information on some of the byproduct species in particular), so is a good test case for some of the methods developed in the project.

Objectives

The project had two key objectives:

1. Develop a framework to cost effectively determine target reference points for target and non-target stocks in multispecies fisheries, pursuant with the Commonwealth Harvest Strategy Policy (HSP) objectives of maximum economic yield; and
2. Demonstrate the applicability of the framework developed using a case study fishery

Method

Method overview

The project was undertaken in four stages, the first involving a literature review and three analytical stages aimed at developing and testing a decision making.

(1) **Undertake literature review:** A comprehensive review of all available literature on MEY in multispecies fisheries was undertaken. Several studies have highlighted the difficulties in targeting individual species within multispecies fisheries from the individual fishers' perspectives (e.g. Squires and Kirkley 1991; Thunberg *et al.* 1995), although relatively few have attempted to determine economically optimal catches from a fleet wide perspective (e.g. Hoff *et al.* 2010), particularly from an operational perspective.

The general applicability of multispecies models for estimating MEY was considered as part of the review. Similarly, the implications of targeting and joint production for MEY were examined in a theoretical context with the aim of informing the subsequent model development.

(2) **Develop generic bioeconomic model**: The key focus of the project was the development of a "generic" bioeconomic model of a mixed fishery from which a framework to estimate appropriate target reference points was developed. The generic bioeconomic model was developed based on the key principles identified in the review. While the aim of the framework was to provide a means to adjust or determine target reference points, it is dynamic in nature as these reference points will change with changes in underlying economic conditions (i.e. prices and costs). Hence, it has the characteristics of a harvest strategy although does not directly link to a target harvest rate. Rather, it identifies the appropriate biomass target given the prevailing economic conditions and underlying biological features of the species.

The model allows for different combinations of fleet types to catch differing combinations of representative species under alternative conditions (e.g. growth rates, initial stock conditions, catchability, prices and costs). The model includes both target and non-target (by-product) species. The species are considered independent biologically (i.e. no predator-prey relationships between the species).

(3) **Conduct simulation based meta-analysis:** The bioeconomic model was run with a wide range of species/fleet combinations, and the model output used to develop a meta-model that summarises the output. The meta-model captures the contribution of different price, cost and fishery conditions to the target reference point measure. This forms the basis of the decision making framework, and provides a means to derive an approximation for the target reference point given limited biological and economic information on the fishery.

Two variants of the meta-model were developed. First, a regression tree was developed to provide a more simple set of decision rules for setting target reference points. Second, a Bayesian Network model was developed to provide a more "detailed" estimate of the target reference point.

(4) **Apply to a generalised case study:** The target strategy framework was applied to the trawl component of the SESSF as a case study. To this end, a simplified bioeconomic model of the fishery was developed that included six separate fishing activities/area combinations. The model is generalised in the sense that it capture key elements of the actual fishery – but is not specified such that tactical evaluations apply. Several variants of the model were developed, including both dynamic and static equilibrium models. The model was used to estimate target reference points in the fishery, and these were compared with the outcomes of the decision making framework derived from the more generic models.

A more detailed description of the methods applied for stages 2-4 is presented below.

Development of a generic bioeconomic model

Ideally, as identified in the literature above, the definition of bioeconomic target reference points would be based on the outcomes from bioeconomic models. However, the development of a series of species or fisheries specific bioeconomic models is a costly exercise, and generally requires more data than are available, especially for some of the less important species (in terms of revenue). The development of bioeconomic models in Australia (and associated economic data collection) has been limited to a relatively small number of fisheries – mostly those that are of relatively high economic importance. An even smaller number of fisheries have these models regularly reviewed and updated.

A key objective of the study was to develop a formal analytical framework on the basis of which a set of rules of thumb could be established, to guide managers in setting appropriate target reference points for species in multispecies fisheries, especially those for which data are limited. The study follows an earlier analysis focusing on single species fisheries, which developed a set of rules of thumb for target reference points based solely on economic and physical characteristics of the fishery (Zhou *et al.* 2012).

We focus particularly on the ratio of B_{MEY} to B_{MSY} as this underlies the current Commonwealth Harvest Strategy (DAFF 2007) in terms of target reference points. As the target reference points are long run equilibrium positions, we use long run equilibrium models to estimate them. Two types of models are commonly applied based on different assumptions about the underlying growth function: the Schaefer model assuming an underlying logistical growth (Schaefer 1954; Schaefer 1957); and the exponential model developed by Fox (1970) based on a Gompertz growth function. Although the logistic model is commonly employed due to its simplicity, the exponential growth model has been found to be more broadly applicable to a wider range of fisheries (Silliman 1971; Halls *et al.* 2006).

While many studies have found that the Fox model often empirically fits the data better than the Schaefer model, they also found that estimates of catch and effort at MEY were similar for the different model forms (e.g. Clarke *et al.* 1992; Chae and Pascoe 2005). This can be illustrated in Figure 1, where the models mostly differ in shape past the point of MSY – a consequence of their different underlying biological assumptions. Although effort and catch at MEY may be similar given both models, the different growth characteristics underlying the models may result in the biomass at MEY being substantially different, especially if expressed as a proportion of the unfished biomass (K) or the biomass at MSY – the two main biological reference points.

In Figure 1a, MSY is achieved at a relatively lower level of biomass with the Fox model (K/e=0.37*K) than the Schaefer model (K/2=0.5*K). However, for a given level of fishing costs and sale prices, the level of effort and catch at MEY are similar given both model assumptions (Figure 1b). However, to reduce sustainable catch below MSY to MEY with the Fox model is associated with a greater increase in biomass. Hence, the ratio of B_{MEY}/B_{MSY} would be expected to be substantially greater in a fishery with exponential (Gompertz) growth than in a fishery with logistic growth.

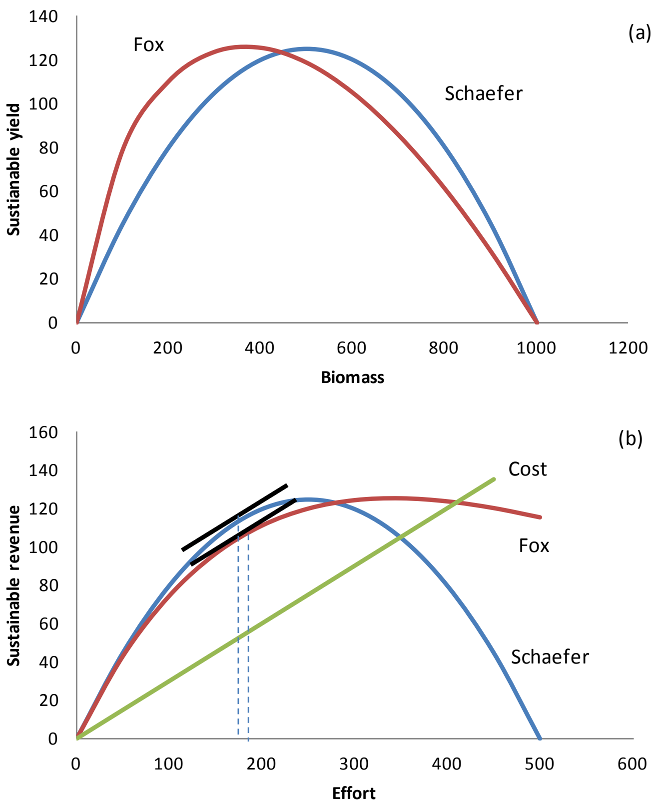

Figure 2. Comparison of (a) growth functions and (b) MEY catch and effort for the two model forms. In both figures, the red line depicts the Fox (1970) model while the blue line depicts the Schaefer (1954) model. In figure 2(b), the lines represent the sustainable revenue for a given level of effort. The green line depicts the total cost curve, assuming a constant average cost per unit of effort. Profits are maximised where the cost line is tangential to the revenue line, which occurs at similar level of fishing effort for both models.

Model descriptions

The models are based on a set of equilibrium yield curves as illustrated in Figure 1 for a mixed fishery, with a randomly varying number of species. The models only differ by the assumption on the growth function. For the Schaefer based model (1a) and Fox model (1b), the equilibrium catch (C_i) of each species i is given by

$$C_i = q_i K_i E - (q_i^2 K_i / r_i) E^2 \quad (1a)$$

$$C_i = q_i K_i E \exp(-q_i E / r_i) \quad (1b)$$

where r_i is the instantaneous growth rate of species *i*, K_i is the carrying capacity of species *i*, q_i is the catchability coefficient of species *i* and *E* is the level of effort applied to the fishery as a whole.

The model is solved as a non-linear optimisation problem with the objective function

$$\underset{E}{Max}\ \Pi = \sum_i p_i C_i - cE \quad (2)$$

where Π is total fishery profits, p_i is the price of species i, and c is the cost per unit of fishing effort. The model determines the level of fishery-wide effort that maximises total fishery profits across all species. The catch of each species at this level of effort is effectively the maximum economic yield of that species.

Of interest in this study is the relationship between biomass at MEY and at MSY. The biomass of each species at MEY is given by

$$B_{MEY_i} = C_i / q_i E \quad (3)$$

whereas B_{MSY} is given by $K_i / 2$ and K_i / e for the Schaefer and Fox model respectively.

Parameter characteristics

The models were run 20,000 times each with the key biological and economic characteristics varying stochastically with a uniform distribution.

The range of parameter values was based around a wide range of species characteristics.[1] Catchability (*q*) was assumed to vary between 0.0001 and 0.05; while the carrying capacity (K) varied between 800 and 60000. Prices were based on the range of prices observed in the domestic market for a wide range of species, and represented by a Poisson distribution with a mean of 2. One (1) was also added to the value to avoid zero prices, effectively giving a mean of 3 with a lowest price of 1. Costs per unit of effort varied randomly with a uniform distribution from 300 to 1800.

An inverse relationship between growth (*r*) and carrying capacity (*K*) was assumed, based on Martell and Froese (2013). This relationship was derived through 10,000 simulations, based on randomly generated values of r and K. The initial values of r were assumed to be log normally distributed with a location parameter of 0.2 and scale parameter of 0.5. The values of K were drawn from the uniform distribution given above. Observations with values of r*K<1000 or r*K>10000 were dropped from the data set, with the before and after distributions of the parameters shown in Figure 2. A log linear

[1] The parameter values used were also informed by the case study. Initially, lower upper bounds were applied, but these were extended based on the information derived from the case study.

regression model of log(r) against log(K) was estimated (Table 1), from which the relationship was established for use in the bioeconomic models. A random error temr was also added to the estimated *r* (given K) with a mean of zero and the standard error given by the residual standard error in Table 1.

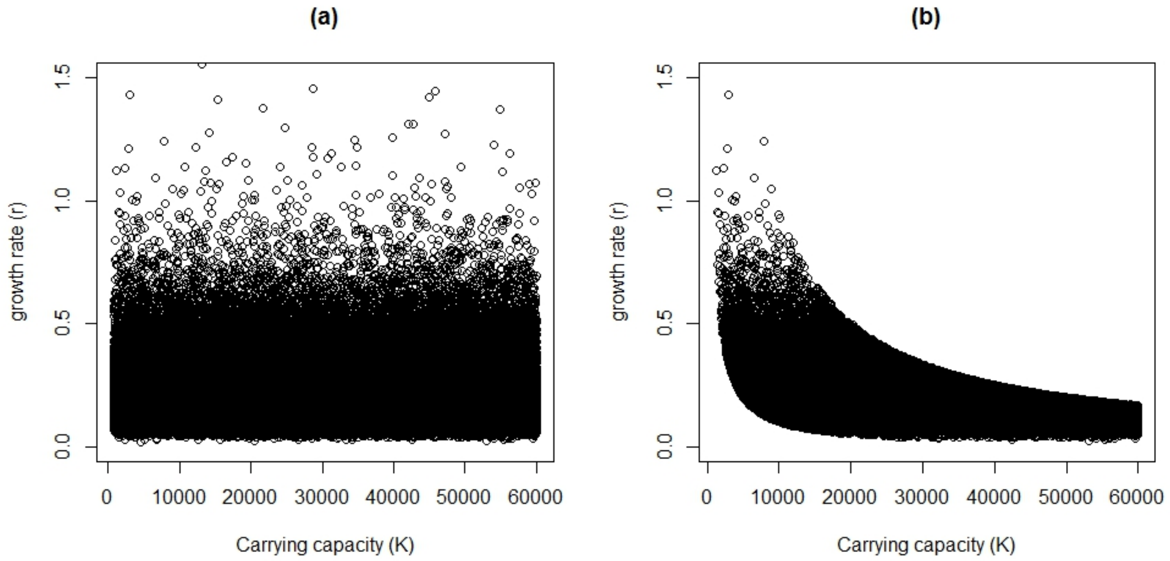

Figure 3. (a) Complete set of randomly generated values and (b) subset with unrealistic combinations removed

Table 1. Regression of log(r) against log(K)

	Estimate	Std error	t value
Intercept	1.461	0.022	66.22
Log(K)	-0.316	0.002	-144.89
Residual standard error	0.395		

The number of species in each model run was based on a uniform distribution with a minimum of 3 and a maximum of 20. The resultant distribution of species in the different simulations is presented in Figure 3.

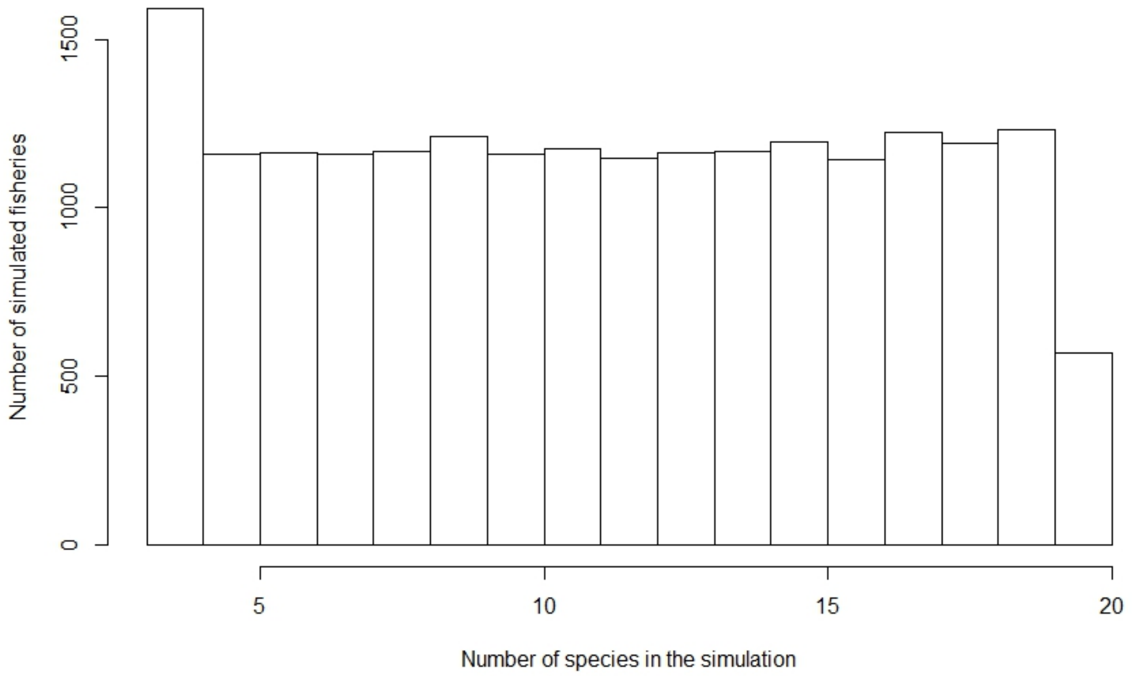

Figure 4. Distribution of the number of species included in the different stochastic simulations

The random combinations of biological parameters resulted in a wide variety of simulated fisheries in terms of similarity of species considered in single simulations. That is, in some simulations the species had similar biological characteristics, while in others they had widely varying characteristics. A concern was that the resultant “rules of thumb” may be affected by the degree of differences between the species that compose individual fisheries. A measure of the similarity of species within a simulation (i.e. within a fishery) was calculated based on a distance measure derived from the geometric means of the coefficients of variation of the growth, catchability and carrying capacity parameters in each simulation. The distribution of these distance measures (representing the degree of species similarity within simulated fisheries) is given in Figure 4. The simulations included some fisheries that consisted of species with very similar characteristics, and others with very different characteristics.

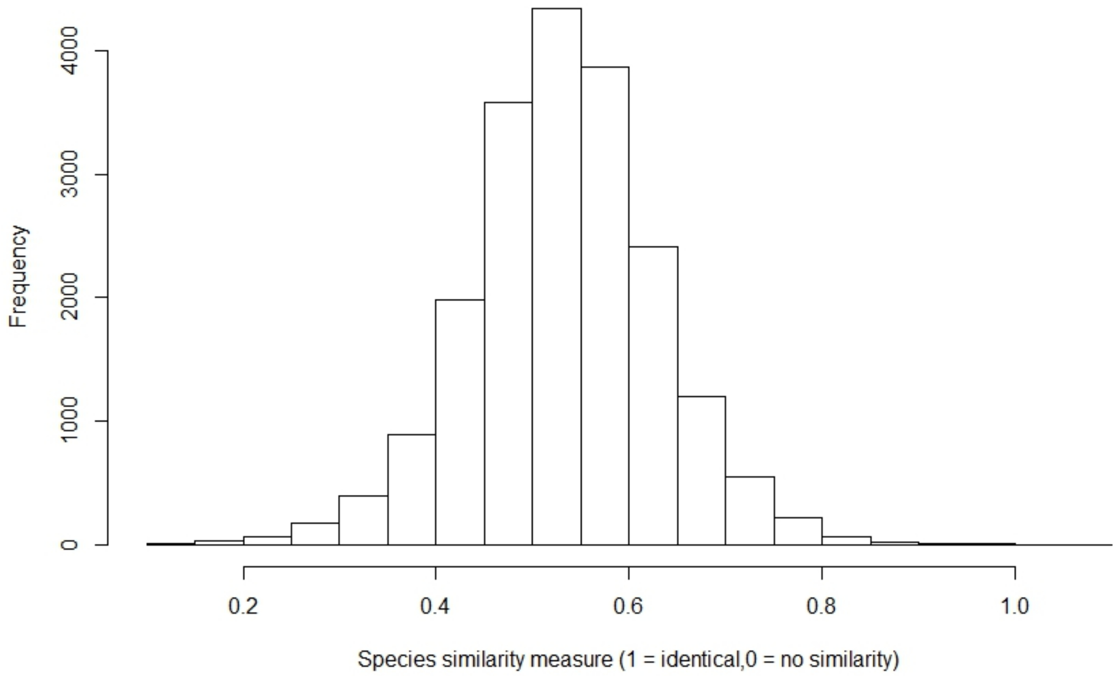

Figure 5. Distribution of species similarity index values (i.e. distance measure) within the simulated fisheries

In most mixed fisheries, much of the revenue is provided by a small set of species even though a much larger number of species is commercially landed. These key species are most likely to have more information than the less valuable species, and hence are more likely to be candidates for formal stock assessments. The contribution of each species in total revenue for a given fishery can be measured as the revenue share of this species: $p_i C_i / \sum_i p_i C_i$. The distribution of the revenue shares and the maximum revenue share in each simulation is given in Figure 5. From this figure, most species individually contributed less than 10 per cent of the total revenue, with the highest proportion of species each contributing less than 5 per cent of revenue. However, most simulations had at least one species with a revenue share of 20% or greater.

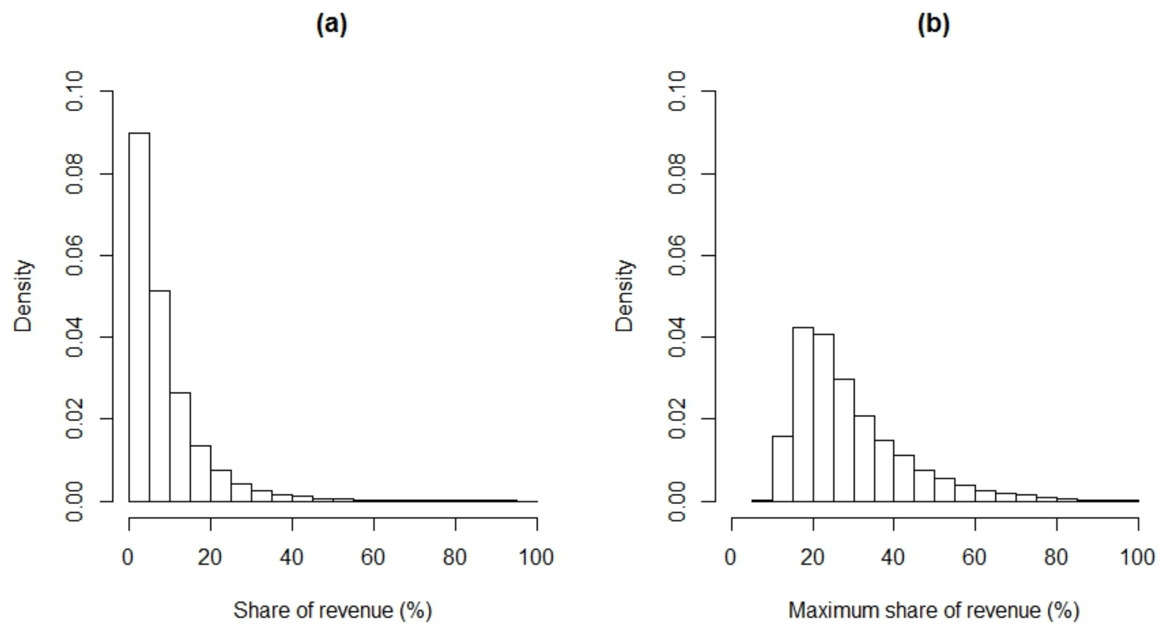

Figure 6. Distribution of (a) revenue shares and (b) maximum revenue share in the set of simulated fisheries

Development of a generic decision support system

Two approaches were applied in the development of the generic decision support system: Classification and Regression Tree (CART) analysis and Bayesian Network analysis. Both have advantages and disadvantages. The regression tree (CART) approach provides a simple set of "rules of thumb" for determining an appropriate target reference point. However, this provides a deterministic outcome only without a measure of uncertainty around the value. The Bayesian Network has an additional feature in that it can capture both uncertainty in the species characteristics as well as uncertainty in the outcome. Both these approaches are described below.

CART analysis

Classification and regression tree analysis is a non-parametric approach to classifying outcomes as a function of a series of inputs or conditions. CART is analogous in some respects to a clustering technique, but rather than grouping similar outcomes together, it takes into consideration the values associated with the characteristics leading to each outcome. The results of the CART analysis is a dichotomous decision tree, where each path – defined by a series of dichotomous splits – specifies the conditions that lead to the most probable outcome. Hence, the tree can be viewed as a series of rules that can be used to predict the most likely outcome given an underlying set of conditions (Lawrence and Wright 2001). That is, each terminal node is uniquely defined by a set of rules.

The CART approach involves a series of binary splits, where the data are split into two groups based on a key input, and these groups are subsequently split into a further two groups (and so on). Each branch of the tree ends in a terminal node, and each observation falls into one and exactly one terminal node. The approach can use either to model either categorical (e.g. a rank) or numerical outcomes (e.g. price of a house, or in this case the target reference point).

Since the model is non-parametric, no assumptions are necessary in terms of the underlying distributions of the input or output data. Further, CART can utilise both numerical data as well as categorical predictors that may be either ordinal or cardinal (Lewis 2000). CART has been applied in a wide range of fields (e.g. health (Lemon *et al.* 2003; Fonarow *et al.* 2005); engineering (Bevilacqua *et al.* 2003) and agriculture (Tittonell *et al.* 2008)), but is considered particularly suited for the analysis of complex ecological data, which require a flexible and robust analytical method which can deal with non-linear relationships and high-order interactions (De'ath and Fabricius 2000; Vayssières *et al.* 2000; De'ath 2002).

The output of interest from the generic modelling exercise was the ratio B_{MEY}/B_{MSY}. Given that this is a numerical output, a regression tree (rather than categorical tree) was estimated. The key inputs into the regression tree model were the key biological inputs (carrying capacity and growth rate), technological inputs (catchability) and economic inputs (prices and costs). As the fisheries were multispecies, other inputs included the number of species in the fishery, the degree of homogeneity of the species (measured as the Euclidian distance from the mean catchability, growth rate and carrying capacity), and the revenue share of the species in the total catch.

Given that for many species (particularly the minor species in the fishery), the exact value of these parameters will not be known, The inputs were categorised into five groups representing the 20 per cent, 40 per cent, 60 per cent, 80 per cent and 100 per cent quantiles, where the quantiles were derived from the stochastically derived input data in the 10000 model runs. For simplicity, these were described as low (<20%), below average (20-40%), average (40-60%), above average (60-80%) and high (>80%) respectively. For the regression tree analysis, they were denoted as 1 to 5. The output measures (i.e. B_{MEY}/B_{MSY}) were also rounded to one decimal point.

The regression trees were derived in R (R Core Team 2012) using the R package “tree”.

Bayesian Networks

Bayesian networks are essentially graphical models to which probabilities of certain outcomes given certain situations or observations can be assigned. These probabilities can be derived through the use of expert opinion (in which case the models are generally described as Bayesian Belief Networks or BBNs), or derived from observations. Bayesian Networks have been applied to fisheries in numerous cases, particularly when the effects of qualitative as well as quantitative factors are of interest (e.g. Little *et al.* 2004; Haapasaari *et al.* 2007; Pollino *et al.* 2007; Levontin *et al.* 2011; van Putten *et al.* 2013).

Bayesian network models provide a probability of an outcome rather than a discrete (deterministic) outcome. From the probability distribution, a mean (expected) outcome and confidence interval can be determined. The Bayesian Network “learns” from the data by comparing the observed outcomes with the different combinations of inputs, and hence from any combination of inputs one can derive a probability of different outcomes occurring.

For consistency, the Bayesian Network model was derived using the same data that were used to derive the regression tree models. The Bayesian Network model, however, is less “rules” based, and is able to consider all information that is available – even that which is not used in the "rules" of the regression tree. A further advantage of the Bayesian Network is that the inputs can also be given a probability distribution. That is, when there is uncertainty as to which category the species fall into then probabilities can be (subjectively) assigned to different levels, and these can be used to determine the most likely outcome.

The Bayesian Networks were derived using NETICA (www.norsys.com).

Sensitivity analysis

Sensitivity analysis can be used to measure the degree to which findings at any node (e.g. a particular input, such as price) can influence the outcomes (or beliefs) at another node (e.g. the target reference point), given the set of findings currently entered. For the purposes of this study, it can indicate which inputs will be the most informative in determining the target reference points. The results are indicative only, as the sensitivity analysis considers only individual sensitivities – changes in inputs in combination may have a larger impact that the "sum" of individual changes in inputs (Jensen and Nielsen 2007).

"Evidence"(in terms of actual input values) used in Bayesian Networks is often uncertain in itself, and the cost of increasing the precision may be high. Sensitivity analysis can also be viewed as a means of determining which variables (indicators) require the most attention to get accurate data (or at least more precise assessments) as these will be the ones that the outcomes are most sensitive to (Jensen and Nielsen 2007).

Sensitivity analysis can also be used as part of the model evaluation. The sensitivity measures can be compared with a priori expectations about importance of particular nodes (inputs) to ensure that the model is behaving as expected (Chen and Pollino 2012). If the plotted sensitivity function does not behave as expected, this may indicate errors in the network structure or the conditional probability tables (CPTs) (Pollino et al. 2007).

Two forms of sensitivity analysis are available in NETICA, both relating to sensitivity to findings: mutual information (entropy reduction) and the expected reduction of real variance. Other approaches have also been proposed (Bednarski *et al.* 2004), but these are not automated within NETICA.

Entropy relates to the uncertainty of a variable (Q) characterised by a probability distribution, $P(q)$ (Korb and Nicholson 2003; Pollino et al. 2007). Entropy reduction reports the expected degree to which the joint probability of Q and F diverges from what it would be if Q were independent of F. That is, it is a measure of the mutual information shared between the two nodes. If $I(Q,\mathrm{F})$ is equal to zero, Q and F are mutually independent (Pollino et al. 2007)

In NETICA, the mutual information (I) between Q and F is measured in "bits". The expected reduction in entropy of Q (measured in bits) due to a finding at F[2].

[2] http://www.norsys.com/WebHelp/NETICA/X_Sensitivity_Equations.htm

$$I = \sum_q \sum_f \log_2 \left[\frac{P(q)}{P(q)P(f)} \right] \tag{4}$$

where *q* is a state of the query variable (i.e. the objective) and *f* is a state of the varying variable (the indicator). The measure is logged with a base of 2, which is traditional for entropy and mutual information so that the units of the results will be "bits".

Variance Reduction refers to the expected reduction in variance of the expected real value of Q due to a finding at F.

$$Vr = \sum_q P(q)\left[X_q - \sum_q P(q)X_q \right]^2 - \sum_q P(q|f)\left[X_q - \sum_q P(q|f)X_q \right]^2 \tag{5}$$

where *Xq* is the numeric "real" value corresponding to state q (i.e. the objective). In this case, "real" refers to the expected value of continuous nodes, or discrete nodes which have a real numeric value associated with each state. In our model, all nodes are continuous, with a value ranging from 0 (zero) to 1.

The results of the sensitivity analysis depend strongly on network parameters and on the current states of all observable nodes (Bednarski et al. 2004). In our analysis, we assumed no prior information on the states of the nodes, with each state having an equal probability. The Variance Reduction analysis hence assesses the effect on the objective node from moving from no information to full information (i.e. moving to either a zero or 100 per cent likelihood of a state), given that no information (uninformed priors) exist in the other nodes not be adjusted.

Development of the fishery specific case study model

Achieving maximum economic yield in fisheries requires the estimation of appropriate target reference points. In Commonwealth fisheries, these have been based on the ratio of biomass at MEY to the biomass at MSY. For many fisheries, relatively little information is known about the biology and economics underlying the level of harvest and economic performance of the fleet. In such cases, a default target reference point of $B_{MEY} = 1.2B_{MSY}$ has been set under the Commonwealth Fisheries Harvest Strategy Policy and Guidelines (DAFF 2007).

As is recognised in the Commonwealth Fisheries Harvest Strategy Policy and Guidelines, in multispecies fisheries, a common target reference point for all species is unrealistic. A generic framework was developed to provide more appropriate proxy target reference points based on limited information on the species. A multispecies generic fisheries bio-economic model was developed and the optimal biomass for a wide range of species under different combinations of growth, catchability, cost and price assumptions was tested. The results of the stochastic simulations with the generic model were summarised using two approaches: a decision tree (derived from a regression tree) and a Bayesian network. These provide a framework for estimating potential target reference points based on semi-quantitative information about the species biology, costs of fishing and prices.

To test the applicability of the generic framework, a bioeconomic model of a multispecies multi-fleet fishery was also developed, based on the Commonwealth trawl sector of the Southern and Eastern

Scalefish and Shark fishery (SESSF). While realistic in terms of basic biological and economic characteristics for the species and fleets considered, the bioeconomic model is not a “true” model of this actual fishery. Only a subset of species from the fishery is included in the model; and the associated fleets that target those specific stocks. The model is used to estimate bioeconomic target reference points for the species considered (given the limitations of the model), allowing for different fishing strategies to be defined spatially and by gear (analogous to the metier concept used in many bioeconomic models). Thus it illustrates the utility of the approach rather than being a “true” case study that can be used to infer actual real time tactical management options.

The outcomes from the two decision frameworks (decision tree; Bayesian network) were compared with the outcome from the fishery specific bioeconomic model. Further, the target reference points from the two decision frameworks were imposed on the fishery specific bioeconomic model and the effects of these on fishery profits estimated. These are also compared with the effects of the default (1.2B_{MSY}) target reference points for B_{MEY}.

The Southern and Eastern Scalefish and Shark Fishery (SESSF)

The application of the model is based on the case of the Southern and Eastern Scalefish and Shark Fishery (SESSF) and more particularly on a component of the SESSF, that being the Commonwealth Trawl Sector (CTS). The CTS itself is a diverse sector comprising of two main fleets (trawlers and Danish seiners), and is one of Australia's oldest commercial fisheries. The bulk of the catch in the fishery consists of twenty demersal species or species groups managed by quota with the main markets being the Sydney and Melbourne fish markets (mostly fresh, some frozen) (Penney *et al.* 2014). The key species landed are Tiger flathead, Pink ling, Silver warehou and Blue grenadier (not considered here, see rationale below). Thus as a case study it meets the requirement of multispecies and multi-gear fishery and assists in achieving the aim of being able to determine a possible range of appropriate target reference points for the key managed species.

The Commonwealth Trawl Sector covers an area of the Australian Fishing Zone extending southward from Sandy Cape in southern Queensland, around the New South Wales, Victorian and Tasmanian coastlines to Cape Jervis in South Australia (Figure 6). The trawl sector contains vessels using one of two fishing gears – otter trawl or Danish seine. Otter trawlers generally operate on the continental shelf and upper shelf to around 500 metres, and harvest a range of demersal species on the shelf such as Tiger flathead, John Dory, Morwong and Silver trevally, and offshore species such as Gemfish, Silver warehou, Pink ling, Ocean perch and Mirror dory. The Danish Seine fleet comprises generally smaller, lower engine power vessels operating in shallower waters and target three main species (Tiger Flathead, School whiting and Morwong).

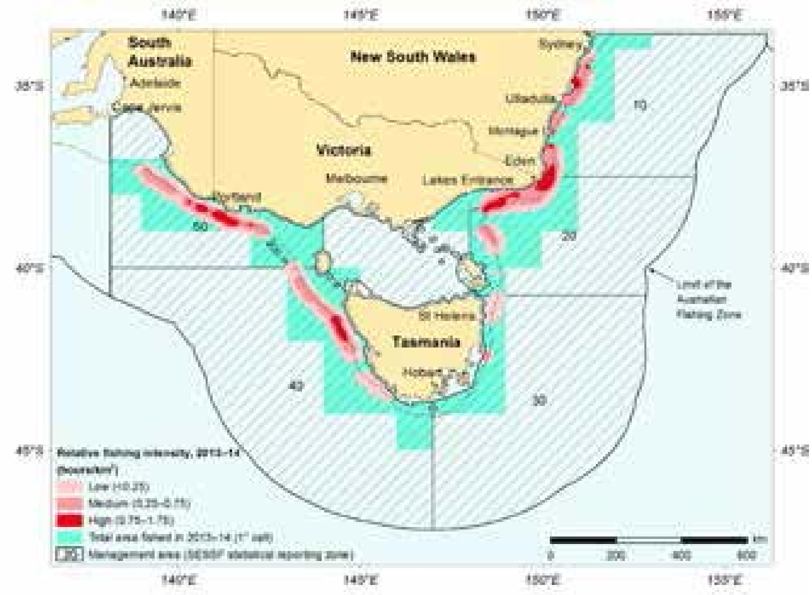

Figure 7. Location and relative fishing intensity of the Commonwealth Trawl Sector, 2013-14 fishing season (source: Georgeson *et al.* 2014).

The location of the key ports in the CTS, these being Ulladulla, Eden, Lakes Entrance, Hobart and Portland, is also identified in Figure 6. The total landings of all the species in 2012-13 was 10,724t. The Commonwealth Trawl sector is financially the largest component of the SESSF. In 2012-13, the CTS had a gross value of production of $50.3 million, representing 62% of the gross value of production of the whole SESSF,(Stephan and Hobsbawn 2014).

Previous bioeconomic modelling in the fishery

There has been only limited bioeconomic modelling of the fishery over the last 20 years. Campbell *et al.* (1993) developed a single species model of the orange roughy fishery, and found that, for a non-zero discount rate, the optimal biomass was lower than that which produced MSY. Orange roughy is a rarity, however, in that it is a very long lived species with a substantial age at sexual maturity. Pascoe (2000) developed a bioeconomic model with a range of fishing activities (gear, season and spatial) to estimate the short term economic impact of avoiding gemfish. The model was based on observed catch rates in each fishing activity/season without an underlying biological model. In contrast, Punt *et al.* (2002b) developed a detailed biological model of the fishery without an economic component.

First attempts at estimating economic target reference points in the fishery were made by Kompas and Che (2006), although the paper is difficult to obtain. Their model was revised by Kompas *et al.* (2009b), and used to estimate target biomass for four trawl species based on a logistic (Schaefer 1954; Schaefer 1957) surplus production model.

More recently, fisheries-focused ecosystem models have been developed that include an economic component (Hutton *et al.* 2010; Savina *et al.* 2013). These models are strategic in nature, and are not suitable for estimating target biomass levels.

Specific species and fleet structures used in the case study model

The model of the fishery was developed primarily to test the generic framework. Development of a full bioeconomic model that could be used for management purposes was beyond the scope of the project.[3] However, a model capturing the key characteristics of the SESSF was considered desirable.

A set of criteria was established to determine the most suitable species to include in the study and determine the choice of fleets. First, the model was to be based mostly on the eastern part of the fishery, so species that were caught predominantly in the west were excluded. The exception to this was the western stock of Morwong, which were an important component of one of the fleet segments included in the model. Second, species that were caught predominantly by non-trawl methods (gillnet or hook) were excluded (even though they may also be caught by trawl as by-product). Finally, species that were highly targetable were excluded as these could be effectively considered single species sub-fisheries (e.g. Blue grenadier, Royal red prawns and Orange roughy). This resulted in thirteen species that were caught predominantly in the east by otter trawlers and Danish seiners in varying combinations (Table 2).

Catches of all other species (excluding those listed in Table 2 but not included in the model) were aggregated into an “other” category that were included in the model but without numerical replication of a dynamic stock model for each species. Catch-effort relationships for these species were estimated as a quadratic function from fishery data over the period 1983-2012 (Figure 7). Implicitly, the analysis assumes that these stocks are all in equilibrium at each level of observed effort.[4]

The trawl component in the model included several different fishing strategies, targeting a range of species which is mixed in nature. Within a mixed fishery, catch composition can only vary through changing either the gear or the area fished, and an economic target reference point needs to take into account where this optimal level of effort is applied across the fishery. The concept of a “metier” is useful in such a context.[5] A metier represents a fishing activity or strategy that is defined by area and gear, and is associated with a particular catch composition as a result (Biseau 1998). The use of metiers in bioeconomic models to represent fleet activity is relatively common in European models (Pascoe and Mardle 2001; Ulrich *et al.* 2002; Pelletier *et al.* 2009), and has previously been applied to Australian fisheries (Dyson and Thanassoulis 1988; Ziegler 2012). It differs from the concept of a sub-fleet in that a sub-fleet generally consists of a subset of a fleet with similar characteristics, whereas a metier represents a fishing activity that different vessels may participate in.

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3 For example, the model of the Northern Prawn Fishery used for management purposes has evolved over more than 30 years (Dichmont et al. 2010), and has received substantial more resources that was available for the case study.

[4] This assumption seems reasonably realistic for the trawl fleets, although for the two Danish seine fleets there were some substantial divergences away from the quadratic catch function (Figure 7), suggesting either substantial random variations in catch (e.g. due to environmental factors) or that the species that make up the “other” catch were far from equilibrium.

[5] The term metier derives from the French métiers, which means a specialised work activity.

Table 2. Species/stocks considered suitable for inclusion in case study

	Suitable	Mostly Western	Predominantly non-trawl	Highly targetable
Morwong	X			
Morwong West	X			
School Whiting	X			
Eastern Gemfish	X			
Silver Warehou	X			
Tiger Flathead	X			
Pink Ling West		X		
Pink Ling East	X			
Blue Warehou West		X		
Blue Warehou East	X			
School Shark		X	X	
Blue Grenadier				X
Blue eye Trevalla			X	
John Dory	X			
Redfish		X		
Ocean Perch	X			
Mirror Dory	X			
Ribaldo	X			
Gummy Shark			X	
Silver trevally	X			
Royal red prawns				X
Orange Roughy				X

In this case study, six metiers were identified for inclusion in the model:

Trawlers operating in

- Shelf trawl – Eden to Sydney (NSW)
- Shelf trawl – Eastern Bass Strait (EBS)
- Offshore - NSW
- Offshore – EBS

Danish seiners operating in

- Bass Strait (west of Lakes Entrance)
- Eastern Bass Strait (east of Lakes Entrance, Eden to NE Tas) (EBS)

The key unit of fishing effort included in the model is the number of shots in each metier. From the data, many trawlers operated in all four trawl metiers, while some only operated in one or two. Similarly, most Danish seiners operated in both metiers, but tended to operate most in one or the other. Hence, vessels were not assigned to a metier directly, and the model was free to allocate fishing effort to each metier (essentially reflecting changes in vessel fishing activity). In terms of numbers of active fishing vessels in the Trawl and Danish seine fleets, these two fleets had 39 and 13 boats, respectively in 2009.

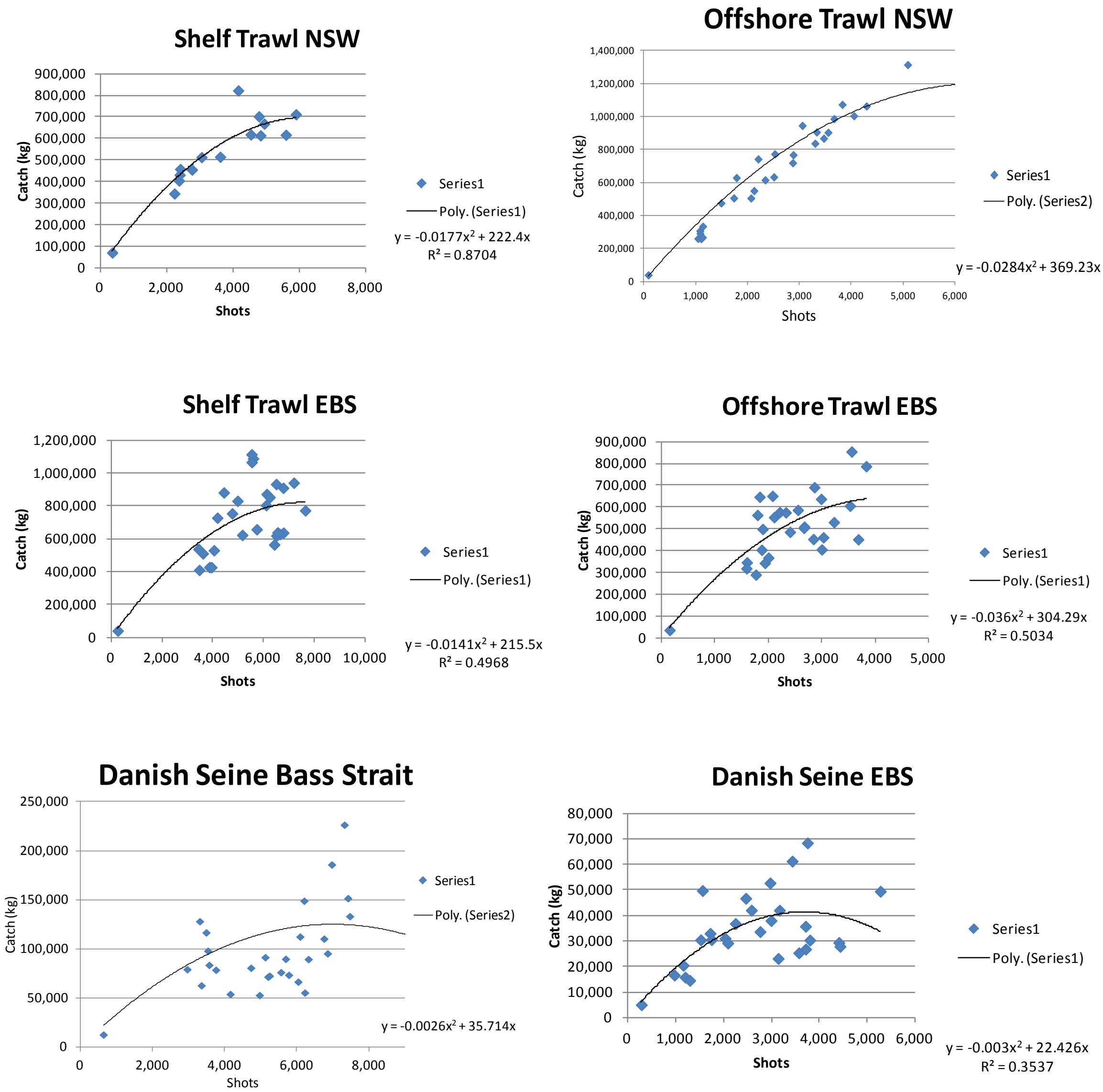

Figure 8. Catch and effort relationships for other species in each metier

Model descriptions

The models are based on the metier concept (as outlined above), where a metier is a fishing activity that is spatially and gear type specific. The model contains six metiers: four metiers based on trawl gear and two metiers based on Danish seine.

Two variants of the model were developed: a static equilibrium model and a dynamic model, in which dynamic MEY is estimated as the level of fishing effort, catch and biomass over time that maximises the net present value of profits.

Static equilibrium model

The model is a static long run equilibrium model assuming Gompertz growth as developed by Fox (1970). Catch of each species *s* in the model is given by

$$\mathrm{Catch_s} = \mathrm{K_s} \sum_{m=1}^{6} \left(\mathrm{q_{s,m}E_m}\right) \ \mathrm{e}^{-\sum_{m=1}^{6}\left(\mathrm{q_{s,q}E_m}\right)/\mathrm{r_s}} \qquad (6)$$

where *Ks* is the environmental carrying capacity (also equivalent to the unexploited biomass B_0) of species s, E_m is the level of effort (shots) in metier *m*, $q_{s,m}$ is the catchability of species *s* in metier *m*, and r_s is the instantaneous growth rate of species *s*. $Catch_s$ is the total catch of the species *s* across the fishery, which is a function of total effort employed across all six metiers.

Catch of the key species in each metier ($MCatch_{sm}$) is given by

$$\mathrm{MCatch_{s,m}} = \mathrm{K_s q_{s,m} E_m} \ \mathrm{e}^{-\sum_{m=1}^{6}\left(\mathrm{q_{s,q}E_m}\right)/\mathrm{r_s}} \qquad (7)$$

which is a function of the effort applied in each metier but also the total effort in the fishery. Catch of other species is estimated in each metier ($Ocatch_m$) as a quadratic function of fishing effort in the area, given by

$$\mathrm{OCatch_m} = \alpha \mathrm{E_m} - \beta \mathrm{E_m}^2 \qquad (8)$$

where α and β are regression coefficients (given in Figure 2).

Revenue in each metier is given by

$$\mathrm{Revenue_m} = \sum_s \mathrm{p_s MCatch_{s,m}} + \mathrm{p_o \ OCatch_m} \qquad (9)$$

where p_s is the price of species *s* and p_o is the average price of all ‘other’ species caught in the fishery.

As the model is a long run model, all costs are considered variable. However, the different cost components are considered separately in order to test the sensitivity of the optimal economic target reference points to changes in specific key costs (e.g. fuel costs). Some costs (fuel, other running costs and vessels costs) are related to the level of effort, while others are related to the level of revenue (e.g. crew costs) or catch (marketing and freight costs). In the model, both of these latter costs are assumed to be proportional to revenue. Costs in each metier are given by

$$\mathrm{Costs_m} = (\mathrm{f_m} + \mathrm{o_m} + \mathrm{v_m})\mathrm{E_m} + (\mathrm{c_m} + \mathrm{m_m})\mathrm{Revenue_m} \qquad (10)$$

where f_m is the average fuel cost per shot in metier *m*, o_m is the average other running costs (e.g. ice, food), v_m is the average vessel cost (derived from total vessel “fixed” costs including opportunity cost of capital and average shots per vessel), c_m is the average crew share and m_m is the average freight and marketing cost (expressed as a percentage of revenue).

The objective function of the model is to maximise total fishery profits, given by

$$\max_E \mathrm{Profits} = \sum_m (\mathrm{Revenue_m} - \mathrm{Costs_m}) \qquad (11)$$

As the model is an equilibrium model, the estimated catch for each species is the maximum economic yield for that species (in the multispecies context). From this, the biomass at maximum economic yield for each species ($BMEY_s$) can be derived as

$$\mathrm{BMEY_s} = \mathrm{Catch_s} / \textstyle\sum_m \mathrm{q_{s,m} E_m} \tag{12}$$

while the biomass at MSY for a Fox model is given by

$$\mathrm{BMSY_s} = \mathrm{K_s e^{-1}} \tag{13}$$

From these, we can derive the ratio of the target reference points, namely $BMEY_s/BMSY_s$.

Two variants of the equilibrium model were developed, one using the nlminb routine in R (R Core Team 2012), and the other using ADMB (Fournier *et al.* 2012). The aim of the dual optimisation approach was to ensure that, given the high level of non-linearity in the model, the model was able to find global optima. It also provided a 'solution-check' in that any preliminary coding and runs across models could be easily compared providing some confidence in both model specification and results.

Dynamic model

The dynamic model estimates catch, effort and biomass over time. For a given metier *m*, the catch of species *s* in time t ($C_{m,s,t}$) is given by

$$C_{m,s,t} = q_{m,s} E_{m,t} B_{s,t} \tag{14}$$

where $q_{m,s}$ is the catchability coefficient relating to species *s* in metier *m*, $E_{m,t}$ is the level of effort expended in each metier *m* (in shots) in time *t* and $B_{s,t}$ is the level of biomass of species *s* in time *t*. The total fishery revenue (R_t) in time *t* is given by

$$R_t = \sum_{m,s} p_s C_{m,s,t} \tag{15}$$

where p_s is the price of species *s*, assumed to be constant in real terms over the duration of the analysis.

Fishing costs include variable costs and fixed costs. If we assume a constant average number of shots per vessel, and that changes in effort levels represent changes in boat numbers, then all costs can be considered variable (i.e. a function of total fishing effort) for simplicity. Some costs, such as crew and marketing costs vary based on revenue, while other costs vary with fishing effort directly. We can estimate total fishing costs in each time period (CST_t) by

$$CST_t = \sum_{m,s} (cw_m + mkt_m) p_s C_{m,s,t} + \sum_m (f_m + o_m) E_{m,t} \tag{16}$$

where cw_m is the crew share in metier *m*, mkt_m is the marketing costs in metier *m* expressed as a proportion of revenue, f_m is the fuel costs per shot fishing in metier *m* and o_m are the other costs, expressed in an average per shot.

Fishery profit in time *t* (π_t) is given by

$$\pi_t = R_t - CST_t \tag{17}$$

and the net present value (NPV) over the period of the analysis given by

$$NPV = \sum_{t=1}^{T} \frac{\pi_t}{(1+i)^{t-1}} \tag{18}$$

where *i* is the discount rate and T is the terminal year of the analysis (T=100).

The biology is represented by the dynamic form of the Fox (1970) model, given by

$$B_{s,t+1} = B_{s,t} + B_{s,t} r_s \ln\left(\frac{K_s}{B_{s,t}}\right) - \sum_m C_{m,s,t} \tag{19}$$

where r_s is the instantaneous growth rate and K_s is the carrying capacity. In the first year, $B_{s,t=1} = B_{s,0}$, where $B_{s,0}$ is the “known” biomass in 2009.

The model is coerced into equilibrium by imposing the condition

$$B_{s,t+1} = B_{s,t} \quad \forall \quad s; t > x \tag{20}$$

where x is the length of time over in which the fishery reaches equilibrium. This is achieved in the model by imposing a penalty in the objective function based on deviations from this condition, such that the objective function becomes

$$\min \quad -NPV + \sum_{t>x} \rho (B_{t+1} - B_t)^2 \tag{21}$$

where ρ is a penalty parameter.

The dynamic model was developed in ADMB (Fournier et al. 2012). An earlier version of the model was also developed in SCILAB.

Model parameters

The species related parameters currently employed in the model are given in Table 3. Prices for each species (and the average price of other species) were derived from the ABARES fisheries statistics for the year 2009/10.

Catchability of each species in each metier was determined jointly by dividing the observed catch in 2009 by the observed total shots in each area in 2009 (to give catch per shot), then dividing this by the estimates of the stock abundance of each species in 2009. That is

$$\hat{q}_{s,m} = \frac{C_{s,m}}{E_m} / \widehat{B_s} \quad (22)$$

where $\hat{q}_{s,m}$ is the catchability of species *s* in metier *m*, $C_{s,m}$ is the observed catch of species *s* in metier *m* in 2009, E_m is the observed number of shots in metier *m* and $\widehat{B_s}$ is the estimated biomass of species *s* in 2009.

Table 3. Species level parameters used in the analysis (r, K and price (p))[a,b]

Species	Code	Growth (r)	Carrying capacity (K)	Comments	$\hat{B}_s$ (tonnes)	Price (p)
Blue Warehou	TRT	0.069	16086	Fixed K	1824	2.33
Flathead	FLT	0.153	44566		23070	5.23
Gemfish	GEM	0.208	40000	Fixed K	4177	2.83
John Dory	DOJ	0.044	5431	CPUE	1666	6.80
Ling	LIG	0.215	11960		5698	6.50
Mirror Dory	DOM	0.614	13389		4581	2.54
Morwong –East	MOW_E	0.128	30231	Fixed K	7412	2.52
Morwong- West	MOW_W	0.151	4447		3139	2.52
Ocean Perch	RE1	0.311	4657	CPUE	3527	2.74
Ribaldo	RBD	0.288	1077	CPUE	447	2.85
Silver Trevally	TRE	0.197	10654	CPUE	2294	1.75
Silver Warehou	TRS	0.204	38577		17573	2.78
Whiting	WHS	0.420	13586	Fixed K	8508	2.76
Other species		-	-			2.75

a) $r, K, \hat{B}_s$ derived from logbook data by project team. Data covered the period 1913-2009 for some species and from 1985-2009 for all species (see Tuck 2010);b) p derived from ABARES fisheries statistics (Skirtun *et al.* 2013).

Values for growth (*r*) and carrying capacity (*K*) were derived by fitting the Fox (1970) model to annual total biomass and estimated total catch from the most recent available SESSF Tier 1 stock assessments (e.g. see Tuck (2010)). Depending on the species, the available fishery time-series began in the period 1913 to 1984, and the finished in 2008 or 2009. Where the Fox model did not provide a value for *K* consistent with the initial biomass estimated by the stock assessment, the assessed initial biomass value was used as a fixed value for K for the Fox model (marked "Fixed K" in comments in Table 3). For species without available stock estimates, the model was fitted to the available standardised fishery CPUE series (marked "CPUE" in comments in Table 3). Thus, the time series of biomass produced by the Fox model are consistent with the biomass from available stock assessments, or the commercial CPUE and catch for species with no stock assessment.

Vessel level cost parameters currently used in the model are given in Table 4. Cost parameters were derived from the ABARES fisheries survey report for the year 2010/11 (George and New 2013). Separate costs were identified for the Danish seine and trawl fleets, but these did not distinguish between fishing area ('Original' data – Table 4). Therefore, as an alternative scenario, different costs were estimated for trawlers if they were fishing on the shelf or the slope, in either NSW or Bass Strait, based on earlier ABARES surveys that reported trawler fishing costs by inshore/offshore activity (Galeano *et al.* 2004)((‘Modified’ data – Table 4). Similar proportional differences between cost per shot of the inshore and offshore fleet in the earlier survey were assumed to be valid for the more recent information.

Fuel and other vessel costs were estimated on a per-shot basis. Vessel costs included fixed costs on the basis that all costs were variable in the longer term. This differs to a degree from the way in which costs are treated in some other Australian bioeconomic models (e.g. Punt et al. 2011). However, it allows for the effects of varying fleet size without the need to explicitly separate shots per boat and number of boats and is a practical approach applied on other bio-economic models in particular circumstances.[6]

Table 4. Metier level cost parameters used in analysis

Metier	Fuel cost ($/shot)	Vessel costs ($/shot)	Crew share	Marketing and Freight
Original				
Shelf trawl NSW	526	865	0.3	0.13
Offshore trawl NSW	526	865	0.3	0.13
Shelf trawl EBS	526	865	0.3	0.13
Offshore trawl EBS	526	865	0.3	0.13
Danish Seine Bass Strait	107	245	0.44	0.16
Danish Seine EBS	107	245	0.44	0.16
Modified				
Shelf trawl NSW	470	796	0.3	0.13
Offshore trawl NSW	526	955	0.3	0.13
Shelf trawl EBS	470	796	0.3	0.13
Offshore trawl EBS	526	955	0.3	0.13
Danish Seine Bass Strait	107	245	0.44	0.16
Danish Seine EBS	107	245	0.44	0.16

Derived from Galeano et al. (2004) and George and New (2013)

[6] See for example Hoshino *et al.* (2012), Clarke et al. (1992) and Bjørndal *et al.* (2012). If used for actual management purposes, a more detailed specification of costs would be required. For example, Pascoe *et al.* (2014) found that roughly half of the repairs and maintenance costs were variable, and around 65 per cent of the otter trawl costs.

Results

Literature review

The estimation of economic based target reference points – and maximum economic yield (MEY) in particular – in single species fisheries is well established (Gordon 1954; Scott 1955; Anderson 1986). Maximum Economic Yield (MEY) in a fishery can be defined as the point at which the sustainable fishing effort level and catches entail maximum profits, or the greatest difference between total revenues and total costs of fishing (Kompas 2005). This point will change with input and output prices, and is dynamic in nature. While MEY can be formally derived in fisheries with reasonably good biological and economic data (Dichmont et al. 2010), recent focus on data poor fisheries has also allowed proxy estimates of economic target reference points to be made for Australian fisheries based on fisheries characteristics (Zhou et al. 2012). To date, such proxy measures have been developed for single species fisheries only.

Many of Australia's fisheries interact with multiple species at the same time. This may be due to a number of different fishery characteristics:

- Technical interactions: within a single fishery, the same fishing gear may catch several species simultaneously. Such technical interactions occur in fisheries where the species are caught together as either "target" or "byproduct" species, or as a mixed set of species with no single target; This may be more complicated in cases in which different sub-fisheries (in terms of gear types) are spatially overlayed, catching different combinations of the same sets of species;
- Biological interactions: a fishery may affect multiple species indirectly, through the biological interactions between the species directly impacted from fishing, and their predators, prey or competitors.

In line with the purpose of this project, the focus of this review is on the first category of fisheries (i.e. those with technical interactions). While the second category of fishery poses similar challenges in determining MEY, it also entails increased levels of complexity, particularly as regards the biological feedbacks (i.e. trophic interactions) that need to be considered when setting reference points (Matsuda and Abrams 2006). An additional complexity arises from the fact that biologically interacting species may also be jointly caught, when models often assume that the species can be separately targeted (e.g. Anderson 1975; Silvert and Smith 1977; May *et al.* 1979).

The additional complexity in determining MEY in fisheries characterised by technical interactions has been long established in the fisheries economic literature, which points to the need to consider the effects of different levels of effort on the sustainable yields of all the species caught (e.g. Anderson 1975; Clark 1976; Silvert and Smith 1977). Cases with spatial overlay between fisheries have also been considered, where deriving estimates of MEY requires taking into account the impacts of one fishery on the other (Anderson 1975). An important result of studies that consider these two types of fisheries is that the biomass of each species at the fishery-wide MEY may be lower than the biomass at which MEY would be reached if each species was caught independently of the others (Duarte 1992).

The Commonwealth Fisheries Harvest Strategy Policy (HSP) and Guidelines (DAFF 2007) state that fisheries harvest strategies should be designed "to pursue maximising the economic yield from the fishery, and ensure key commercial fish stocks remain above the levels at which the risk to the stock is unacceptably high". In fisheries where B_{MEY} is unknown, a proxy of $1.2B_{MSY}$ is to be used instead. In fisheries that target or catch multiple species, the guidelines propose to apply MEY "across all species in the fishery", implying that secondary (lower valued) species may be fished at levels that result in biomass levels lower than their individual B_{MEY}. The guidelines stress, however, that all species should be maintained above their limit reference point (DAFF 2007). In most cases, this is taken as 20% of the unfished biomass (Mace 1994), and is used as the proxy default in the HSP where no other information exists.

The guidelines also stress that consideration should also be given to:

- demonstrating that economic modelling and other advice supports such actions;
- no cost-effective alternative management option is available (i.e. gear modifications or spatial management) that can more effectively separate the species (i.e. into effectively a set of single species fisheries); and
- the associated ecosystem risks have been considered in full.

In this section, we present a brief review of the literature regarding the estimation of MEY in multispecies fisheries, and develop a model-based analytical framework which allows us to formally address the question of estimating MEY in a mixed-fishery. The stochastic model developed allows exploration of the determinants of MEY in a fishery characterized by joint production. Based on simulation results, we develop an initial set of "rules of thumb" to estimate appropriate target reference points when full fisheries bioeconomic models are not available or data are limited. The implications of the use of these proxy measures for potential fisheries profit are also examined.

Defining multispecies MEY

The problem posed by defining a multispecies MEY is illustrated in Figure 8 for a fishery in which four species are jointly caught. The upper part of Figure 8 illustrates the individual sustainable revenue curves (i.e. sustainable yield times fixed prices) for a given level of fishing effort. The differences in the sustainable revenue curves of different species reflect differences in prices, biological productivity or a combination of both. The fishery total revenue curve (lower figure) is derived by the vertical summation of the individual species revenue curves. Total profits are derived from total revenue less total costs associated with given levels of fishing effort. The vertical green bar identifies the level of fishing effort at which MEY is achieved at the scale of the entire fishery.

In this example, the level of fishing effort that maximises total sustainable fishery profits is around 6 effort units (green vertical line in Figure 8). At this level, species 1 is fished beyond its maximum sustainable yield (MSY). Hence, its multi-species MEY biomass associated with multispecies MEY, ($B_{MEY,1}$)[7] is lower than the biomass $B_{MSY,1}$ that would be identified "on a single species basis". In

[7] Unless otherwise specified, we will define B_{MEY} to represent the biomass level that corresponds to the optimal harvest of an individual species within a mixed fishery when all species in the fishery are taken into account (i.e.

contrast, species 2 is close to its MSY (such that $B_{MEY} \approx B_{MSY}$), and catches of species 3 and 4 are below their MSY and close to what could be considered their respective single species MEY. In this example, profits are also maximised at a level close to maximum sustainable multispecies revenue, although this is not always the case.

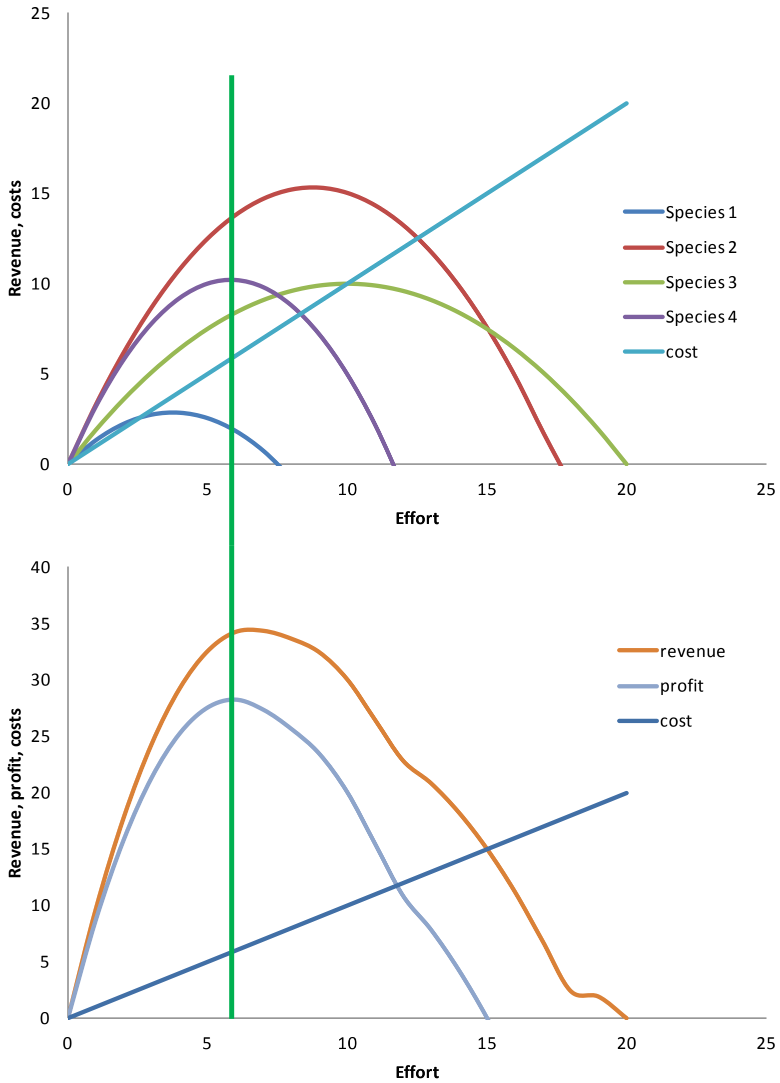

Figure 9. Calculating MEY in a multispecies fishery where four individual species are jointly caught. The dark green line crossing both figures represents the level of fishing effort that maximises profits for the fishery as a whole. For some species, this is above the level of effort that maximises the species revenue, and for others below this level.

Deriving general analytical models to identify conditions for MEY in multispecies fisheries has been described as a formidable, if not impossible task (Silvert and Smith 1977; Chaudhuri 1986). Most attempts have been empirically based, using bioeconomic models to estimate MEY across the set of

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the multispecies MEY). This may be higher or lower than the level of biomass that would produce maximum profits if the species could be caught in isolation.

species in the catch (e.g. Placenti *et al.* 1992; Ward 1994; Sandberg *et al.* 1998; Holland and Maguire 2003; Doyen *et al.* 2012). In a retrospective analysis of what the performance of the New England groundfish fishery could have been under effort scenarios alternative to the historical effort, Holland and Maguire (2003) show that managing fish stocks individually in a multispecies fishery where joint production cannot be avoided may lead to significant reductions in overall revenues from fishing, and increase in the variability of revenues. Using a three-species model of the European Northern Hake fishery, Da Rocha et al (2012) identified a fishery-wide MEY for this fishery to be superior to single species management, leading to higher discounted profits and larger long-term spawning stocks for all the species. Depending on the species, the ratio of B_{MEY} to B_{MSY} ranged from 1.19 to 1.42. Guillen *et al.* (2013) also considered a three species multi-gear fishery in the Bay of Biscay, and found that the ratio of B_{MEY} to B_{MSY} ranged from 1.04 to 2.17.

In Australia, multispecies bioeconomic models have been developed for several fisheries and used to provide management advice and estimates of fishery-level MEY (e.g. Punt et al. 2002b; Kompas and Che 2006; Kompas *et al.* 2009c; Punt et al. 2011; Kompas et al. 2012). Grafton et al. (2012) use a generic bioeconomic model including consideration of the producer surplus for the catching and processing sector, as well as consumer surplus, in a discussion of the benefits of MEY in fisheries such as the Western and Central Pacific tuna fisheries. Their model uses hypothetical calibration data derived from a single species modelling approach. In another study of this same fishery, Kompas et al (2010b) use a multispecies dynamic bioeconomic model with multiple fishing fleets to estimate MEY and the associated optimal allocation of fishing effort across fleets and species. Based on their results, the authors estimate that adopting a multispecies version of B_{MEY} as a target would result in increased fish stocks of the three main target species (up to between 1.19 and 2.47 the estimated single species B_{MSY}), with gains exceeding US$3 billion.

The development of multispecies bioeconomic models requires considerable biological information on each individual species that is often unavailable. In some data poor fisheries where only catch and effort data are available (plus some indicative economic variables), aggregated yield functions have been used. That is, total catch of all species is modelled as a function of total effort. These have been deployed largely in developing countries (e.g. Lorenzen *et al.* 2006) but have also been used in more developed countries where fisheries are based on a large number of species, each contributing a relatively small proportion to revenue (e.g. Chae and Pascoe 2005; Jin *et al.* 2012).

As stressed by Squires (1987) standard bio-economic models often represent fisheries as one of two extreme cases of "a single aggregate input, fishing effort, and either an aggregate output, total catch, ***or*** a separate production process and model for each species". The author goes on to highlight that in reality, fishing firms can be regarded as multiproduct firms producing a set of outputs from a set of inputs. An important question is the extent to which the different species are jointly caught in fixed proportions. True joint production in fisheries – where species are caught in fixed proportions –is relatively rare. The relatively small numbers of studies that have empirically tested for joint production in fisheries have found that the ability to target some individual species may be limited, but not impossible. Most fisheries are characterised by a mix of both substitution and complementary relationships (Squires 1987; Pascoe *et al.* 2007; Pascoe *et al.* 2010b). Studies of fisher behaviour also suggest that apparent targeting behaviour (or lack of) may be an artefact of the management schemes, and changing management may change this relationship as fishers respond to the new incentives created (Christensen and Raakaer 2006). In such cases, changes in catch composition can be achieved through either gear change, or changes in seasonal or spatial fishing patterns.

Several empirical models have addressed the spatial component of mixed fisheries through modelling the fishery at the "metier" level (Pascoe and Mardle 2001; Ulrich et al. 2002; Pelletier et al. 2009; Marchal *et al.* 2011). Metiers correspond to a fishing activity that is defined spatially (i.e. a given location), using a given gear and catching a given combination of species. The models estimate catches, costs and profits based on effort allocation across these different metiers, capturing both multi-gear interactions as well as mixed species catch (technical interactions).

Based on the above review, it becomes apparent that an important distinction should be made between different categories of multispecies fisheries:

- multispecies fisheries may involve mainly joint production, by the same fleet, of a single set of species that are captured in fixed proportions determined by the effort of the fleet. These fisheries, which we will call "single-fleet mixed fisheries" in this report, despite posing complex management problems, are likely to be the ones for which identification of economic reference points is likely to be easiest and least controversial. Figure 8 provides an illustration of such a fishery;
- in other cases, multispecies fisheries may involve multiple fleets with different harvesting technologies, spatial and seasonal patterns of effort allocation, and target sets of species. We will call these fisheries "multi-fleet mixed fisheries". Because they involve fleets that may have very different characteristics and objectives, the level of difficulty and controversy involved in identifying economic reference points in these fisheries is likely to be greater;
- finally, there may be multispecies fisheries in which at least some fleets have the ability to alternate their activity between harvesting sets of multiple species, and focusing on the harvest of single target species. In such cases, identifying optimal levels of fishing capacity and effort is likely to involve an analysis that takes into account both the assessment of the fleet's performance in harvesting the single species, and it's performance in harvesting the multispecies set. We will call these "multi-fishery systems".

Australian experiences

While Australia is the first country in the world to have adopted MEY as the objective of its fisheries management, efforts aimed at estimating MEY in Australian multispecies fisheries have met with only partial success. Developing appropriate bioeconomic models to allow multi-species estimates of MEY is complex, as it requires a large data set on economic variables, as well as data on the biological characteristics of the species impacted by fishing.

A more fundamental problem is the general lack of tactical bioeconomic models for most Commonwealth fisheries (multi-species or otherwise)[8]. With the exception of the Northern Prawn fishery, activity in developing bioeconomic models has been sporadic and usually linked to particular research projects rather than undertaken as ongoing investments in fisheries management. In several

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[8] The same can also be said for State fisheries, although some notable exceptions exist (e.g. Hamon 2011; Hamon *et al.* 2013; Ives *et al.* 2013)

important fisheries, no tactical bioeconomic models are available, while those for other fisheries are dated and unlikely to reflect the current biological understanding of target stocks, consider current fishing technologies or reflect current economic conditions (Table 5). The latter limitation is particularly important, as economic conditions can change substantially over a short time period. For bioeconomic models to be effective in providing relevant management advice, they need to be regularly updated, in both their biological and their economic components.

Table 5. Most recent tactical bioeconomic models for Commonwealth fisheries. In many instances, no models exist

Commonwealth fishery	2009-10 GVP ($'000)	Most recent bioeconomic model	Reference
Northern Prawn	88 828	2011	Punt et al. (2011)
Torres Strait	11 617	2012 (lobster) 1993 (prawns)	Plagányi *et al.* (2012) Reid *et al.* (1993)
SESS Commonwealth Trawl Sector	56 720	2006 (5 species only)	Kompas and Che (2006); Kompas *et al.* (2009a)
SESS Commonwealth Gillnet and Hook Sectors	24 550	2006 (shark and ling)	Kompas and Che (2006); Kompas et al. (2009a)
SESS Commonwealth GAB Trawl Sector	8 977[a]	2012	Kompas et al. (2012)
Eastern Tuna and Billfish – Longline and minor line	30 140	none	
Southern Bluefin Tuna	38 095	1991	Kennedy and Pasternak (1991)
Western Tuna and Billfish	1 656[b]	none	
Bass Strait Scallop	6 400	none	
Southern Squid Jig	93	none	
Other fisheries	60 295	none	

a) 2008-09 as no production data available in 2009-10. b) 2007-08 as no production data available in 2009-10. Source: (ABARES 2011)

The Northern Prawn fishery has had considerable investment in tactical bioeconomic modelling over the last 30 years, involving mostly CSIRO and ABARES[9]. The most recent versions of the model (Punt et al. 2011) represent a substantial investment by scientists, managers and industry (Dichmont et al. 2010). As a result, the model that has evolved is currently providing direct management advice, and is accepted by industry and managers as a valuable management tool (Dichmont et al. 2010). However, the approach considers only three prawn species (grooved and brown tiger prawns, and a combined endeavour prawn group), although the fishery captures many more species in small quantities (e.g. king prawns, leader prawns, banana prawns) which make up only a small portion of the gross revenue in the tiger prawn "season". Further, the model ignores the substantial catches of banana prawns in the first part of the year, which may have implications for optimal effort in the tiger prawn fishery. In addition, the fishery involves a relatively homogeneous fleet, which as previously highlighted, may provide a more favourable context for the identification of economic reference points.

[9] The first bioeconomic modelling analysis in the fishery was undertaken by Clark and Kirkwood (1979)

In contrast, the South East fishery modelling work, which has almost as long a history,[10] has been less successful, mainly due to the large number of species in the fishery and the number of different fleets and gears that catch these species in differing combinations. An analysis of catch combinations in the fishery (Klaer and Smith 2012) suggests that a substantial proportion of most quota species in the SESSF are caught as byproduct when targeting other species (Figure 10). Further, nearly all species are caught to varying degrees with all other species (Klaer and Smith 2012). This in itself is not an issue, as other bioeconomic models with similar levels of technical interaction have been developed and successfully deployed (Pascoe and Mardle 2001; Ulrich et al. 2002; Pelletier et al. 2009; Gourguet *et al.* 2013). In these models, however, key biological parameters were available for all or most of the key species, with the residual species included as fixed proportions in order to determine the full fishery revenue.

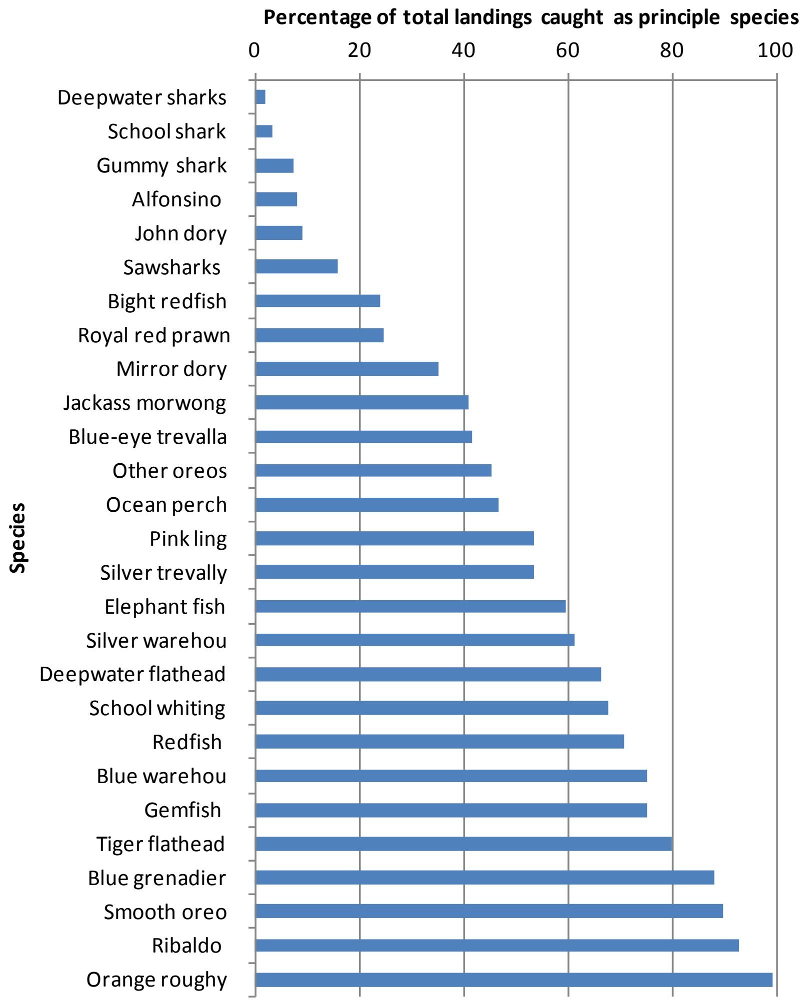


Figure 10. Share (quantity) of SESSF quota species taken as the principle species in the catch (Klaer and Smith 2012)

[10] Early bioeconomic modelling analysis includes a model of the Orange Roughy fishery (Campbell et al. 1993), Southern Shark fishery (Pascoe *et al.* 1992) and South East trawl component (Pascoe 2000; Punt *et al.* 2002a)

A summary of the results of the most recent bioeconomic modelling developed for the SESSF and NPF is given in Table 6. As in many of the models previously cited, the models underlying these results consider only a relatively small proportion of the impacted species, for which appropriate biological parameters are available, thus limiting model usefulness in estimating appropriate target reference points across the complex set of species caught. However, the cost of determining appropriate biological parameters for all species in these fisheries is likely to be prohibitive. For the SESSF Trawl and Gillnet, Hook and Trap sectors, the models effectively estimated single species target reference points, as fishing effort was assumed to be applied to each species separately (Kompas et al. 2009a).

Table 6. Ratio of B_{MEY} to B_{MSY} for selected species

Species	B_{MEY}/B_{MSY}	MEY landings (tonnes)
SESSF Commonwealth Trawl Sector[a]		
Orange roughy in the Eastern Zone	1.20	1200
Orange roughy in the Cascade Zone	1.53	690
Spotted warehou	1.10	4,100
Ling (trawl)	1.29	1,300
Flathead	1.06	3,880
SESSF Gillnet, Hook and Trap Sector[a]		
Ling (auto longline)	1.18	500
Gummy shark (Gillnet)	1.22	1,500
School shark (Gillnet)	1.20	200
SESSF GAB Trawl[b]		
Deepwater flathead	1.31	1182
Bight redfish	1.11	920
Northern Prawn Fishery[c]		
Grooved Tiger Prawns	1.260-1.309	na
Brown Tiger Prawns	1.077-1.119	na

a) 2006-07 prices and costs (Kompas et al. 2009a); b) based on economic data over the range 2007-08 to 2009-10 (Kompas et al. 2012); c) input controlled fishery; based on economic data over several different years (Kompas *et al.* 2010a; Punt *et al.* 2010; Punt et al. 2011)

Results from the generic models

Optimal B_{MEY}/B_{MSY} ratios

The distribution of the optimal B_{MEY}/B_{MSY} ratios for each individual species (i.e. the levels of biomass of individual species that ensure multi-species MEY, as compared to the levels of biomass which would ensure single species MSY) over the 20 000 simulated fisheries is presented in Figure 10 for both models. The current default proxy of $1.2B_{MSY}$ (DAFF 2007) is highlighted in red for comparison.

Based on the Schaefer model, around one quarter (26%) of species simulated had a optimal B_{MEY}/B_{MSY} ratio of less than 1.2, while 1% had an optimal ratio less than $0.2B_{MSY}$ – the current limit reference point for Commonwealth fisheries management (DAFF 2007). In contrast, almost three quarters of the simulated species had optimal ratios above the current default value ($1.2B_{MSY}$) and almost half (47%) had an optimal target reference point greater than $1.5B_{MSY}$. The maximum possible ratio for the Schaefer model is 2, at which point the species is at its carrying capacity and is hence unexploited.

From the Fox model, the median optimal ratio was close to the current default proxy measure (highlighted in red). Because of the different underlying biological model, the ratio of B_{MEY}/B_{MSY} can exceed 2, with a theoretical maximum of 2.72 (at which point the species is at its carrying capacity and hence unexploited). As with the Schaefer model, the optimal ratio was greater than the current default proxy (highlighted in red) for most species in most simulations.

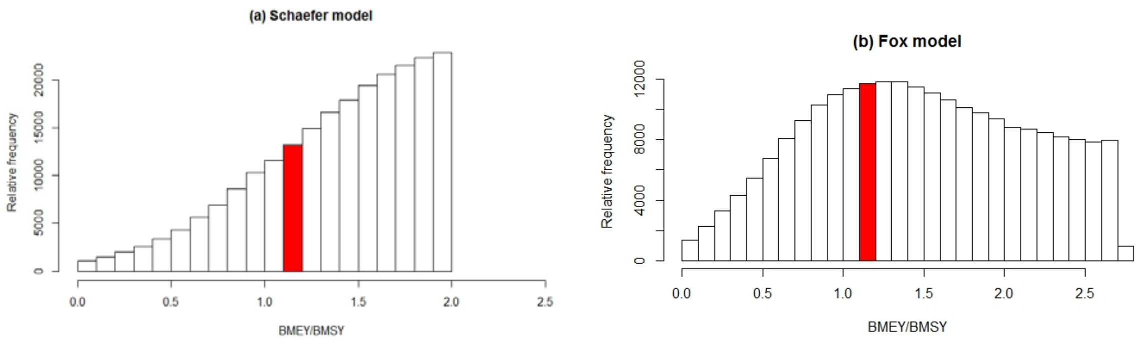


Figure 11. Distribution of estimated optimal B_{MEY}/B_{MSY} ratios in the simulations

The distribution of the optimal B_{MEY}/B_{MSY} ratio was largely invariant to the number of species in the simulated fishery (Figure 11) in the Schaefer model, but the median value appeared to decrease slightly with increased number of species from the Fox model (from around 1.8 with only 3 species to around 1.5 for 10 or more species).

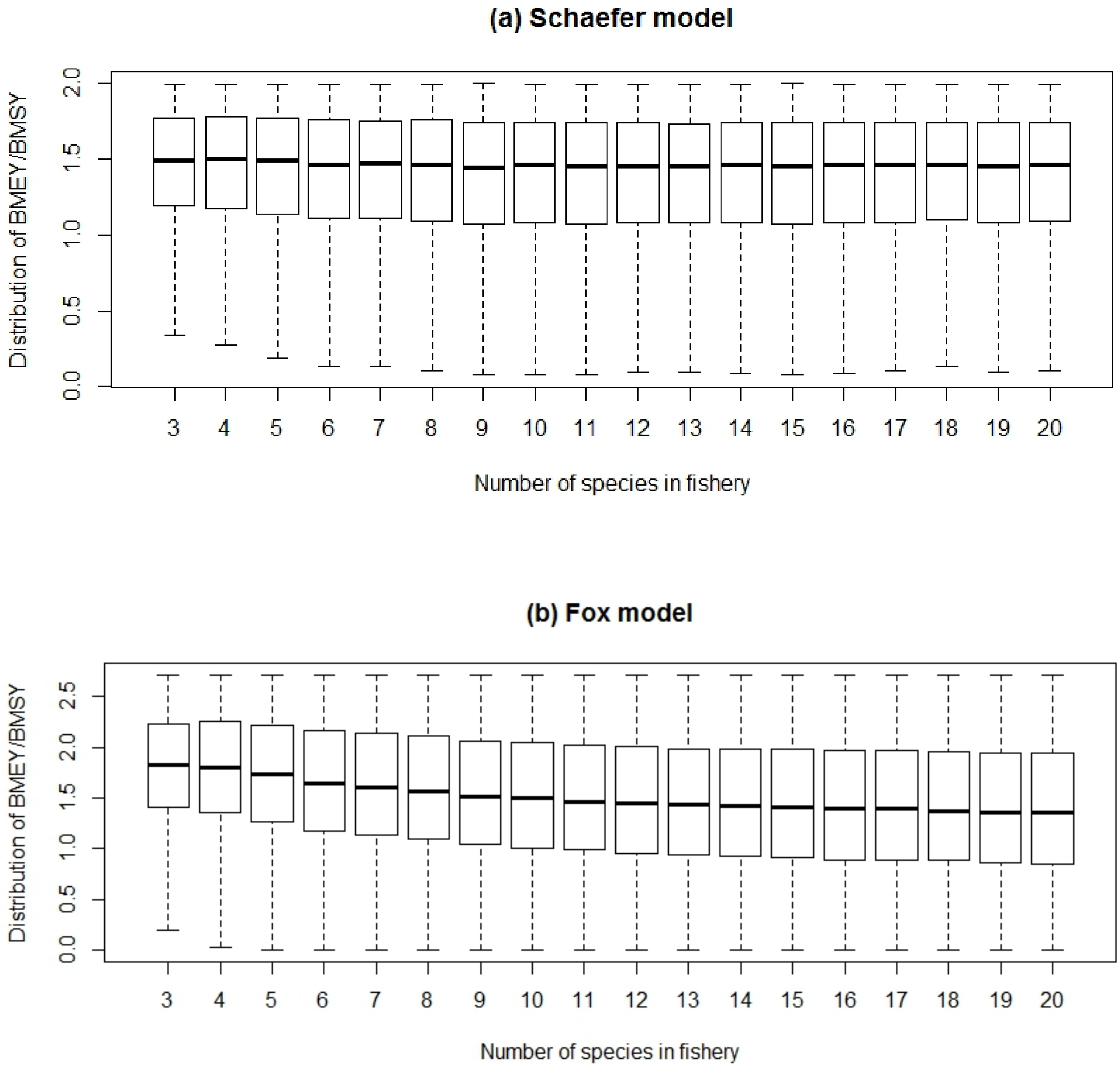


Figure 12. Distribution of estimated optimal B_{MEY}/B_{MSY} ratios by number of species in the fishery

Factors affecting B_{MEY}/B_{MSY}

The relationship between the individual species and fishery characteristics and the optimal B_{MEY}/B_{MSY} ratio was examined through a simple linear regression analysis (Table 7 and Table 8).[11] All parameters were statistically significant at the 0.1% level, although given the large number of observations this is expected.

[11] A log linear regression model was also estimated, but this was no better than the linear model.

Table 7. Simple linear regression results of factors affecting B_{MEY}/B_{MSY} – Schaefer model

	Estimate	Std. Error	t value		Scaled Beta	Rank
Intercept	1.823	0.004	446.740	***	1.389	
Species characteristic						
• Revenue share	1.012	0.008	127.370	***	0.098	3
• p (price)	-0.022	0.000	-60.720	***	-0.031	5
• r (growth rate)	1.658	0.005	341.610	***	0.184	2
• q (catchability)	-25.010	0.035	-720.200	***	-0.359	1
• K (unexploited biomass)	0.000	0.000	-105.810	***	-0.065	4
Fishery characteristic						
• c (cost)	0.000	0.000	39.770	***	0.018	6
• Distance	-0.189	0.006	-32.640	***	-0.016	7
Diagnostics						
• N.Obs	227,181					
• $\bar{R}^2$	0.767					
• F						

Table 8. Simple linear regression results of factors affecting B_{MEY}/B_{MSY} – Fox model

	Estimate	Std. Error	t value		Scaled Beta	Rank
Intercept	2.02	0.01	399.19	***	1.467	
Species characteristic						
• Revenue share	1.22	0.01	122.33	***	0.113	3
• p (price)	-0.03	0.00	-65.75	***	-0.042	6
• r (growth rate)	2.40	0.01	398.38	***	0.266	2
• q (catchability)	-38.02	0.04	-926.21	***	-0.548	1
• K (unexploited biomass)	0.00	0.00	-111.22	***	-0.084	4
Fishery characteristic						
• c (cost)	0.00	0.00	132.40	***	0.074	5
• Distance	-0.24	0.01	-32.91	***	-0.020	7
Diagnostics						
• N.Obs	230,027					
• $\bar{R}^2$	0.84					
• F	172,200			***		

From both models, catchability, growth rate and revenue share where the three main determinants of the optimal ratio. A priori, it would be expected that a species with a high revenue share[12] would have a higher B_{MEY}/B_{MSY} ratio than a species with a relatively low revenue share. Conversely, species that

[12] Revenue shares capture importance in terms of both price and quantity in the fishery. Species with a higher revenue share are more influential in the overall total revenue in the fishery (Figure 1), and have also been found to be reasonable indicator species for the level of effort at MEY when information on the full set of species is poorly understood (Chae and Pascoe 2005). In the analysis, revenue share was not highly correlated with prices.

were highly catchable would have a lower optimal B_{MEY}/B_{MSY} share than a species that had a lower catchability coefficient.

The linear regression model explained around 76 per cent of the variation in the optimal B_{MEY}/B_{MSY} ratio for the Schaefer model and 84 per cent for the Fox model. The linear regression model tended to overestimate the values at the lower end (i.e. optimal ratio of less than 1), and also result in optimal ratios greater than 2 at the upper end for the Schaefer model (Figure 12(a)). The latter is theoretically impossible as, given logistic growth, B_{MSY} = 0.5K and hence a value of the optimal ratio greater than 2 suggests that B_{MEY}>K. Hence the regression model is not ideal in terms of its use as a tool for deriving estimates of the optimal ratio in the case of a species with logistic growth. The regression model performed better for species with exponential growth (Fox model), although there was considerable error in the estimates (Figure 12(b)).

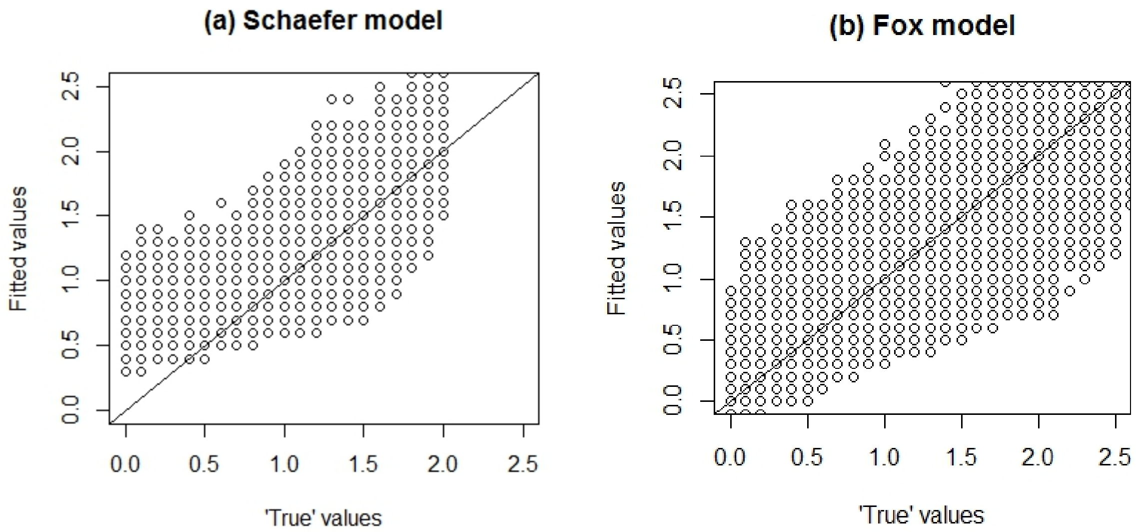


Figure 13. Comparison of estimated and "true" optimal B_{MEY}/B_{MSY} ratios based on the linear regression model

Decisions support system

As outlined in the Methods section, two alternative decision support systems were developed and tested against the case study fishery results. Initially, a regression tree approach was developed, which provides a simple set of "rules of thumb" for determining an appropriate target reference point. A Bayesian Network was also developed as an alternative approach, as it has an advantage in that it can capture some of the uncertainty in the species characteristics as well as uncertainty in the outcome.

Regression tree approach

The regression models above (Table 7 and Table 8), while providing potentially biased estimates of the optimal ratio at lower levels of this ratio, also require detailed information on each of the biological and economic parameters. In many multispecies fisheries, these will not be known with any precision. However, it might be expected that enough information may exist to determine if parameter values are relatively high, medium or low. The parameter data were re-classified into 4 categories: 1) low (the lower 25% quartile); 2) below average (between the 25% and 50% quartile); 3) above average (50%-75% quartile); and 4) high (above the 75% quartile). For revenue share, this roughly equated to <5% of total revenue, 5-10%, 10-20% and >20% of total revenue so these were used as the categories.

A regression tree was estimated using the classified data to provide a simple set of "rules of thumb" (Figure 13). All variables used in the regression model above were also applied in the regression tree analysis, although as is common in such an analysis only a subset of variables were retained in the final structure of the regression tree. In this case, only catchability and growth rates (the two most influential factors) were used for the splits for both models.

For the data derived from the Schaefer model, the resultant optimal values ranged from 0.52 to 1.9, avoiding the low and high values from the regression model. The residual mean deviance of the regression tree was 0.046, with a median residual of 0.025. While further splits (or levels) were possible, these were found to have little influence on the deviance reduction (Figure 14(a)).

For the data derived from the Fox model, the resultant optimal values ranged from 0.59 to 2.3, again avoiding the low and high values from the regression model. The residual mean deviance of the regression tree was 0.102 with a median residual of 0.01. As with the Schaefer model-based regression tree, further splits were found to have little influence on the deviance reduction (Figure 14(b)).

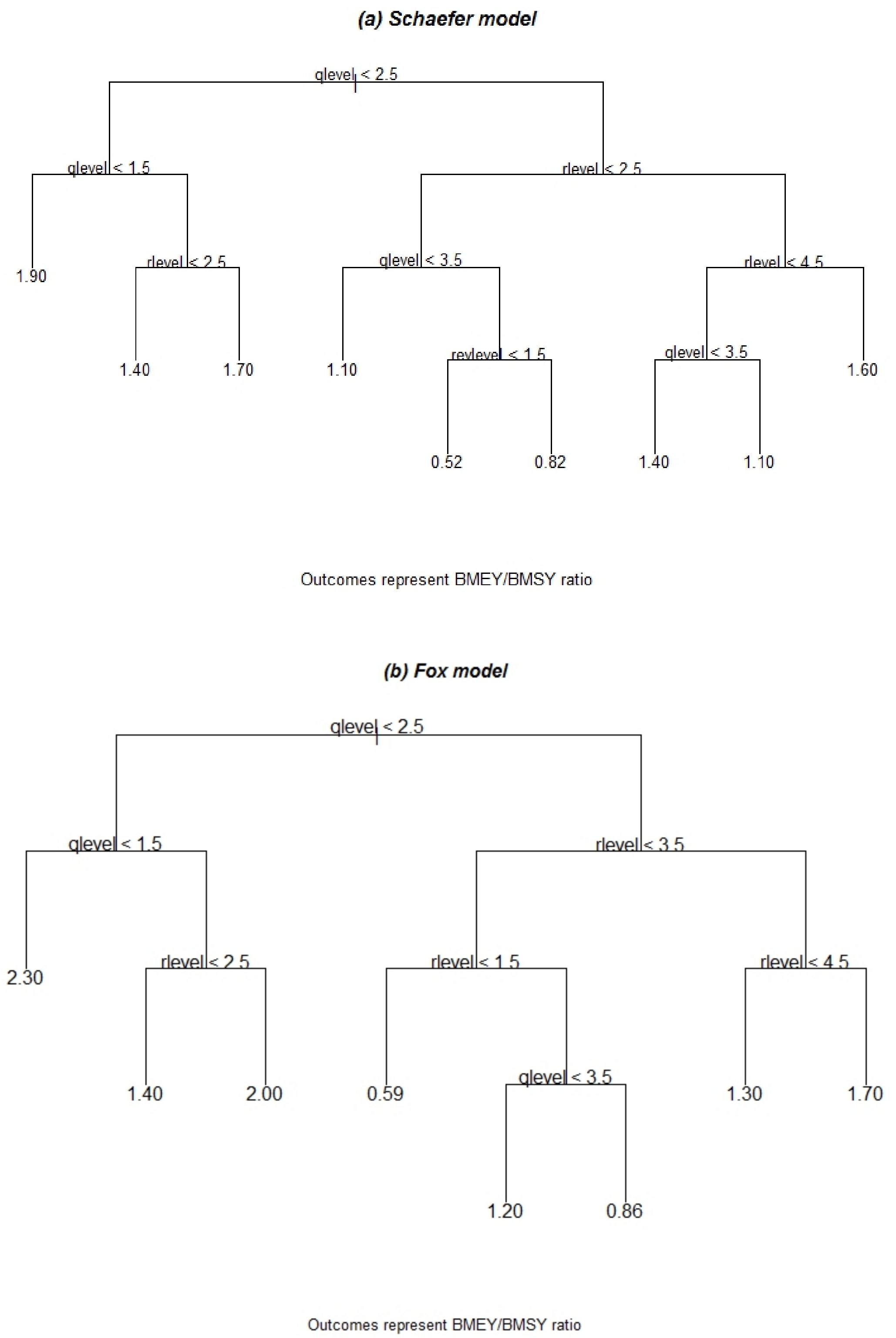


Figure 14. Regression tree models using all data
Note: qlevel represents the quartile value for catchability within the range simulated (4=high, 1=low), and rlevel represents the quartile level for the growth rate

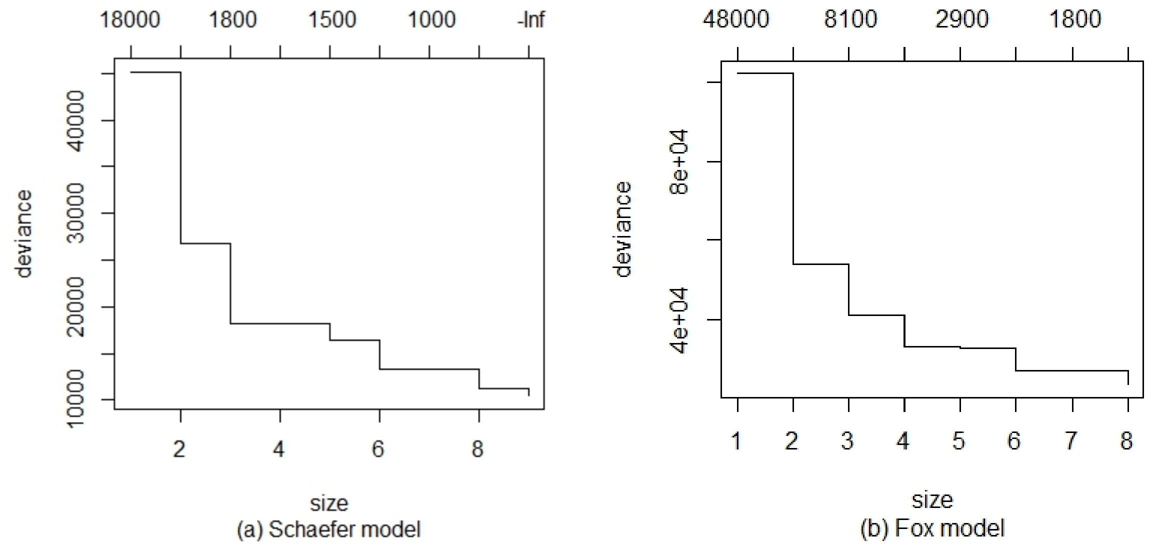


Figure 15. Deviance reduction from further splits in the regression trees

The regression tree model results were compared to the "true" values using a simple linear regression model (Table 9). For the estimates derived from both models, the intercepts were both significantly different from zero, although the slopes were not significantly different from 1, suggesting that the regression tree models were reasonably unbiased. However, the regression tree models only captured 77 around per cent of the variation in B_{MEY}/B_{MSY} for data derived from both models.

Table 9. Simple linear regression results of estimated against "true" B_{MEY}/B_{MSY} ratios

	Schaefer				Fox			
	Estimate	Std. Error	t value		Estimate	Std. Error	t value	
Intercept	0.064	0.002	39.91	***	-0.027	0.002	-14.71	***
Estimated ratio	0.956	0.001	857.85	***	1.014	0.001	869.78	***
Diagnostics								
• N.Obs	227,187				230,033			
• $\bar{R}^2$	0.764				0.767			
• F	735,900			***	75,650			***

The distribution of the "true" optimal ratio at each tree outcome was also examined (Figure 15). There was considerably more variability in the "true" outcome at the lower levels of the regression tree outcomes. This suggests considerable potential for error at the lower levels of the optimal biomass ratio (i.e. for species for which the multi-species optimal biomass would be much smaller than that ensuring single species MSY) using the regression tree.

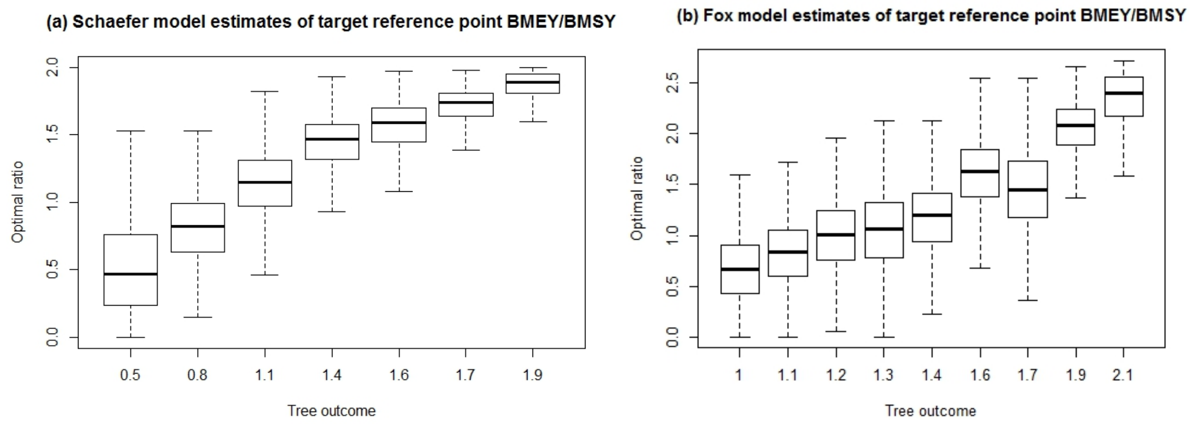


Figure 16. Tree based estimates vs model estimates

Revenue share of each species in the mixed fishery was a key explanatory variable in the regression tree model for the lower level tree outcomes (i.e. $B_{MEY}/B_{MSY} < 1$). Given that information on revenue share is likely to be available in most fisheries even when other data are limited, revenue share was used to further evaluate the results for different categories of species.

The data were sub-grouped into the four revenue categories and a regression tree estimated for each subset (Figure 16 and Figure 17). The results indicate that considerable uncertainty exists for the species with the smallest revenue share, but this decreases as the revenue shares increase. Further, the range of potential B_{MEY}/B_{MSY} ratios decreases as the revenue shares increase. For example, for species representing more than 20% of the total fishery revenue, the optimal B_{MEY}/B_{MSY} ratio from the regression tree ranged from 0.96 to 1.6 for the Schaefer model-derived data, and 0.99 to 2.1 for the Fox model-derived data. In contrast, for species comprising less than 5% of the total revenue, the optimal B_{MEY}/B_{MSY} ratio from the regression tree ranged from 0.38 to 1.9 for the Schaefer model-derived data, and 0.42 to 2.4 for the Fox model-derived data.

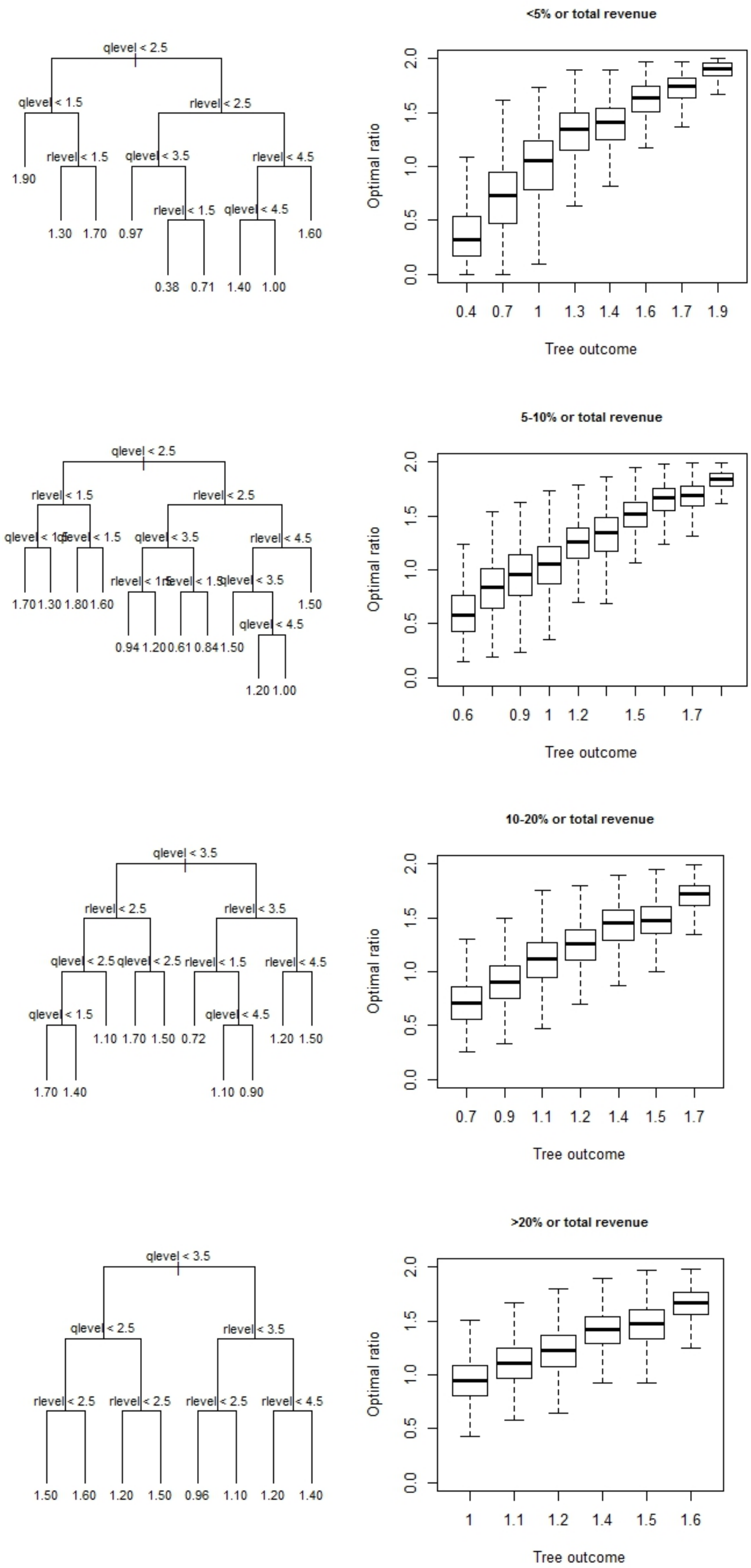


Figure 17. Regression tree from Schaefer model disaggregated by revenue share
Note: qlevel represents the quartile value for catchability within the range simulated (4=high, 1=low), and rlevel represents the quartile level for the growth rate

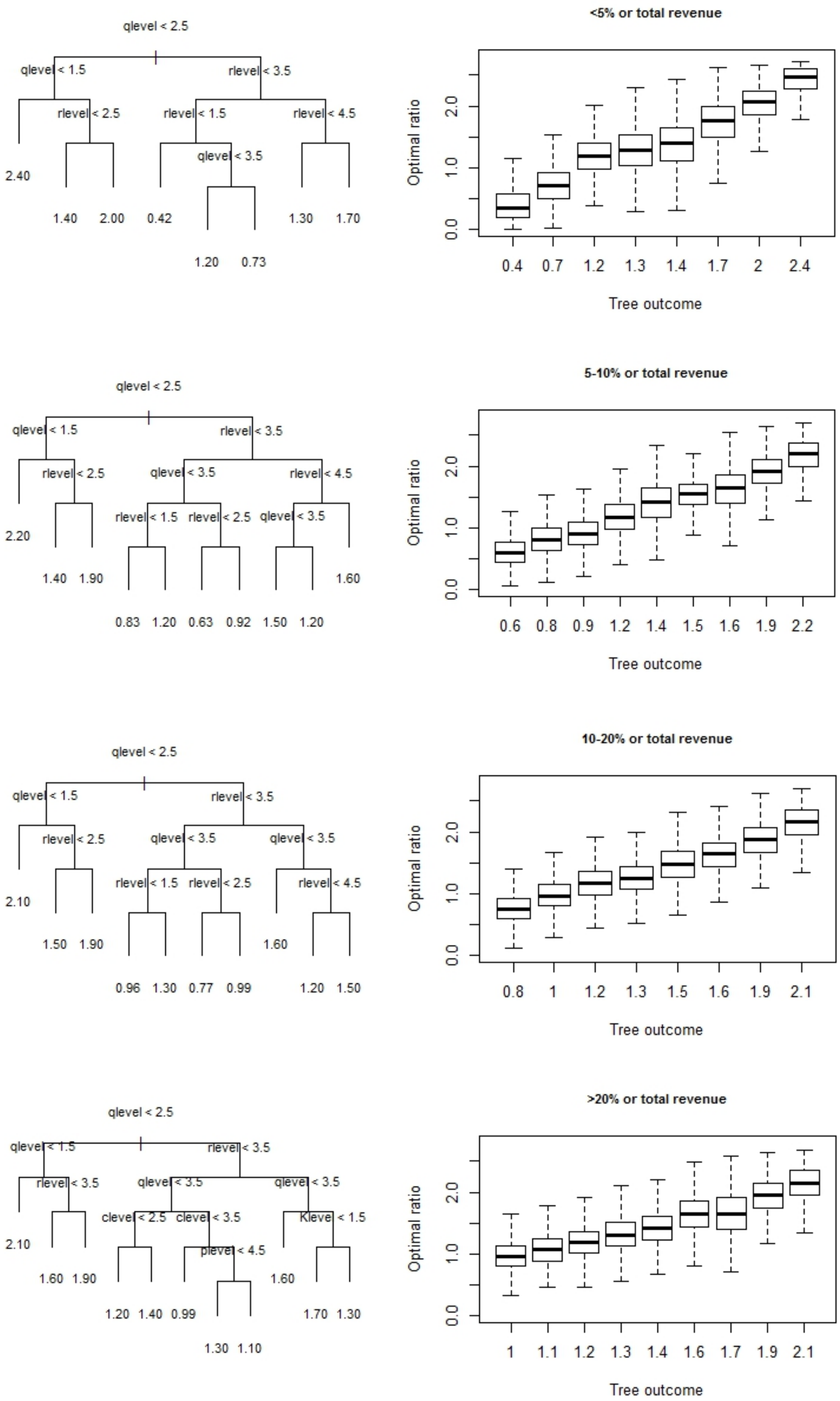


Figure 18. Regression tree from Fox model disaggregated by revenue share

The discrete nature of the regression tree approach results in only a limited number of outcomes. In contrast, the bioeconomic model can provide continuous outcomes given the set of biological and economic parameters. Consequently, the regression tree approach results in a substantially smaller set of potentially "optimal" target reference points than a full bioeconomic model would estimate (Figure 18),[13] although splitting the data by revenue share groups provides a greater number of potential target reference points. While these are presented for the data derived from the Fox model only, similar patterns were observed for the Schafer model-derived data.

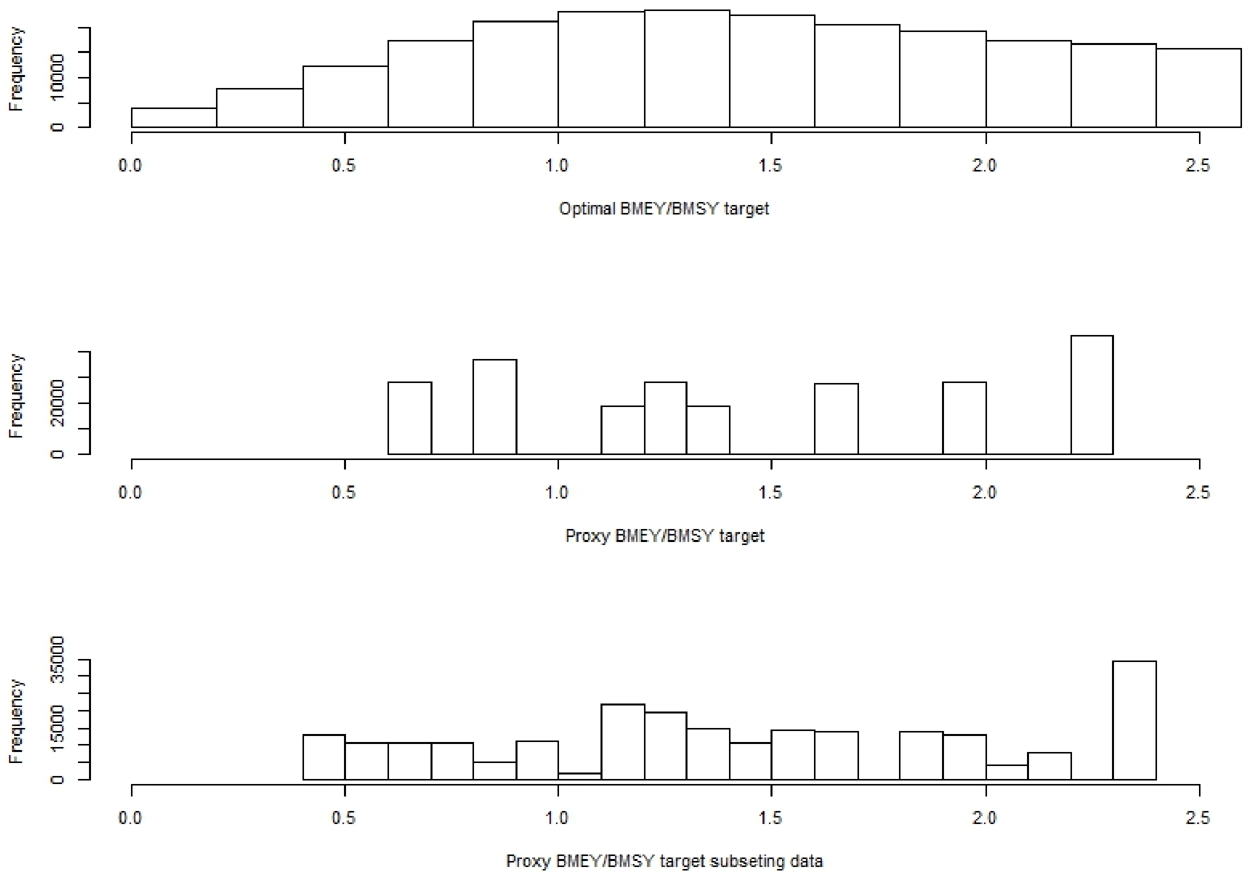


Figure 19. Comparison of the distributions of target reference points B_{MEY}/B_{MSY} derived from the bioeconomic model (top panel), the regression tree using all data (middle panel) and the disaggregated regression tree approach (bottom panel) from the Fox model-derived data.

[13] Note also that the scale on the Frequency axis varies, as the same total number of observations are compressed into fewer target values.

Application of tree based proxy measures to a fishery: implications for profits

The bioeconomic model developed above was run applying two different empirical harvest strategies to the simulated fisheries. The first strategy used the current default target reference point of B_{MEY}=1.2 B_{MSY} for each species (DAFF 2007), while the second used the (disaggregated) regression tree estimate of the B_{MEY}/B_{MSY} ratio previously derived. In both cases, the target reference point was applied only to the main species in value (i.e. the species with the highest revenue share) in each simulated fishery. The mechanism by which this was achieved was by deriving the level of fishing effort required to achieve the target reference point for the main species in terms of revenue share and applying this to the fishery as a whole. As the simulations involved pure "joint" production, then achieving an optimal outcome for the revenue dominant species would also result in an optimal outcome for the other byproduct species. The outcomes (in terms of fishery profit) of these harvest strategies were compared with the "optimal" outcome derived from maximizing MEY at the whole of fishery level.

The difference, in terms of the level of effort required to achieve the target biomass ratio, between the regression tree target reference point and the current default target reference point is illustrated in Figure 19. No obvious pattern was observed for the data derived from the Schaefer model: in some cases, the tree-based effort target is substantially higher than the current default while in other cases it was substantially lower. For the data derived from the Fox model, the level of effort required to achieve the tree based target reference points was generally less than (or equal to) that required to achieve the current default proxy reference point.

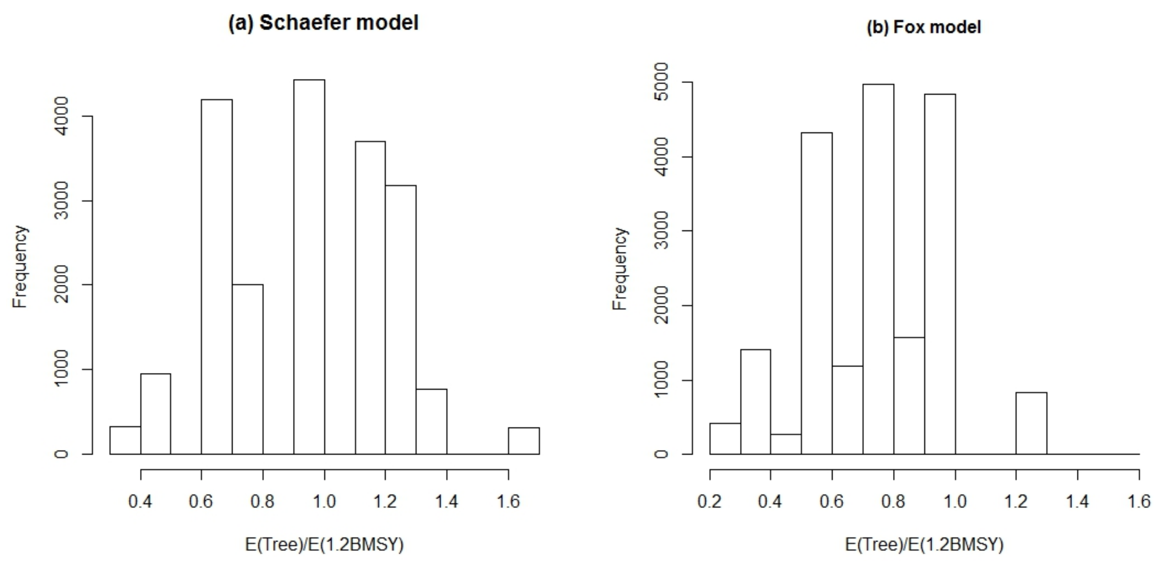


Figure 20. Distribution of differences between the target reference points derived from the regression tree and the default value approaches.

The distribution of economic profits in the simulation model under each approach to setting the target reference point is presented in Figure 20 for the Schaefer model and Figure 21 for the Fox model, along with the optimal level of profits at the “true” fishery-wide MEY (where all species in the fishery are caught at a level that produces multispecies MEY). The distributions are summarised in Table 10. Both proxy approaches result in a number of instances where negative profits are realised, although the tree-based proxy approach results in a higher mean level of profit than the 1.2B_{MSY} proxy. On average, the 1.2B_{MSY} proxy resulted in a 14% (Fox) to 31% (Schaefer) lower profit than the optimal scenario, compared with a 3% (Fox) to 6% (Schaefer) lower profit from the tree-based proxy.

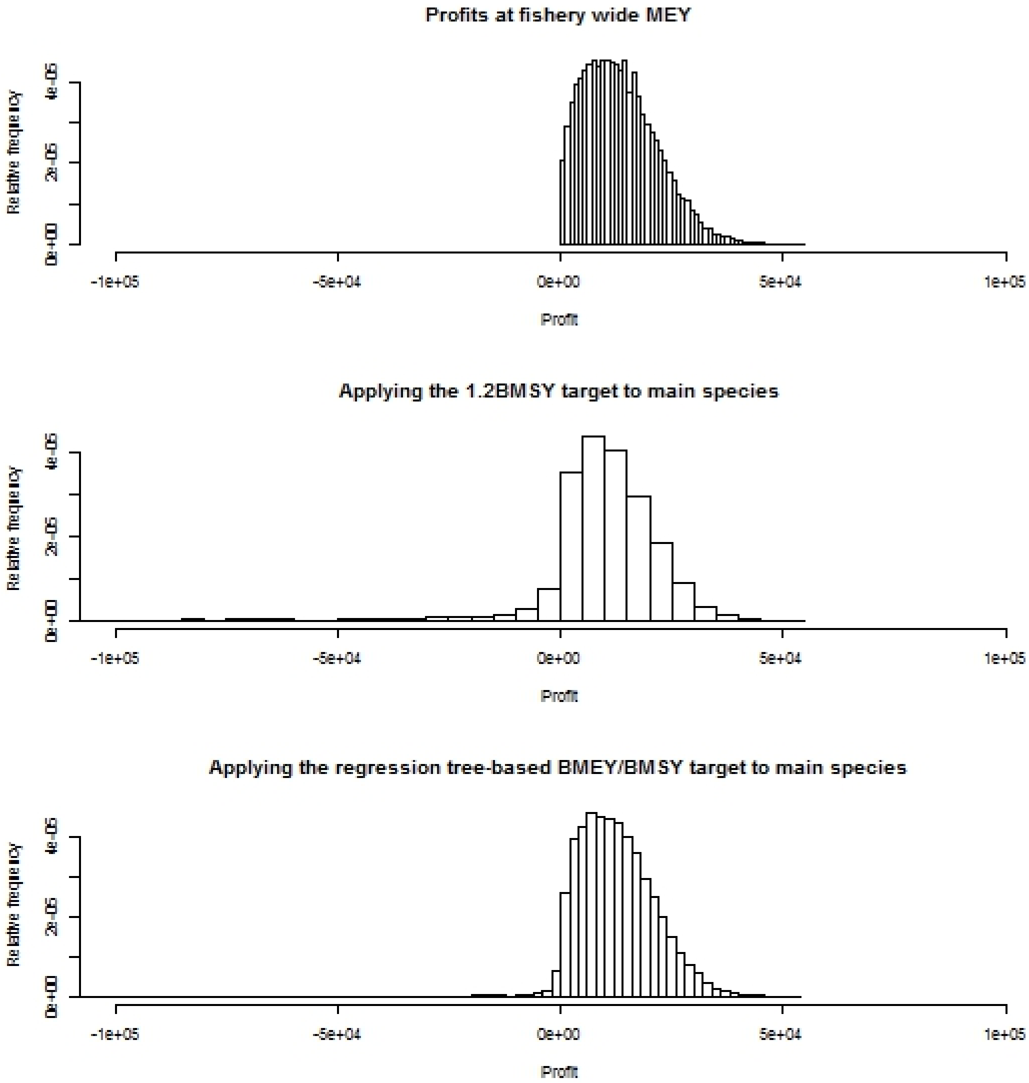


Figure 21. Distribution of profits under optimal and different target reference point proxies - Schaefer model

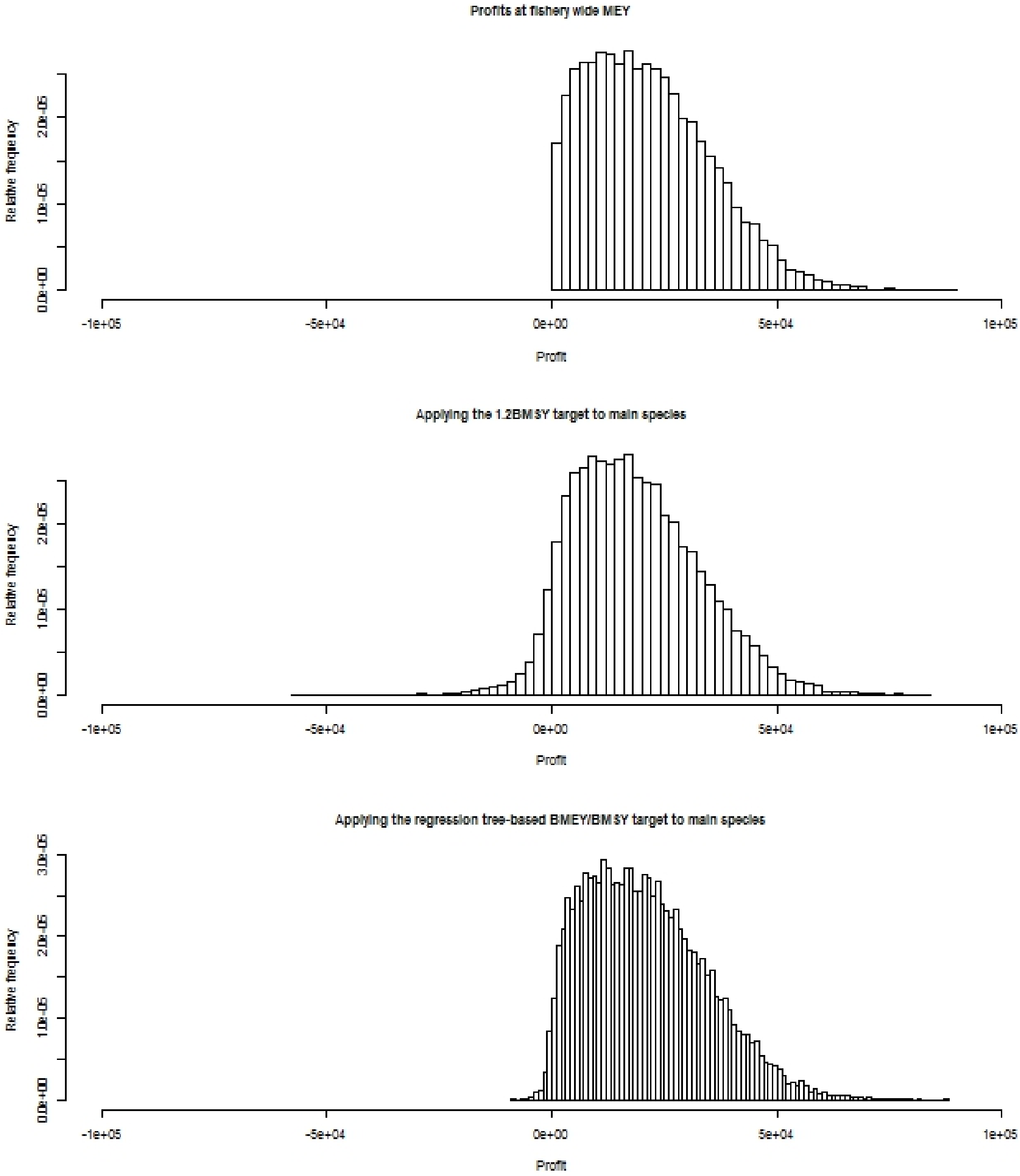


Figure 22. Distribution of profits under optimal and different target reference point proxies - Fox model

Table 10. Distribution of profits under different TRF management strategies

	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
Schaefer model						
• Optimal (MEY)	2.48	6943	12450	13410	18630	54230
• $1.2B_{MSY}$	-2E+06	4575	10320	9241	16820	53460
• Tree-based proxy	-146800	6246	11720	12560	17930	53190
Fox model						
• Optimal (MEY)	0.54	10500	19850	21480	30450	88780
• $1.2B_{MSY}$	-56210	7937	17110	18520	27600	82290
• Tree-based proxy	-8097	10090	19280	20790	29580	87810

From the revenue share based decision trees, most species that had greater than 20 per cent revenue share had an optimal target reference point ratio of between 1 and 1.5 (Figure 22). This explains the apparent "reasonable" performance of the default proxy reference point when applied to the main species. However, less important species (which are more influenced by the species with which they are caught) generally have a substantially wider distribution of optimal target reference point ratios, with a relatively high proportion of species with high optimal B_{MEY}/B_{MSY} ratios (Figure 23). These "minor" species dominate the catch in terms of number of species, and attempting to apply the current default proxy target reference point to these species is likely to be more problematic.

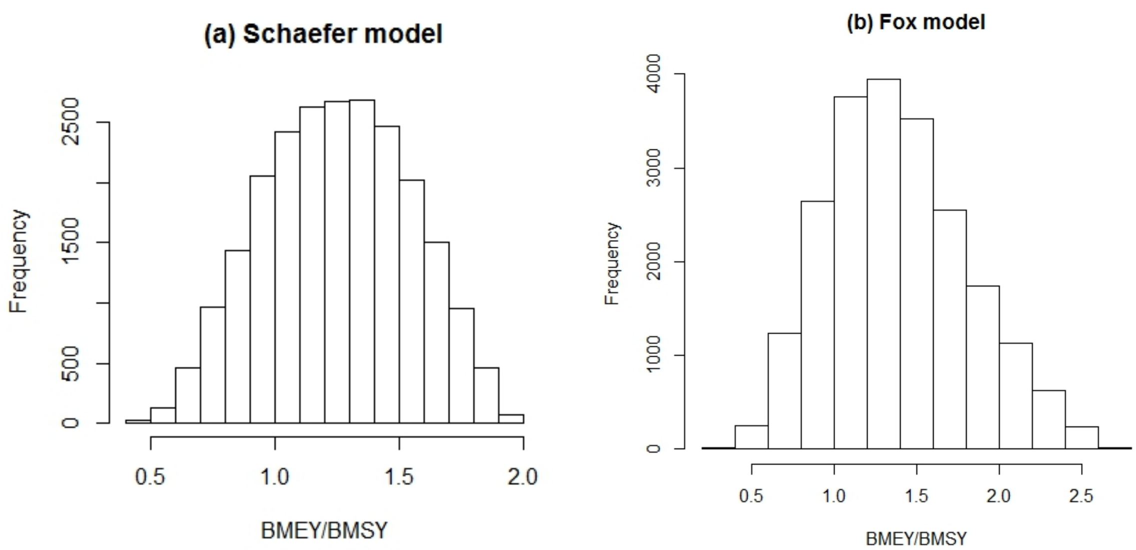


Figure 23. Distribution of BMEY/BMSY ratios for the main (>20% revenue) species in the data from the regression trees

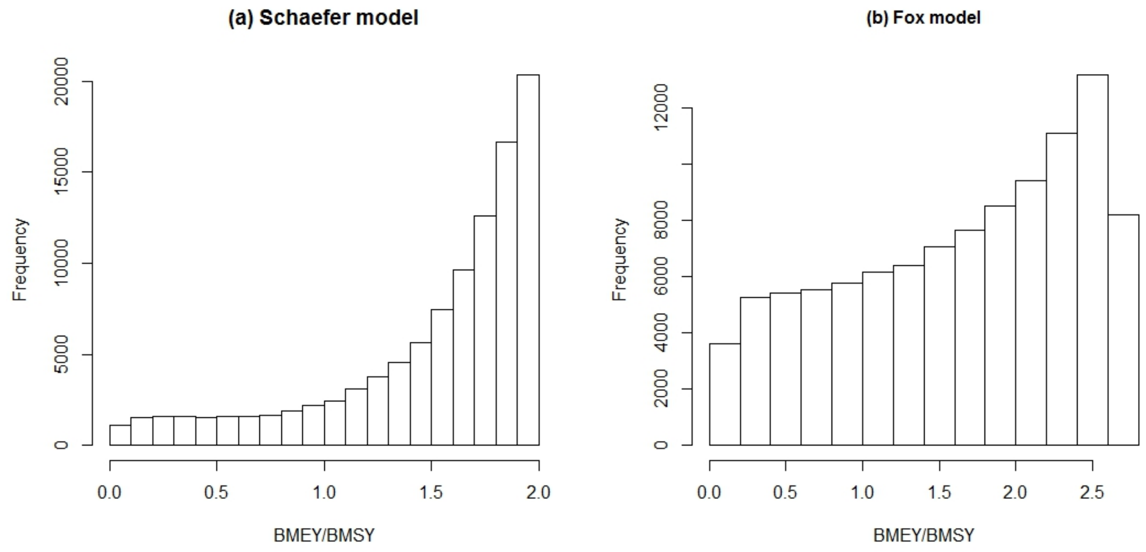


Figure 24. Distribution of BMEY/BMSY ratios for the minor (<5% revenue) species in the data from the regression trees

Bayesian Network approach

The output from the generic models was also used to estimate probabilities for a Bayesian Network. A feature of NETICA (and many other Bayesian Network packages) is its ability to read in data and "learn" to identify non-linear relationships. Separate Bayesian Network models were developed using the output from each type of biological model (i.e. Fox and Schaefer model). Attempts at pooling all data (from both models) were less successful.

Both versions of the Bayesian Network were constructed similarly using the information that was also used in the regression analysis (Figure 24 and Figure 25). However, given the relatively low impact of prices and number of species in the regression models, these were combined to provide a sub-model of revenue share. Hence, either revenue share directly, or information on price and number of species, can be used in the analysis).

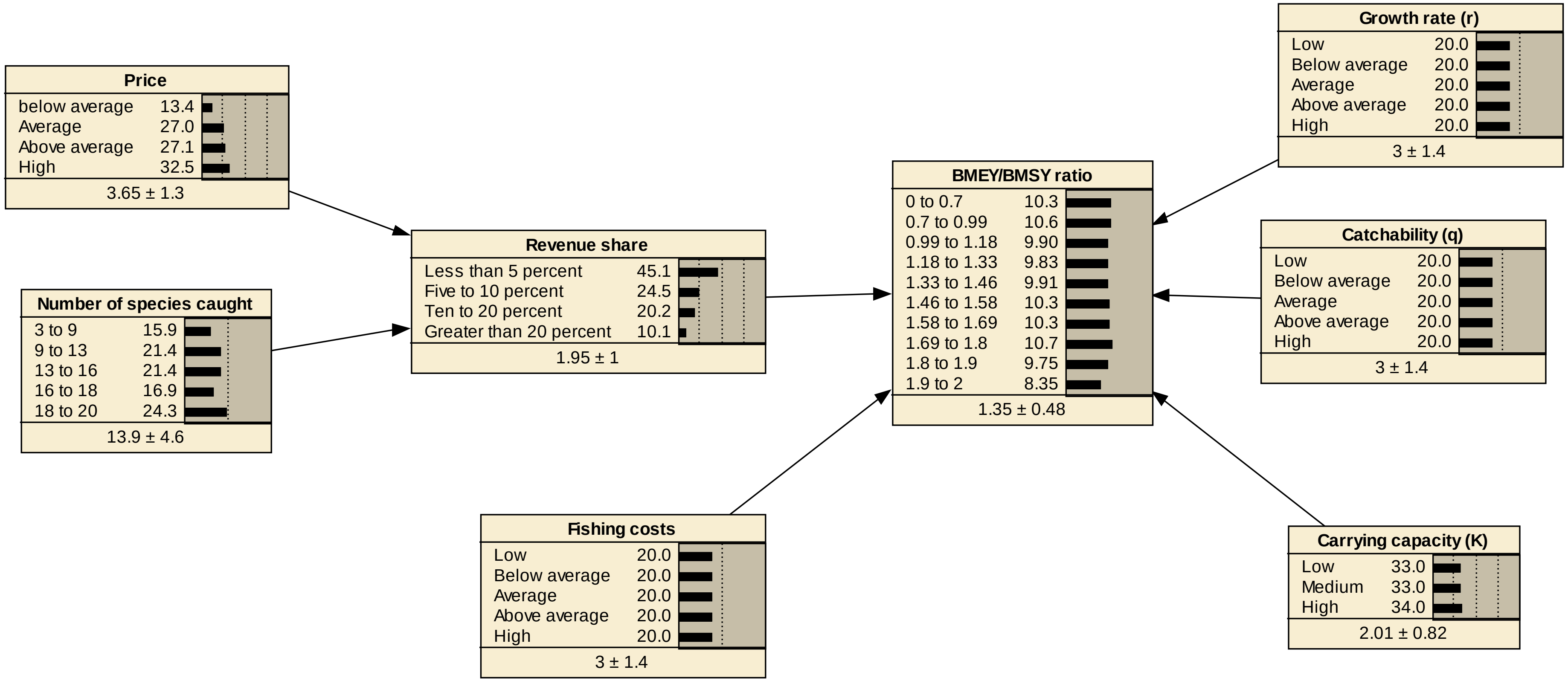


Figure 25. Bayesian Network model derived from the Schaefer generic model

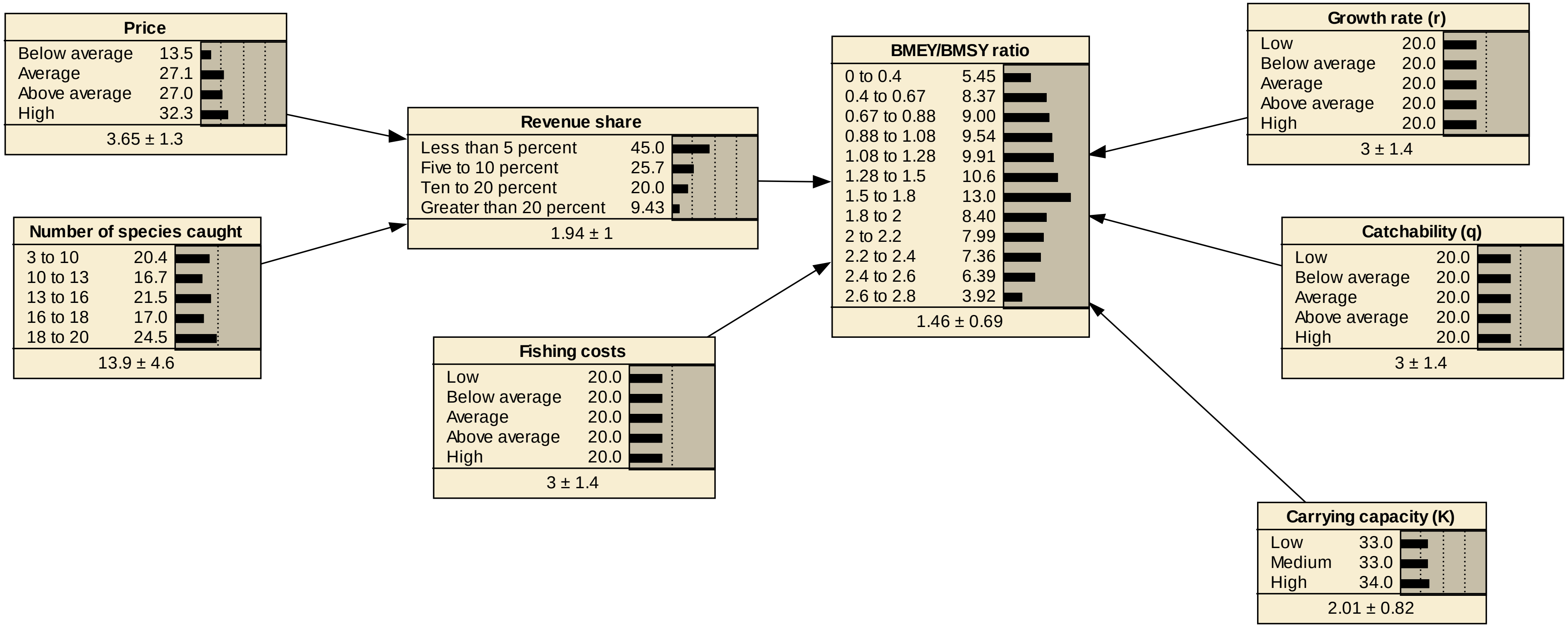


Figure 26. Bayesian Network model derived from the Fox generic model

Two examples of outcomes under different scenarios are presented in Figure 26 and Figure 27. In the former, catchability, growth, carrying capacity and costs are all assumed average, while revenue share is less than 5 per cent. In the latter, growth and costs are assumed low, while catchability and carrying capacity are assumed high, and revenue share is assumed to be greater than 20 per cent. Both models produce relatively similar distributions of the optimal ratios under each set of circumstances. The mean value and standard error is also presented.

(a) Schaefer-based model

BMEY/BMSY ratio	
0 to 0.7	0.60
0.7 to 0.99	2.40
0.99 to 1.18	4.19
1.18 to 1.33	18.0
1.33 to 1.46	28.7
1.46 to 1.58	29.3
1.58 to 1.69	14.4
1.69 to 1.8	1.20
1.8 to 1.9	0.60
1.9 to 2	0.60
1.42 ± 0.2	

(b) Fox-based model

BMEY/BMSY ratio	
0 to 0.4	0.92
0.4 to 0.67	1.02
0.67 to 0.88	2.39
0.88 to 1.08	14.1
1.08 to 1.28	25.9
1.28 to 1.5	28.7
1.5 to 1.8	20.4
1.8 to 2	2.68
2 to 2.2	0.92
2.2 to 2.4	1.02
2.4 to 2.6	0.92
2.6 to 2.8	0.92
1.35 ± 0.36	

Figure 27. Example application with average r, q, K and c; <5% revenue share and 18-20 species

(a) Schaefer-based model

BMEY/BMSY ratio	
0 to 0.7	29.8
0.7 to 0.99	59.6
0.99 to 1.18	5.30
1.18 to 1.33	1.32
1.33 to 1.46	0.66
1.46 to 1.58	0.66
1.58 to 1.69	0.66
1.69 to 1.8	0.66
1.8 to 1.9	0.66
1.9 to 2	0.66
0.749 ± 0.34	

(b) Fox-based model

BMEY/BMSY ratio	
0 to 0.4	2.78
0.4 to 0.67	33.3
0.67 to 0.88	40.7
0.88 to 1.08	13.9
1.08 to 1.28	2.78
1.28 to 1.5	0.93
1.5 to 1.8	0.93
1.8 to 2	0.93
2 to 2.2	0.93
2.2 to 2.4	0.93
2.4 to 2.6	0.93
2.6 to 2.8	0.93
0.803 ± 0.41	

Figure 28. Example application with low r and c, high q and K; >20% revenue share and 18-20 species

Sensitivity analysis

The key measures of sensitivity in the Bayesian Network (i.e. mutual influence and variance reduction scores) are presented in Table 11. The absolute values of the mutual influence and variance reduction scores have little individual meaning, but are used to rank the indicators from most to least important in terms of impacts on the node of interest. The value of the sensitivity analysis scores decline exponentially for all measures. From the mutual information and variance of belief measures, most of the information affecting the overall target reference point is contained in the first three parameters (growth (r), catchability (q) and revenue share (R)) (Figure 28) – consistent with the regression analysis and regression trees.

Table 11. Sensitivity analysis results

		Variance Reduction	Percent	Mutual Info	Percent	Variance Of Beliefs
Schaefer-based model						
Catchability	q	0.0797	35.1	0.4374	13.2	0.0114
Growth rate	r	0.0376	16.5	0.1479	4.5	0.0031
Carrying capacity	K	0.0005	0.2	0.0036	0.1	0.0001
Fishing costs	c	0.0003	0.1	0.0012	0.0	0.0000
Revenue share	R	0.0000	0.0	0.0325	1.0	0.0004
Fox-based model						
Catchability	q	0.1831	38.9	0.4190	11.9	0.0062
Growth rate	r	0.0594	12.6	0.1311	3.7	0.0014
Carrying capacity	c	0.0043	0.9	0.0078	0.2	0.0001
Fishing costs	K	0.0020	0.4	0.0058	0.2	0.0001
Revenue share	R	0.0007	0.1	0.0315	0.9	0.0002

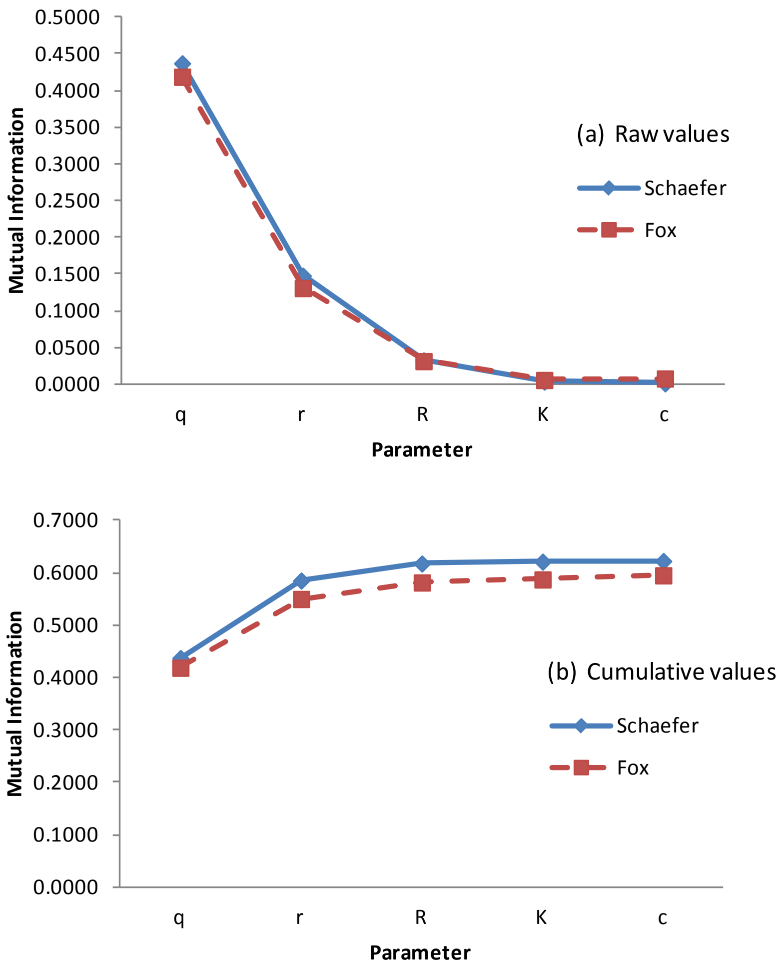


Figure 29. Bayesian Network sensitivity analysis results

Case study model results

Equilibrium model

Both the R and ADMB models provided consistent results; a re-assuring check indicating consistency on the overall analysis. The two models used the current effort (shots) in each metier as the starting values. Furthermore, the R model also used lower and higher starting values to check for problems of local optima.

Optimisation models by their nature may result in extreme and unrealistic outcomes. When left unconstrained, both models set fishing effort to zero in the two inshore trawl metiers and the Danish Seine Bass Strait metier, concentrating effort in the other three metiers. Such an outcome is unrealistic; as not all boats can operate offshore; the catch models do not allow for crowding externalities, and also an area unfished is unlikely to remain unfished in the long term. Restricting the degree to which effort can change in each metier, while not producing a true maximum MEY scenario in the pure sense, is likely to result in a more realistic outcome.

Several alternative scenarios were examined with relatively small impacts on estimated total fishery profits. The scenario used for the final analysis involved a restriction that effort in any one metier cannot be reduced by more than 50%, nor increased by more than 100%. The modified costs were also adopted as these were considered more realistic than assuming the same costs for both inshore and offshore fishing vessels.

Given that the key biological parameters (growth, carrying capacity) are subject to environmental fluctuations, and prices and costs also vary, the model was run stochastically with these parameters varying by a factor of N(1,0.1) (with fuel varying by N(1,0.2) given large fluctuations on fuel prices). The model was run for 10,000 optimisations and the distribution of profits and target reference points estimated.

Optimal profits varied substantially in the fishery depending on the relative biological and economic parameters (Figure 29). Annual sustainable fishery profits averaged around $3.8m, which is less than that currently generated in the fishery (around $4.8m (George and New 2013)).

Variation in profits was most sensitive to variations in vessel and fuel costs (Table 12). The regression coefficients in Table 12 also represent the profit elasticity; that is, the percentage effect on profits of a one percent change in the variable. A one percent increase in fuel costs resulted in a 1.1 per cent decrease in profits (and vice versa), while a one percent increase in vessel costs resulted in a 2.1 per cent decrease in profits. In contrast, changes in price(s) had little impact on profits.

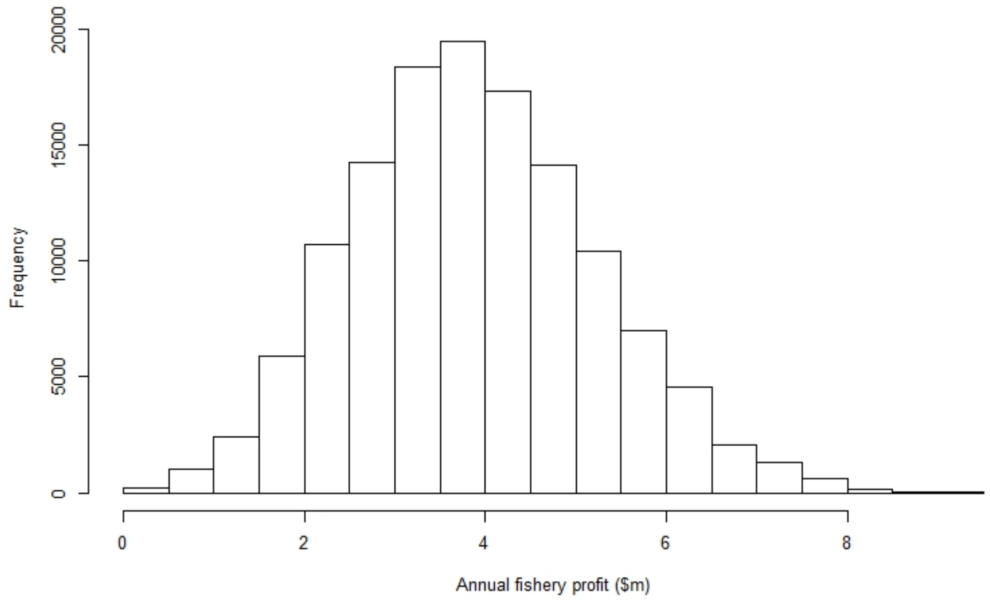


Figure 30. Distribution of annual profits at MEY with varying biological and economic parameters

Table 12. Log-linear regression results of factors affecting fishery profits

	Estimate	Std. Error	t value	Sig
Constant	8.16	0.00	13188.40	***
log(r)	0.09	0.01	14.25	***
log(K)	0.29	0.01	47.77	***
log(p)	0.01	0.01	2.34	*
log(c)	-2.15	0.01	-357.95	***
log(f)	-1.16	0.00	-399.49	***
NOBS	129,955			
$\bar{R}^2$	0.694			
F	58960			***

*** Significant at 0.1% level; ** Significant at 1% level; * Significant at 5% level

The distribution of the “optimal” B_{MEY}/B_{MSY} ratios also varied considerably (Figure 30). For most species, the optimal B_{MEY}/B_{MSY} ratio exceeded 2, with only flathead (FLT) and John Dory (DOJ) consistently being less than 2.

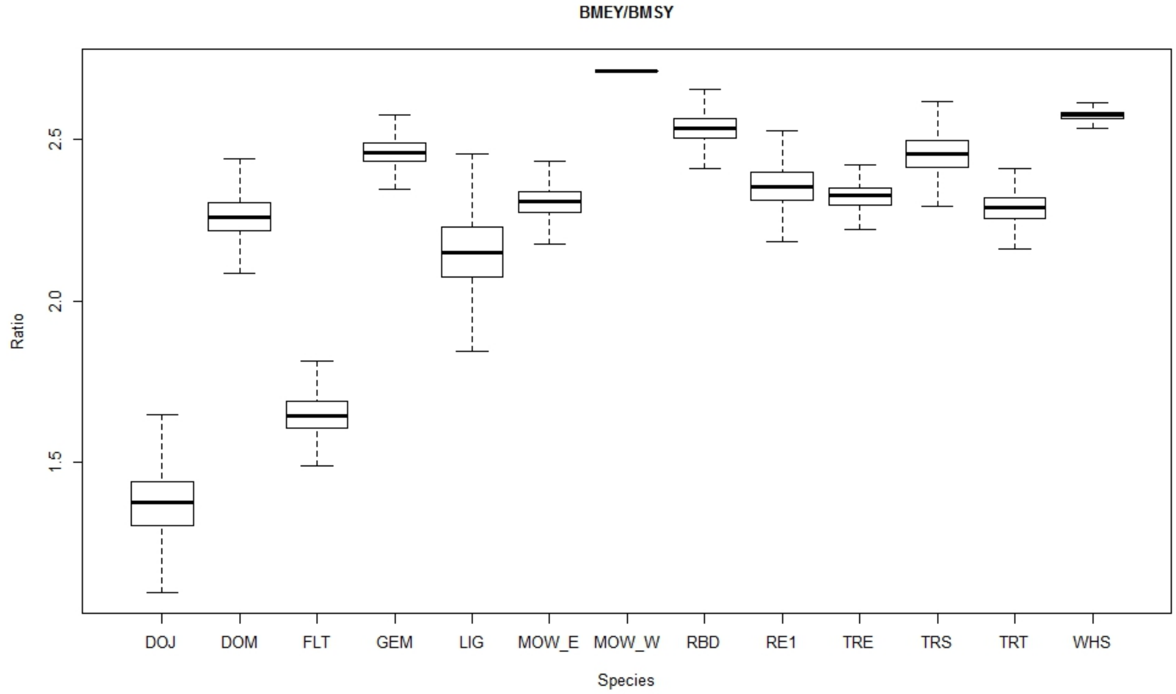


Figure 31. B_{MEY}/B_{MSY} ratios at fishery MEY

Dynamic model

The dynamic version of the model was run assuming a 5 per cent discount rate. A wide range of assumptions were also tested, including different restrictions on effort change, different cost assumptions (i.e. same costs or different costs for inshore/offshore fishing), and different terminal conditions. Details on model runs and results are given in Appendix A. An example of one run is given in Figure 31.

In all the dynamic model runs, as with many such bioeconomic models, the optimal solution was to effective close the fishery by reducing fishing effort in the first year to zero to allow stocks to rapidly recover to a higher level. This is not a realistic scenario, as most fishing businesses could not afford to remain idle for a year or so. Imposing fishing effort levels derived from the equilibrium model onto the dynamic model resulted in similar outcomes in terms of long run biomass levels, but a lower net present value due to a slower recovery rate (see Appendix A).

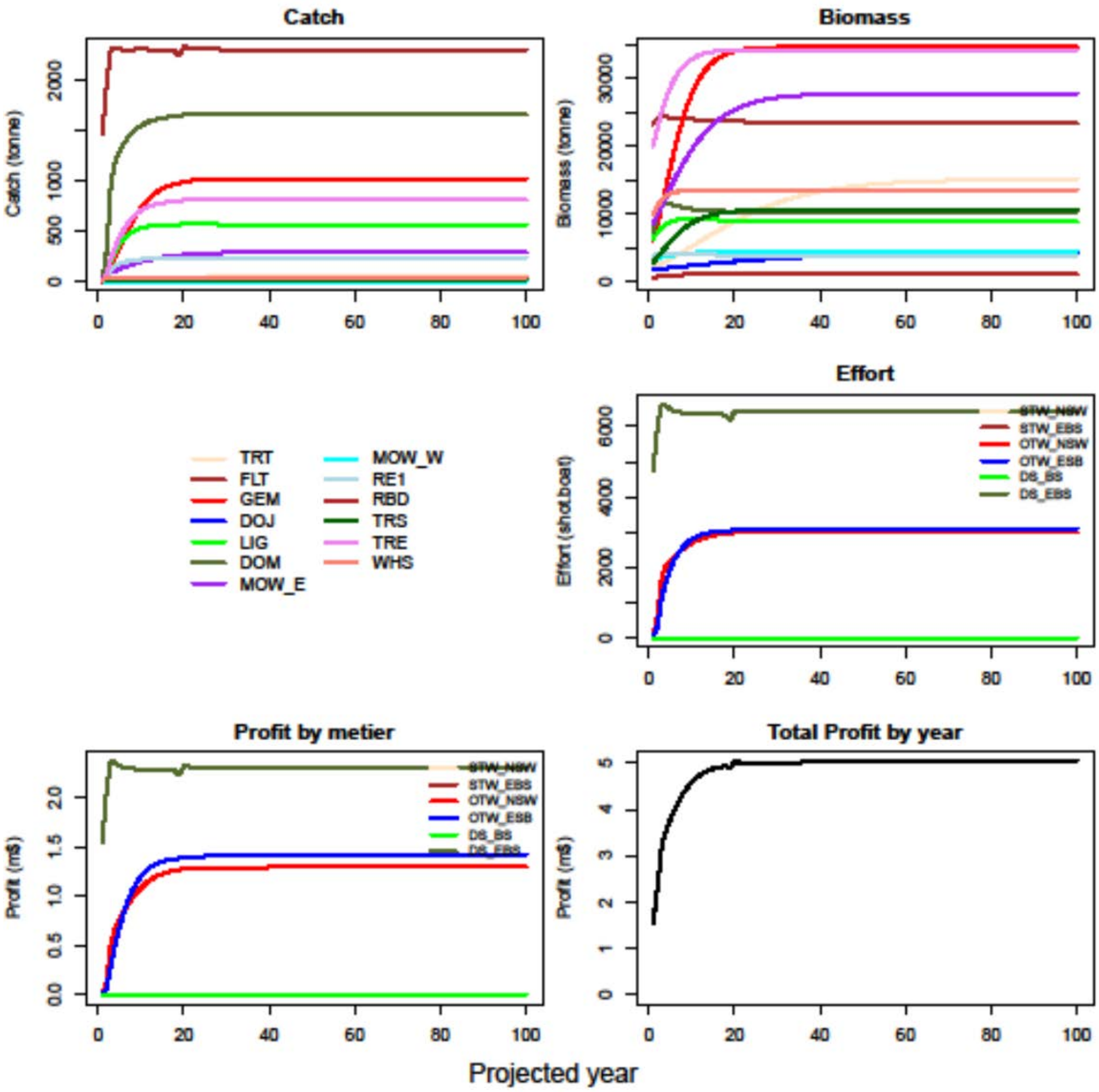


Figure 32. Example dynamic model run

Comparison of model results

The main aim of the dynamic model was to determine the effects of discounting on the long run optimal B_{MEY}/B_{MSY} ratio. Only a five percent discount rate was applied as this is consistent with analyses in other Commonwealth fisheries (Punt et al. 2011).

For most species, discounting had little impact on the long run optimal level of biomass (Figure 32). The one exception to this was flathead, where the dynamic optimal level of biomass was around 10 per cent lower. Flathead is the main species in the fishery, accounting for around one third of the fishery revenue leading to slightly greater fishing pressure when the objective of maximum NPV across all species in a dynamic bio-economic is achieved explaining the small deviation.

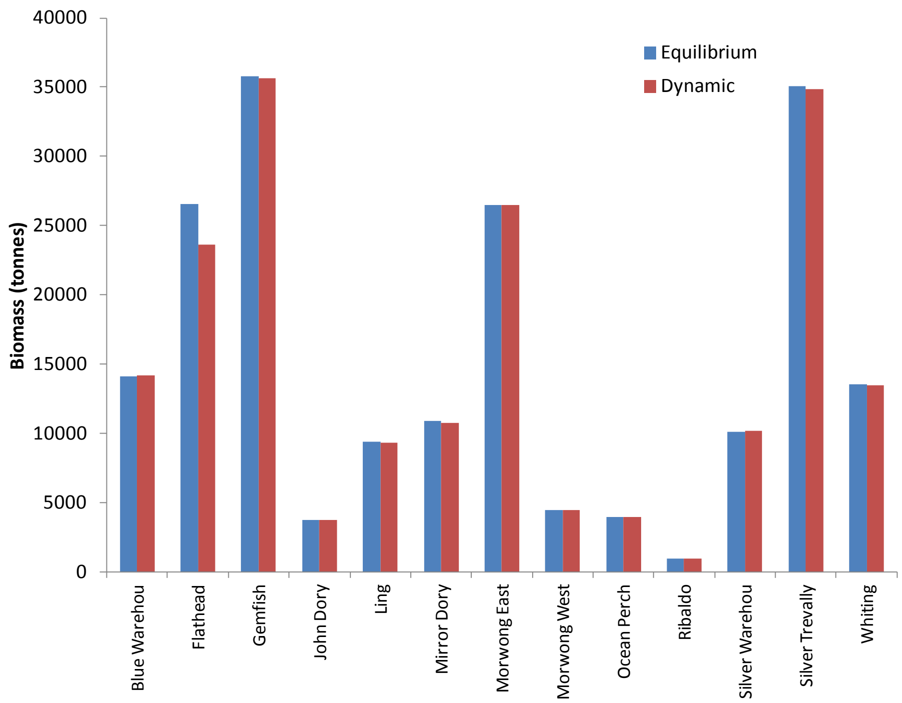


Figure 33. Biomass at the end of the simulation period (100 years)

Application of the generic framework to the case study fishery

Outcomes from the generic framework

As previously described, the generic framework involved the development of two decision support systems derived from on a series of stochastic optimisations using a generic multispecies model. Both approaches summarise the stochastic model runs using relative measures of the key biological and economic parameters. The first approach involved the development of a regression tree, which provides a deterministic estimate of the optimal B_{MEY}/B_{MSY} ratio also given the key biological and economic characteristics (Figure 17). The second approach involved the development of a Bayesian Network (Figure 25), in which the probability of a particular B_{MEY}/B_{MSY} ratio is determined given the combination of biological and economic characteristics in the fishery. Both approaches were tested against the outcomes from the more specific bioeconomic model of the fishery. Thus a 'three-way' comparison provides a useful and 'best-practice' approach for model uncertainty analysis, data input checks and validity and an indirect exploration of all input assumptions.

Both approaches use relative measures of the key parameters. In the case of the Bayesian Network, these are described as "low", "below average", "average", "above average" and "high" for most parameters. The Regression tree uses similar categories, but denoted on a scale of 1 (low) to 5 (high). The Bayesian Network model is also more inclusive of parameters that (using regression analysis) were found to be important but were not included in the regression trees (due to the dominance of the key biological and technical parameters r and q).

The key model parameter "values" applied to the generic framework, and the resultant outputs, are given in Table 13. Although the correlation between the different estimates are high (r>0.8 in all comparisons), both the decision tree and Bayesian Network tend to underestimate the higher values from the bio-economic model, as illustrated in Figure 33.

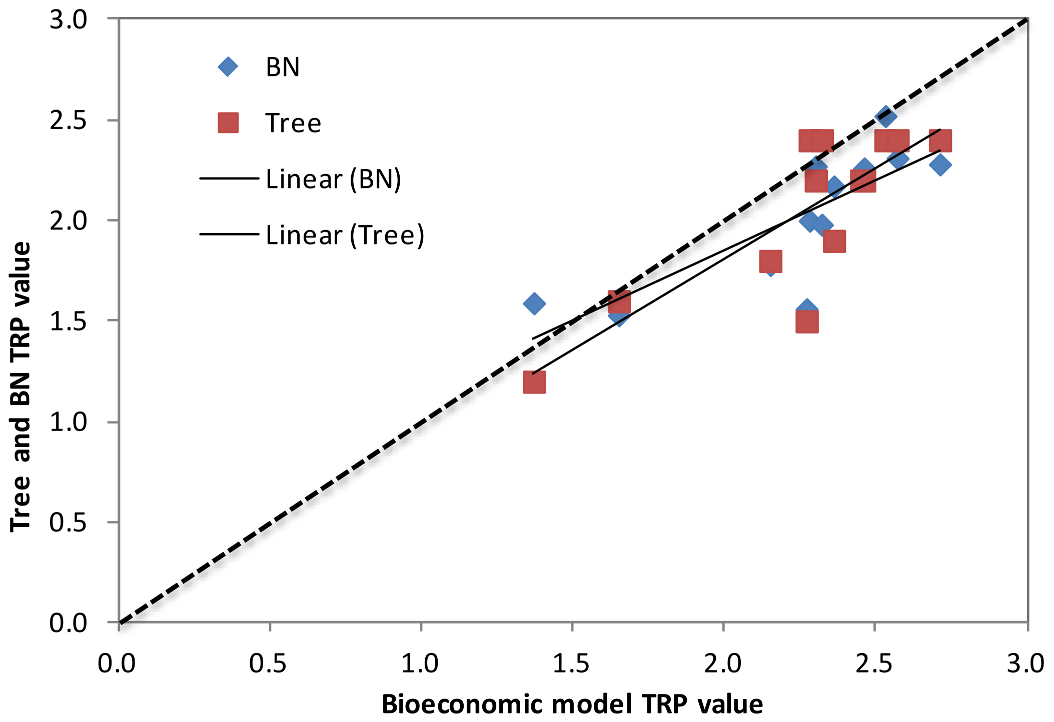


Figure 34. Comparison of tree and BN target reference point ratio values with bioeconomic model

The Bayesian Network model provides a probability distribution associated with each outcome – ratio B_{MEY}/B_{MSY} (Table 14), and from than an error term that provides a degree of confidence in the estimate (Table 13 and Table 14).

Table 13. Model input values and outcomes

Species	Model inputs					B_{MEY}/B_{MSY} estimate			
	Growth rate (r)	Catchability (q)	Carrying capacity (K)	Harvest costs (c)	Revenue share	Bioeconomic model	BN mean	BN +/-	Tree
TRT	Low	Low	Low	Average	1%	2.28	2.07	0.45	2.4
FLT	Average	Below average	High	Below average	33%	1.65	1.61	0.33	1.4
GEM	Above average	Low	High	Above average	7%	2.46	2.28	0.35	1.9
DOJ	Low	Low[1]	Low	Average	1%	1.37	1.69	0.57	1.4[4]
LIG	Above average	Below average	Low	Above average	11%[2]	2.15	1.95	0.45	1.9
DOM	High	Above average	Low	Above average	11%[2]	2.27	1.75	0.33	1.5
MOW_E	Below average	Low	Average	Average	5%[5]	2.30	2.31	0.33	2.4
MOW_W	Average	Low	Low	Low	0%	2.71	2.30	0.31	2.4
RE1	High	Below average	Low	Above average	2%	2.36	2.26	0.22	2.0
RBD	High	Low	Low	Above average	0%	2.53	2.56	0.19	2.4
TRS	Average	Below average[1]	Low	Average	2%	2.32	2.06	0.41	2.4[3]
TRE	Above average	Low	Average	Above average	8%	2.45	2.29	0.37	2.2
WHS	High	Below average[1]	Low	Low	2%	2.57	2.34	0.29	2.4[3]

1. Very close to border of low and below average so BBN set at 0.5 probability at each; 2) Very close to border with 5-10% so BBN set at 0.5 probability at each; 3. Used the low q setting for consistency with BBN; 4) used the below average q setting for consistency with BBN; 5. Just below 5% so used 0-5%.

Table 14. Probability distributions of the BMEY/BMSY ratio from the Bayesian Network model

BMEY/BMSY ratio	TRT (Blue Warehou)	FLT (Flathead)	GEM (Gemfish)
0 to 0.4	0.68	0.76	0.65
0.4 to 0.67	0.68	0.76	0.65
0.67 to 0.88	0.68	0.76	0.65
0.88 to 1.08	0.68	0.76	0.65
1.08 to 1.28	1.37	5.34	0.65
1.28 to 1.5	3.42	26.0	0.65
1.5 to 1.8	15.8	42.7	0.65
1.8 to 2	17.1	16.0	0.65
2 to 2.2	16.4	3.82	17.0
2.2 to 2.4	17.8	1.53	41.8
2.4 to 2.6	16.4	0.76	34.0
2.6 to 2.8	8.90	0.76	1.96
	2.07 ± 0.45	1.61 ± 0.33	2.28 ± 0.35

BMEY/BMSY ratio	DOJ (John Dory)	LIG (Pink Ling)	DOM (Mirror Dory)
0 to 0.4	0.71	1.48	0.47
0.4 to 0.67	2.56	1.48	0.47
0.67 to 0.88	2.94	1.48	0.47
0.88 to 1.08	7.38	1.48	0.47
1.08 to 1.28	12.5	1.48	2.15
1.28 to 1.5	12.8	1.48	13.6
1.5 to 1.8	19.4	14.1	41.8
1.8 to 2	10.4	22.7	20.9
2 to 2.2	8.59	28.0	11.8
2.2 to 2.4	9.27	17.7	5.88
2.4 to 2.6	8.59	7.09	1.49
2.6 to 2.8	4.82	1.48	0.47
	1.69 ± 0.57	1.95 ± 0.45	1.75 ± 0.33

BMEY/BMSY ratio	MOW_E (Morwong east)	MOW_W (Morwong west)	RE1 (Ocean Perch)
0 to 0.4	0.17	0.22	.093
0.4 to 0.67	0.17	0.22	.093
0.67 to 0.88	0.17	0.22	.093
0.88 to 1.08	0.17	0.22	.093
1.08 to 1.28	0.17	0.22	.093
1.28 to 1.5	0.34	0.43	.093
1.5 to 1.8	3.59	2.15	0.56
1.8 to 2	11.6	9.03	6.21
2 to 2.2	15.9	20.4	25.6
2.2 to 2.4	23.2	26.9	43.5
2.4 to 2.6	26.5	26.0	22.8
2.6 to 2.8	17.9	14.0	0.83
	2.31 ± 0.33	2.3 ± 0.31	2.26 ± 0.22

RBD (Ribaldo)

BMEY/BMSY ratio	
0 to 0.4	.082
0.4 to 0.67	.082
0.67 to 0.88	.082
0.88 to 1.08	.082
1.08 to 1.28	.082
1.28 to 1.5	.082
1.5 to 1.8	.082
1.8 to 2	.082
2 to 2.2	0.49
2.2 to 2.4	9.07
2.4 to 2.6	47.5
2.6 to 2.8	42.3
2.56 ± 0.19	

TRS (Silver Warehou)

BMEY/BMSY ratio	
0 to 0.4	0.23
0.4 to 0.67	0.23
0.67 to 0.88	0.23
0.88 to 1.08	0.36
1.08 to 1.28	1.58
1.28 to 1.5	4.41
1.5 to 1.8	19.4
1.8 to 2	16.6
2 to 2.2	19.4
2.2 to 2.4	14.6
2.4 to 2.6	14.9
2.6 to 2.8	8.07
2.06 ± 0.41	

TRE (Silver Trevally)

BMEY/BMSY ratio	
0 to 0.4	0.73
0.4 to 0.67	0.73
0.67 to 0.88	0.73
0.88 to 1.08	0.73
1.08 to 1.28	0.73
1.28 to 1.5	0.73
1.5 to 1.8	0.73
1.8 to 2	2.19
2 to 2.2	10.2
2.2 to 2.4	44.5
2.4 to 2.6	32.8
2.6 to 2.8	5.11
2.29 ± 0.37	

WHS (Whiting)

BMEY/BMSY ratio	
0 to 0.4	.088
0.4 to 0.67	.088
0.67 to 0.88	.088
0.88 to 1.08	.088
1.08 to 1.28	.088
1.28 to 1.5	0.28
1.5 to 1.8	2.63
1.8 to 2	7.78
2 to 2.2	16.2
2.2 to 2.4	25.5
2.4 to 2.6	30.2
2.6 to 2.8	17.0
2.34 ± 0.29	

Testing the target reference point proxies

The Bayesian Network and regression tree derived proxy target values (Table 13) were imposed in the equilibrium bioeconomic model to estimate the impact of these on profitability of the fishery. The values were tested under conditions of uncertainty, through randomly varying biological and economic conditions over 1000 simulations. For comparison, the average “true” optimal TRP values derived from the bioeconomic model over the 1000 stochastic simulations were also applied. These, theoretically, should provide the best outcomes, as they were derived from the fishery specific model outcomes rather than the generic based decision rules. The current default proxy target reference point (TRP) of B_{MEY}= 1.2 B_{MSY} was also applied and tested.

As the measures are imprecise, it is impossible to achieve all simultaneously. The model was set up as a goal programming model,[14] with the proxy biomass target reference points for each species being the goals, and the objective function set to minimise the weighted normalised deviations from the goal. The weights were set as the revenue shares, on the basis that getting the most important species

[14] Goal programming approaches have been used to develop multi-objective bioeconomic models in a number of instances (e.g. Mardle *et al.* 2000; Pascoe and Mardle 2001)

right is more important for long term profitability than the less important species. By weighting the minor species less, it is implicitly assuming that greater deviations from the TRP are acceptable.

Initial runs with the model found that profitability was severely compromised in the attempt to achieve the biomass targets. As profit did not feature in the objective function, effort combinations were selected by the model that resulted in low economic performance. Thus the objective function was modified to include a profit goal, namely the average profit that was realised in the bioeconomic model. Profit was given a weight of 0.4 and the biomass targets a combined weight of 0.6. While partially arbitrary, studies of objective preferences in Commonwealth fisheries found that managers tend to value stocks twice as much as economic performance (implying a 66:33 weighting), while industry prefer a fairly equal weighting (50:50) (Pascoe *et al.* 2009). Industry will also be aiming to maximise profits within the constraints imposed by management, so including profits in the objective function is justified from this perspective also.

Given this, the objective function was given by

$$\text{Min } 0.6 \sum \left(revshare * \frac{abs(B/BMSY - TRP_T)}{TRPB_T} \right) + 0.4 * \frac{abs(\pi - \pi_T)}{\pi_T} \quad (23)$$

where TRP_T is the target biomass reference point (i.e. B_{MEY}/B_{MSY}), B is the model estimated value of the biomass (which is then divided by B_{MSY}), π_T is the target profit and π is the estimated profit. Absolute values were used as both positive and negative deviations were to be minimised equally.

The resultant set of biomasses at MEY relative to B_{MSY} for each species over the 1000 simulations are given in Figure 35. In Figure 35, the thick bar represents the median observed outcome (B/B_{MSY}) over the 1000 simulations while the box represents the range in 50 per cent of the simulations, and the outer bars represent the range in 95 percent of the simulations. Even using the fishery-specific average TRP estimates (derived from the bioeconomic model), there was considerable variability in the outcomes. Similar levels of variability was observed in the simulations using the two alternative proxy measures, although less variability was observed for the case using the current default proxy measure (1.2 B_{MSY}) for reasons that will be outlined below.

The divergence between the target reference point (B_{MEY}/B_{MSY}) and observed outcome (B/B_{MSY}) is given in Figure 36. In all cases there was some divergence from the target, including the case for the bioeconomic model estimated average values (as the average values are not always applicable when conditions change). However, divergences from the target were relatively small for the bioeconomic model "full information" values as well as for the Bayesian Network and regression tree based proxy measures (Figure 36 and Figure 37). Divergences were substantially greater for the 1.2B_{MSY} proxy for B_{MEY}, as would be expected as these were substantially lower than the bioeconomic model estimates based on full information. For most stocks the resultant biomasses were more than 100 per cent greater than the default proxy target values (Figure 36), reflecting the fact that the default TRP was generally lower than the optimal TRP for most species. Further, given that the optimal TRP varied considerably between species due to their different biological characteristics, imposing a common TRP was not feasible.

In most instances, the models were able to achieve close to the target profit level (Figure 38) as well as the biomass targets, although in a small number of cases the use of the proxy measures – and also the full information bioeconomic based targets – resulted in some losses. The model based on the

1.2B$_{MSY}$ proxy for B$_{MEY}$ appeared to perform best in terms of profitability, but this was largely an artefact of the model. Since achieving the target biomasses for all species simultaneously was impossible, the model minimised the sum of deviations by focusing on profits only.

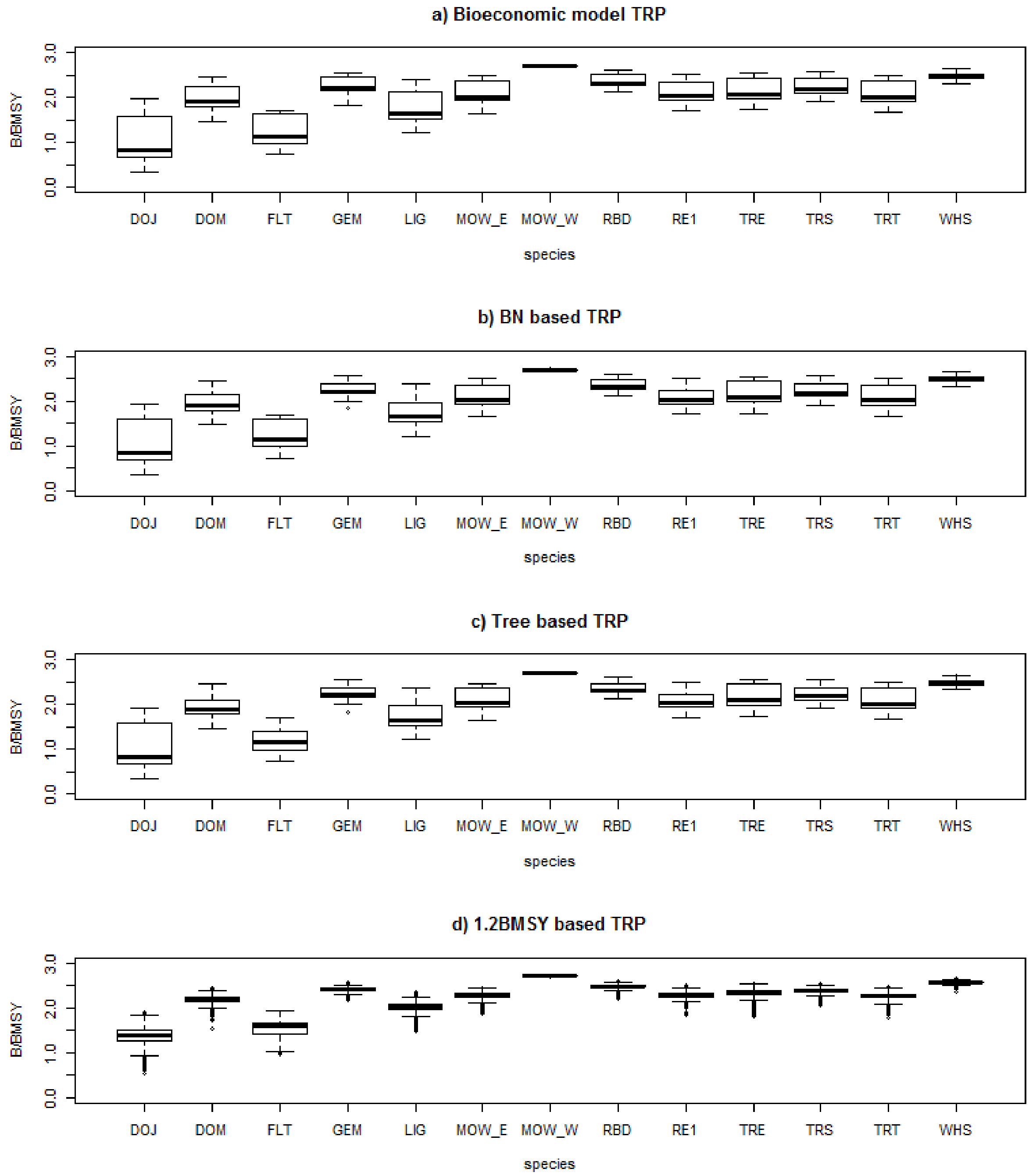


Figure 35. Resultant B$_{MEY}$/B$_{MSY}$ ratios achieved

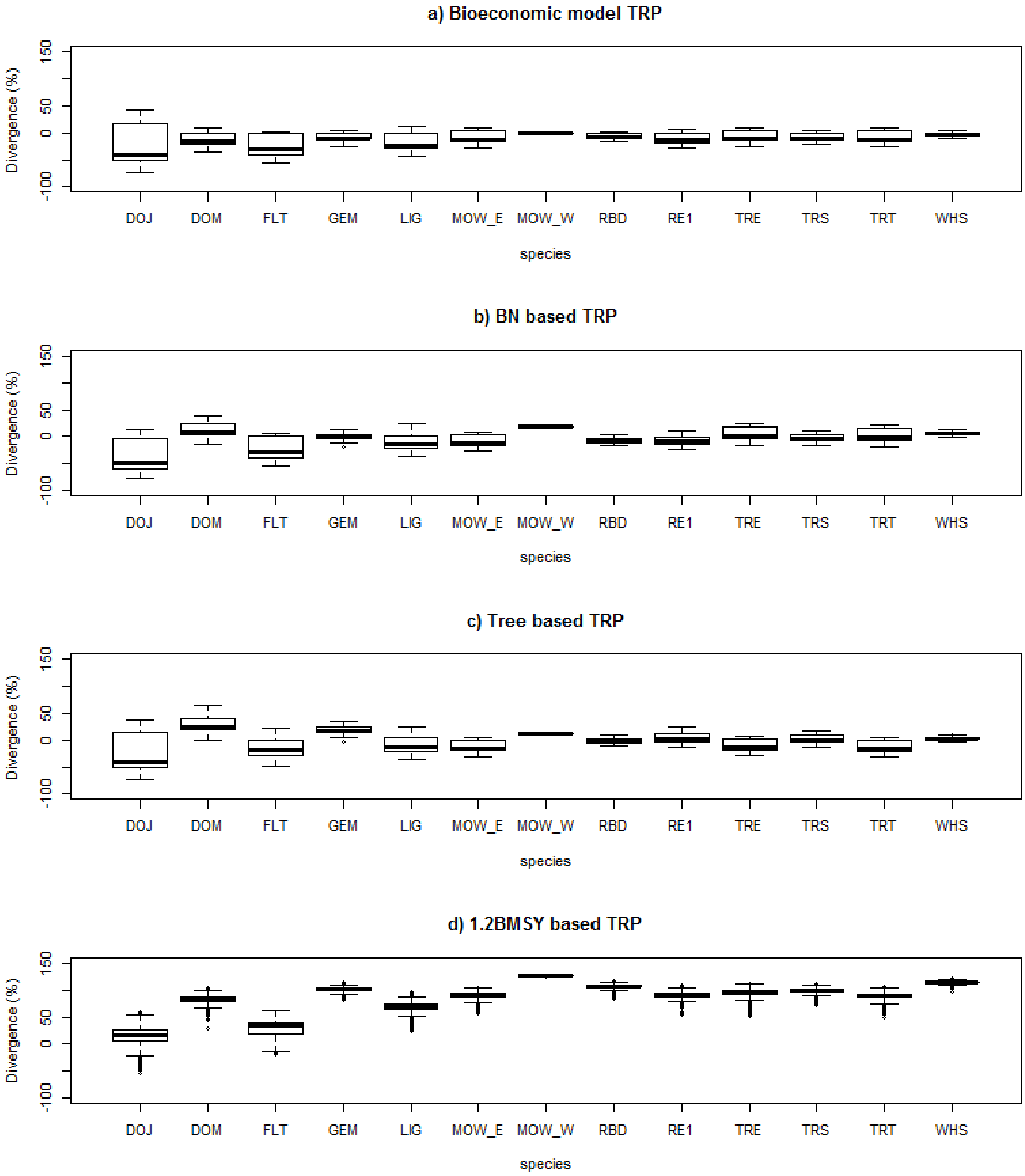


Figure 36. Divergence from the biomass target (%)

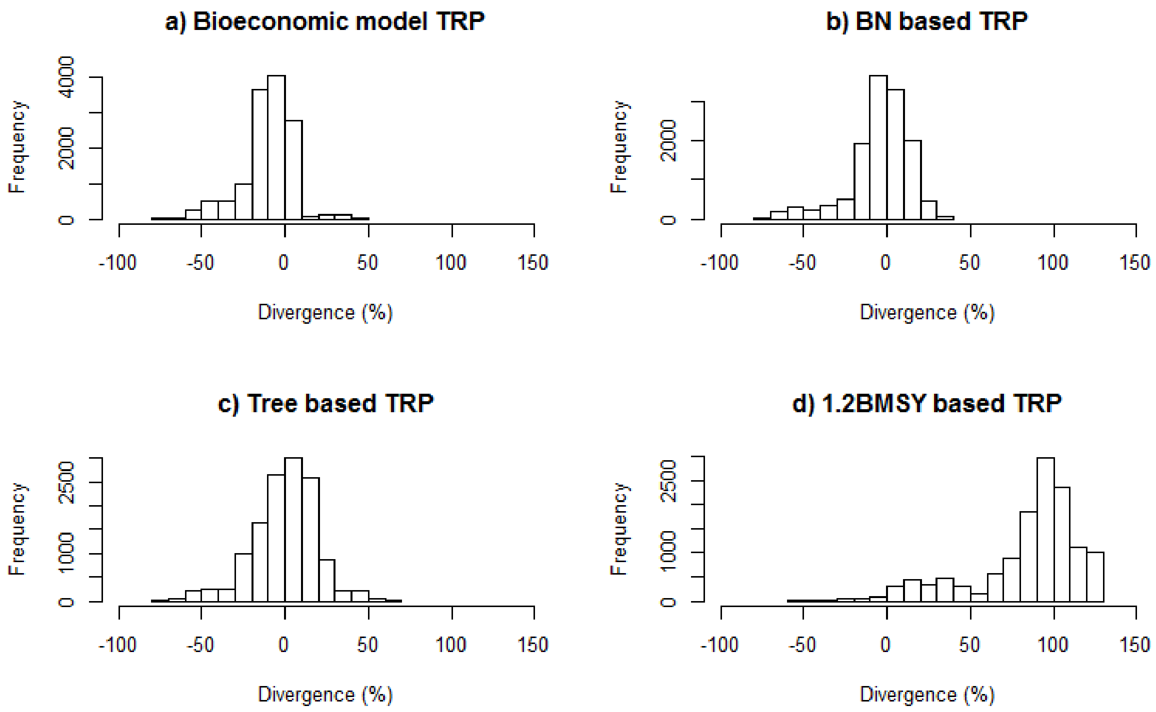


Figure 37. Overall divergence from biomass targets for all species combined

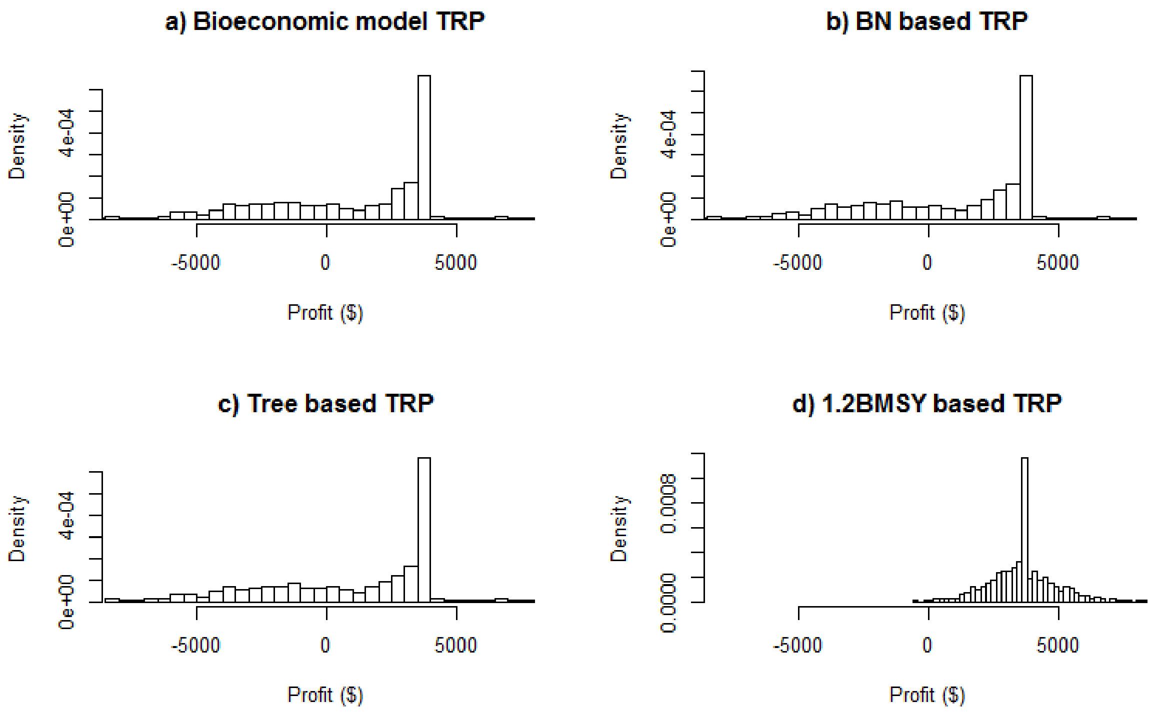


Figure 38. Fishery profit distribution

The profits derived from the bioeconomic model (the "best" information scenario) and the tree and Bayesian Network based proxies were compared to further assess the performance of the proxy TRP approaches. The current default proxy TRP ($1.2B_{MSY}$) was not considered given its inability to come close to a feasible compromise solution. In most cases, both approaches resulted in similar fisheries profits to those derived using the bioeconomic model based TRPs (Figure 38), varying by +/- 2% in most cases. Generally, both approaches produced similar outcomes, although there were a number of cases where one method outperformed the other (Figure 39). However, these represented only a small number of incidents, and there was no obvious factors resulting in one method outperforming the other.

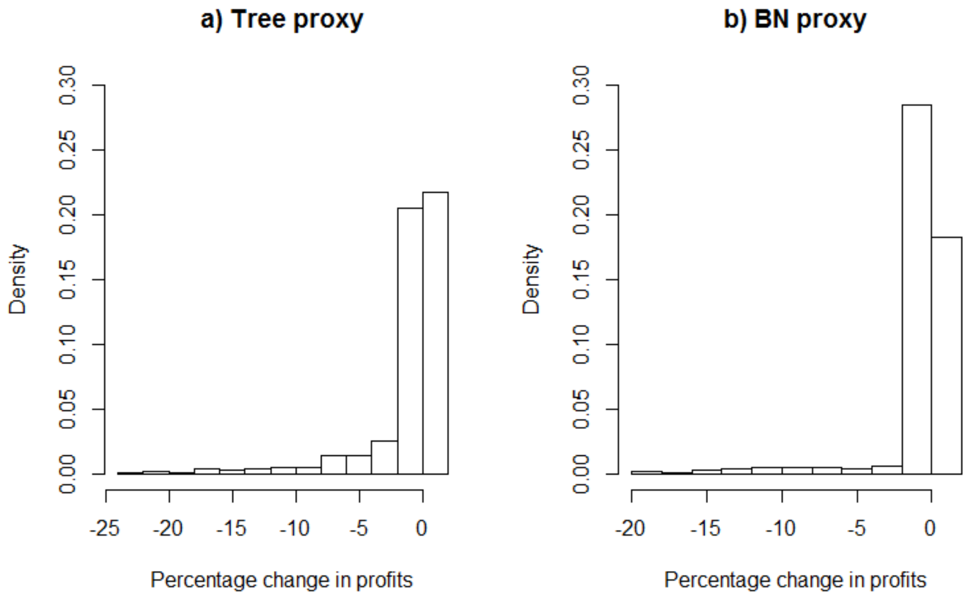


Figure 39. Difference between profits from bioeconomic model and proxy TRPs

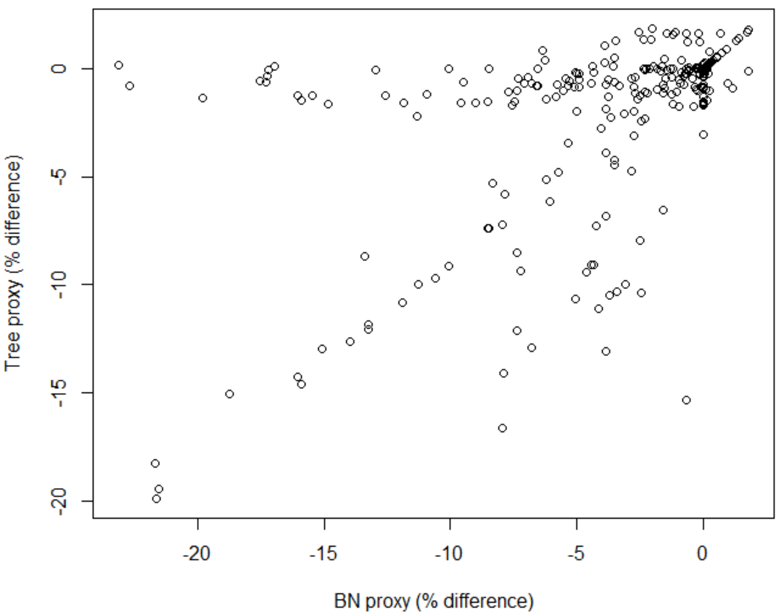


Figure 40. X-Y plot of difference between profits from bioeconomic model and proxy TRPs

Discussion

The key aim of the project was to develop an approach for determining target reference points consistent with the Commonwealth Fisheries Harvest Strategy (DAFF 2007) for species within mixed fisheries when a full bioeconomic model was not available or practical. Two decision support systems were developed derived from generic multispecies bioeconomic models and used to provide guidance as to appropriate economic target reference points based on limited information about the species in the fishery. The decision support systems were applied to a case study fishery, and the outcomes compared to a simplified bioeconomic model of the fishery.

The analyses suggest that the generic based proxy estimates of the target reference points are equally as reliable as the more fishery-specific bioeconomic model based estimates given the likely variability in biological, technical and economic parameters from year to year. The Bayesian Network based estimates were generally closer to the model based estimates than the regression tree based estimates, but both performed reasonably well.

The current default of $1.2B_{MSY}$ (i.e. assuming $B_{MEY} = 1.2B_{MSY}$) performed poorly, as the proxy value was substantially different from the "true" value in most instances. While it appears to result in a higher level of profits in the case study analysis, this is an artefact of the goal programming model, which essentially abandoned trying to achieve the biomass targets (which were unachievable) and focused on trying to only achieve the profit targets.

The analysis has focused on B_{MEY} relative to B_{MSY}. This ratio is affected not only by the key parameters representing the biological, technical and economic characteristics of the species, but also the assumed underlying function form of the growth models. Generally, the optimal B_{MEY}/B_{MSY} ratio was higher when assuming an exponential growth function (Fox model) than when assuming a logistic growth model (Schaefer model). The current harvest strategy also considers B_{MEY} relative to B_0 (or K). The values can be converted readily. Given B_{MSY}=K/e for the exponential growth model (Fox 1970), then $B_{MEY}/B_{MSY} = B_{MEY}/(K/e)$ so that B_{MEY} /K=B_{MEY}/B_{MSY}/e. Hence, while the ratios from the exponential growth based models appear high in terms of B_{MSY}, this is partly an artefact of the mathematics underlying the Fox growth model. For example, an outcome of B_{MEY}=$2.15B_{MSY}$ for ling is equivalent to B_{MEY}=$0.79B_0$, which would also be equivalent to B_{MEY}=$1.78B_{MSY}$ if a logistic model had been assumed.

The ratio B_{MEY}/B_0 was also derived for each model run to test whether these values were more consistent across assumed growth models. The results (Figure 38) suggest that the optimal biomass as a proportion of unfished biomass was lower assuming an exponential (Fox) growth model than a logistic (Schaefer) model. Variation in this optimal value also declined as revenue share increased. Around 4 per cent and 1 per cent of optimal B_{MEY}/B_0 ratios were less than $0.2B_0$ (the limit reference point) for the Fox and Schaefer models respectively.

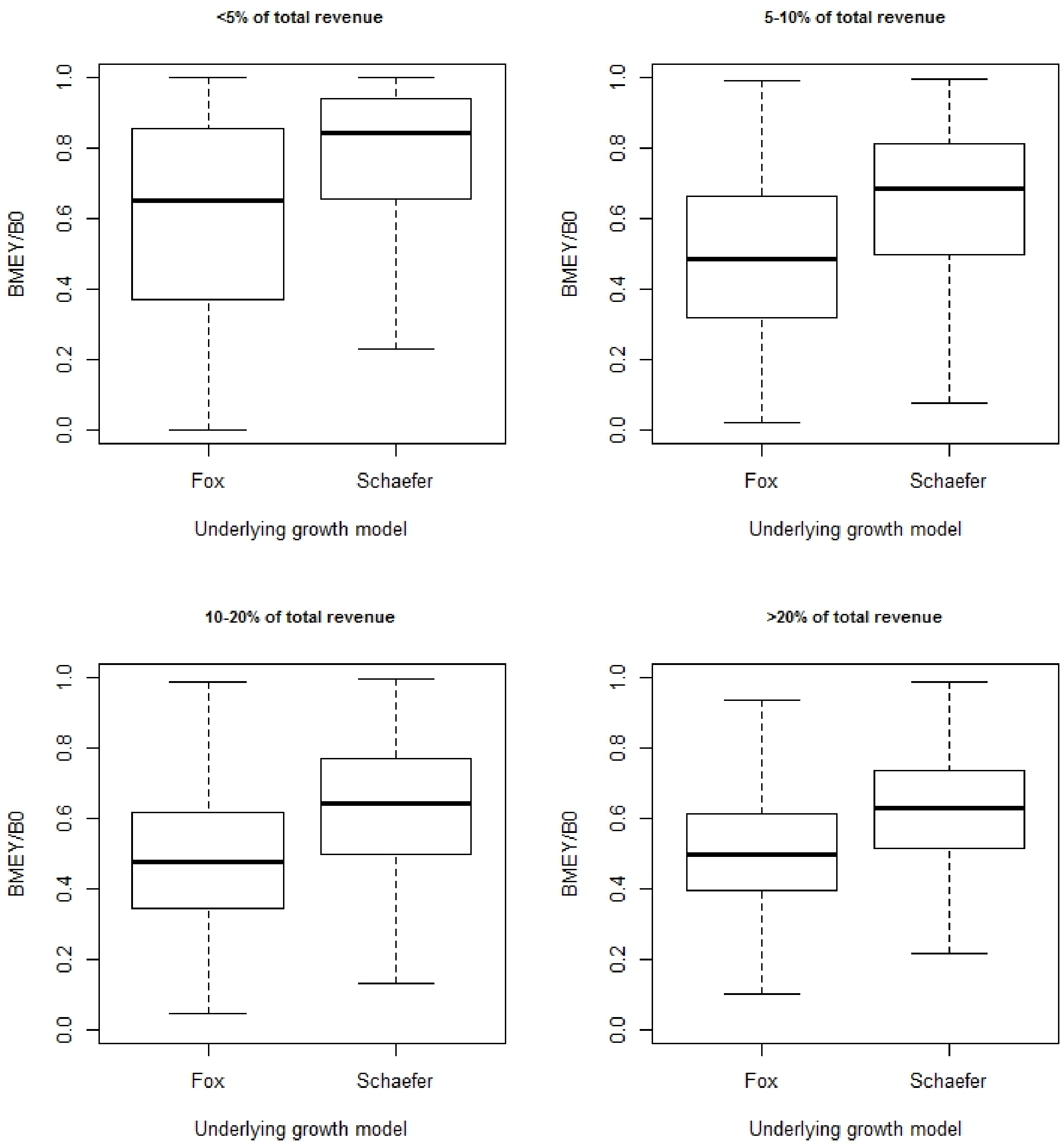


Figure 41. Target reference point expressed as proportion of unfished biomass

A complication illustrated by the analysis is that any target reference point is really a moving target (Dichmont et al. 2010). Even when using target reference points based on a reliable model of a fishery, fluctuations in biological and economic conditions will generally result in that target being inaccurate when actually implemented (except through chance that the conditions experienced are identical to those used to estimate the target). An advantage of the Bayesian Network proxy is that a confidence interval is also estimated, so that a fishery could be considered to be operating at (or close to MEY) if the biomasses are within the likely range given by the confidence intervals.

The analysis also raises the question as to the practicality of simultaneously achieving targets for a multitude of species in multispecies fisheries. A recent review of the harvest strategy policy (DAFF 2013) suggested that, in the case of multispecies fisheries, the proxy target reference point should be applied to the key species only. The harvest strategy policy itself suggests that the targets should be set for key commercial species, but defines these as target species in the fishery (DAFF 2007). Implicitly, any species with a quota (in an output controlled fishery) could be considered a key species, with the quota aimed at achieving some form of biomass target.

The management strategy implemented in the generic model analysis is based on a more liberal interpretation of key species, with the appropriate proxy target reference point being applied to the dominant species (in terms of revenue share) only. As the generic model is based on a purely mixed fishery, achieving an optimal outcome for one species allows direct derivation of the optimum targets for the rest of the species in the fishery. Even in the case study fishery that had six different fishing metiers catching different combinations of species with some degree of "targeting" in each, much of the catch was taken as byproduct. The goal programming model addressed this to some extent as the weights attached to each target were set as the revenue share. While the minor species had very little weight attached to their target, the targets were still largely achieved due to the complementary nature of the targets for the major species.

While not explored in this project, there is likely to be merit in considering different approaches, with management strategies based on targets set for a subset of species (most likely those that contribute the greatest to revenue), and the remaining species monitored. Just how many species to control and which criteria to use to determine the most appropriate species is an area for future research. In some circumstances, imposing target reference points and quotas on some species may be counterproductive, particularly if data are limited and the species are largely caught as byproduct. The potential benefit of this research, however, could be reduced discarding (through inappropriate quotas being set on minor species) and improved fishery profitability without necessarily risking sustainability. A range of possible approaches to manage byproduct species have been reviewed elsewhere (Pascoe *et al.* 2010a), such as mix of individual quotas for key species and royalties for byproduct species. Pearse and Walters (1992); Walters and Pearse (1996); and Walters (1998) also suggest a range of strategies for combining input and output controls.

The generic models are also based on equilibrium growth models. These are rarely used in stock assessments, which tend to use more dynamic modelling approaches. The concept of MEY, where applied, is also a dynamic concept that aims to maximise profits over time. Including a discount rate into the analysis results in a different dynamic MEY to the static values estimated in the above model (Grafton *et al.* 2010). However, a dynamic estimate of MEY would be very case specific, and a more purpose built model would be required to estimate it (such as that for the Northern Prawn fishery, for example (Punt et al. 2011)).

Two variants of the case study model were developed – one a long run equilibrium and the other a dynamic model. With the exception of one species (flathead), the optimal biomass from the equilibrium and dynamic fishery models were very similar. This species was also the main species in terms of contribution to fishery revenue (around one third), and the biomass in the dynamic model was around 10 per cent lower than that of the equilibrium model. With only one example against which to compare models and species, it is difficult to determine if any general conclusions can be made about the influence of revenue share on the difference between a static and dynamic MEY in multispecies fisheries. The observed difference for flathead – 10 per cent – is within the confidence bounds of the Bayesian Network based proxy measures in most cases. Further, aiming for a slightly higher biomass is more precautionary, and may be appropriate in any case given uncertainty in fisheries for which these proxy measures are likely to be applied.

The analysis suggests that both the regression tree based and Bayesian Network approach are substantially better (in terms of approximating optimal target reference points) than the current default B_{MEY}= 1.2B_{MSY}. Most notably from the analysis, applying the default proxy to multiple species results in an infeasible combination of targets.

The approaches developed in this study could be used to estimate target reference points for multiple species in a mixed fishery that are more likely to be compatible with one another, provided the appropriate economic and biological information was available. The regression tree and Bayesian Network model was based on categorical information (i.e. above or below average values) so precise information is not necessary, which is advantageous in data poor fisheries and/or where collecting data on a continuous basis is not cost effective.

Conclusion

The main aims of the project were to develop a framework to cost effectively determine target reference points for target and non-target stocks in multispecies fisheries, pursuant with the Commonwealth Harvest Strategy Policy (HSP) objectives of maximum economic yield; and demonstrate the applicability of the framework developed using a case study fishery. In this study, two cost effective decision support systems were developed derived from a series of simulations. The first, derived using a regression tree approach, provides a series of “rules of thumb” for determining an appropriate economic target reference point based on relative catchability, growth rates and revenue share of the catch. The second – involving a Bayesian Network model – incorporates more information about the species if available and provides confidence intervals around the estimated economic target reference point.

Both approaches performed well when applied to the case study fishery (trawl component of the Southern and Eastern Shark and Scalefish fishery), and much better than the current default proxy target reference point of B_{MEY}=1.2B_{MSY}.

The analysis also conflicts with the Harvest Strategy Policy, albeit only likely applicable to a very small number of cases. In a small number of instances, the optimal level of biomass of some species was below the biological limit reference point, which is not permissible under the policy. While not explicitly examined, imposing a minimum B_{MEY}/B_0 ratio of greater than 0.2 would result in the remainder of the species being harvested at a sub-optimal rate. The potential cost of this was not examined in the project. Applying the regression tree based biomass ratios ensures that an explicit target reference point below the limit reference point is not imposed (as the lowest ratio was 0.5). However, the tree based ratios were most uncertain at the lower end of the range, and managing the fishery to achieve targets at the lower end is likely to have greater consequences for fishery profits than managing at the top end. The Bayesian Network model allowed for values at the lower end of the range.

While not an aim of the project, the results from the analysis lend support to a management strategy of applying target reference points to the main species (in terms of revenue share) only. In addition to being more easily achievable, such a management strategy also seems more likely to result in an outcome that is close to the true optimum. The exact criteria by which (and how many) species should be selected is likely to require further simulation work. Similarly, management measures for ensuring the remaining species are also harvested optimally requires further consideration.

Implications

The project has produced a generic framework for RAGs and MACs (the key end-users) to provide target reference points consistent with the Harvest Strategy Policy (HSP) in cases where a purpose built bioeconomic model of the fishery is currently unavailable, but some information exists to estimate reference points such as MSY on a single species basis, and some basic economic information exists, or can be inferred by expert judgement. The model and principles can also be extended to State fisheries, enabling profitability in these fisheries to be increased where economic objectives are considered important.

As a consequence of this, the project will help improve profitability in Australian fisheries through identifying target biomass levels within multispecies fisheries that are compatible with the objective of maximising economic returns from the use of Australian fisheries resources. The key benefits of this will include increased profit per boat (through greater utilisation of the catch); improved management practices (through less discarding); and enhanced resource sustainability (through appropriate TACs being set for all species).

Recommendations

The project results have identified several areas for further consideration, both in terms of management implementation and also future research.

Implications for management

- From the results of the study, the designation of a simple default proxy target reference point as $B_{MEY}=1.2B_{MSY}$ needs to be reconsidered, particularly in the case of multispecies fisheries.
- The results in this study provide an alternative approach for deriving more appropriate target reference points. This approach should be considered by RAGs and MACs in setting future targets.
- The project has identified the difficulties in attempting to achieve a large number of targets simultaneously, even if these targets are obtained with good information. Given many species may constitute a small proportion of the fishing revenue, then their optimal catch may be achieved indirectly through controlling the activities of only the major (in terms of revenue) species in the fishery.
- If only major species are subject to targets as suggested above, then setting quotas (to achieve target reference points) for a broader number of species maybe both unnecessary and counterproductive in some cases. In these circumstances, consideration also needs to be given to potentially different governance systems to address these species and how they may help move a multispecies fishery as a whole towards MEY in the face of imperfect information and potentially incorrect catch targets. This includes establishing how input and output controls may (or may not) work with limited information (e.g. Pearse and Walters 1992; Walters and Pearse 1996; and Walters 1998 suggest a range of strategies), and will also need to consider other approaches, some of which may not be currently in use in Australian fisheries.

Areas for further research

- Determining an appropriate set of criteria for establishing how many and which species should be controlled is an area for further research. The benefits of this research may be substantial as it is likely to result in lower costs and discarding, and potentially higher profits due to fewer constraints on activities.
- The current study also considers only commercially caught species, but increasingly consideration is given to bycatch or non-commercial species and this may also affect definitions of MEY. Further research is required to consider how these target reference point measures may also account for discarding, bycatch and potentially other environmental externalities.
- The current project has assumed the definition of MEY as that level of effort, catch and biomass that maximises industry profits, consistent with the Harvest Strategy Policy and Guidelines. However, there has been considerable debate recently in the fisheries literature

about the definition of maximum net economic returns (NER) (e.g. Christensen 2010; Norman-López and Pascoe 2011; Grafton et al. 2012; Wang and Wang 2012; Pascoe et al. 2013), particularly in regard to the scope of the definition of benefits as well as the way in which they are derived. This debate has largely confirmed the approach adopted in the harvest strategy policy (DAFF 2013), although implications of bycatch and other potential environmental externalities has not been fully considered in MEY determinations. Further research is required to assess the implications for the different interpretations of MEY for fisheries management in Australia, particularly consistency with the intentions of the Fisheries Management Act and Harvest Strategy Policy and also in light of the recent Borthwick review (Borthwick 2012). This will require estimating the optimal level of biomass, effort and harvest level in the fishery given different assumptions about NER.

Extension and Adoption

Conference presentations:

- AARES (Australian Agricultural and Resource Economics Society) Annual Conference February 2013 (Sydney) – generic modelling
- AARES Annual Conference February 2014 (Port Macquarie) – case study application
- IIFET (International Institute of Fisheries Economics and Trade) Biennial Conference (Brisbane), July 2014

Papers (still in preparation):

- *Setting economic target reference points for multiple species in mixed fisheries*, to be submitted to *Fish and Fisheries*, June 2015
- *Dynamic versus static maximum economic yield in multi-fleet mixed fisheries*, to be submitted to *Marine Policy*, June 2015

Project coverage

Article SETFIA newsletter (based on press release) April/May 2012

Project materials developed

The project has developed a generic bioeconomic model that can be applied to any number of species in a mixed fishery. With minimal information, the model can be tailored to a particular fishery by providing more fishery specific biological and economic information. The model is developed in R, which is freely available.

The project also developed a bioeconomic model that is strategically applicable to the trawl component of the SESSF. This model does not include all species, but can be further developed to include the full set of species in the future. Two variants of the model were developed: a long run equilibrium model (in R and ADMB) and a dynamic model (developed in ADMB).

The project also developed two decision support frameworks that can be used to estimate appropriate target reference points for species in mixed fisheries. The regression tree based model is stand-alone. The Bayesian network model requires NETICA. A free version of the software is available (GENIE) but the model would need to be converted to run in the free software.

Several papers are still in preparation based on the results of the project.

Appendices

A. Dynamic model runs

B. List of researchers and project staff

Appendix A: Dynamic model runs

A set of scenarios were run to compare the output of a series of dynamic runs in terms of: total NPV, biomass and catch over time as well as effort over time. The resultant total profit and profit per metier for each time step was also calculated and presented (see Table A. 1 and Table A. 2). The total time period over which all runs were computed was T=100 years.

The aim of the analysis was to avoid the classic analytical bio-economic control theory solution where NPV is maximised when the stock is exploited at sustainable levels most of the time period (for T=1 to 99 years) and then in the final time step (T=100) all of the stock is harvested (that is unsustainably harvested) (Scenario 9a and 9b - Table A. 1). That is, effort increases to very high levels in the final year and the biomass of every species is removed from the ocean. This is the best mathematical solution given the problem set (and has no constraint for realism). In optimal control problems (and often arising when there is restricted-time) the extreme switch from one state to another is typically referred to as a “bang-bang” solution. One option that can be implemented to avoid the “bang-bang” solution was to place a constraint on the potential magnitude of year-on-year effort increases (or decreases), that is Scenario 1a/b. However, Scenario 1a/b was replaced by Scenario 2 to 7 as in this scenario (1a/b) effort continues to increase (unrealistically) towards time T=100 (and Profit by Year goes to zero). Scenario 1b is the same as 1a except costs higher and thus the NPV is lower.

The optimal solution in terms of this analysis, that is this context as it avoids the ‘bang-bang” solution is Scenario 2a (and b), in that NPV is the maximum of all scenarios (excluding Scenario 4a which is not the current situation [B_0 for each stock was modified], and the “bang-bang” solution: Scenario 9a/b). The only downside for Scenario 2a/b is that only 3 of the metiers remain (two otter trawl and one Danish Seine). Scenario 2b is the same as 2a except costs are higher and thus the NPV is lower. In addition, due to higher costs there is lower effort in some metiers and 4 of the metiers remain.

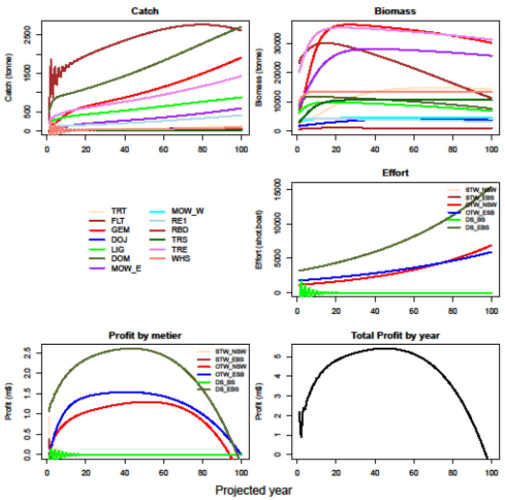
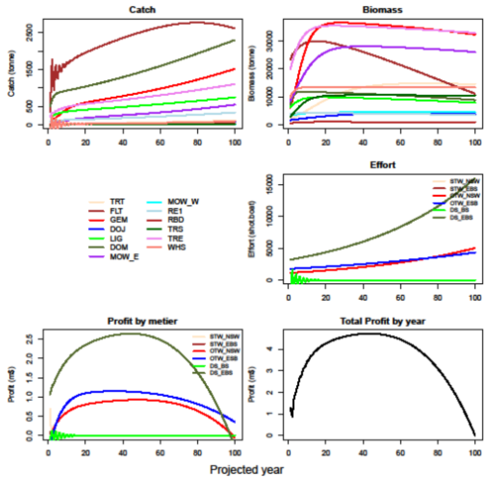
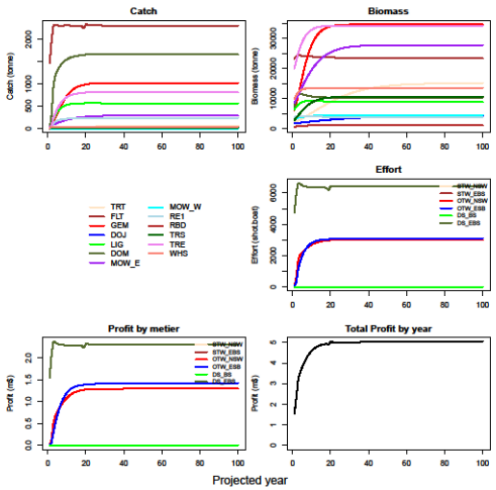
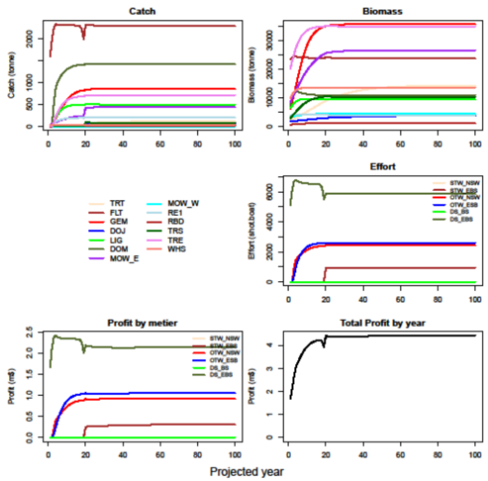
Scenario 3a and 3b were run in order to reduce the likelihood that effort goes to zero in the 3 metiers (as in Scenario 2a/b); thus a lower bound was set on effort in any metier of 1000 shots per year. The result is that the least efficient metiers remain in the fishery and experience negative profits [Scenario 10a/b is derivation of 3a/b except the lower bound constraint on effort is set at a different level for Danish seiners compared to otter trawlers].

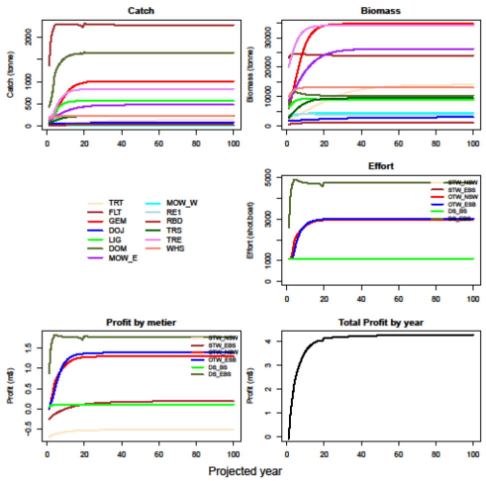
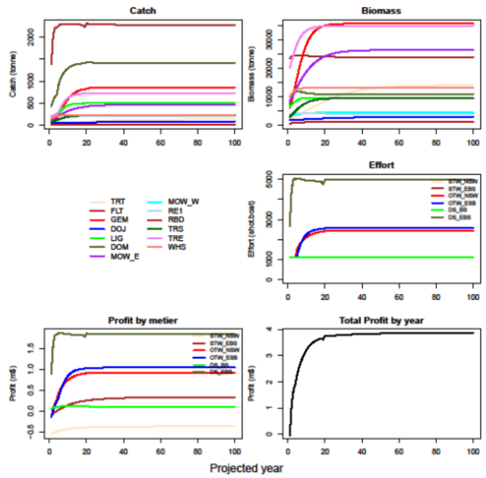
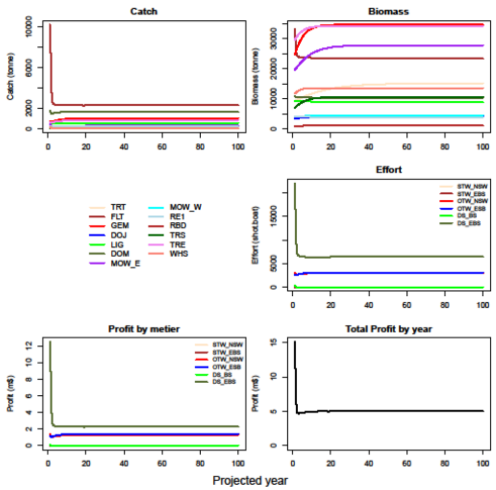
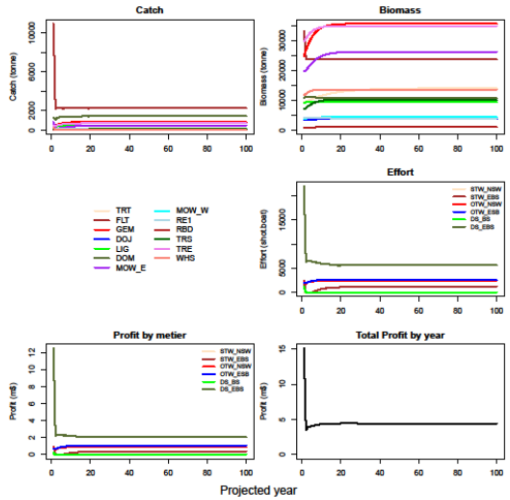
Scenario 4a and b were run to test the stability of the model. B_0 values were set at 1.5 times of the current biomass levels in order to check if model run reaches same solution state as Scenario 2-7 which it does. The NPV are positively exaggerated given higher starting B_0 values (see Table A. 1 and Table A. 2).

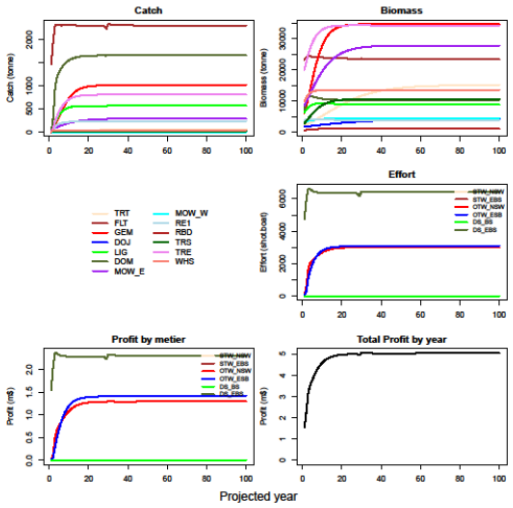
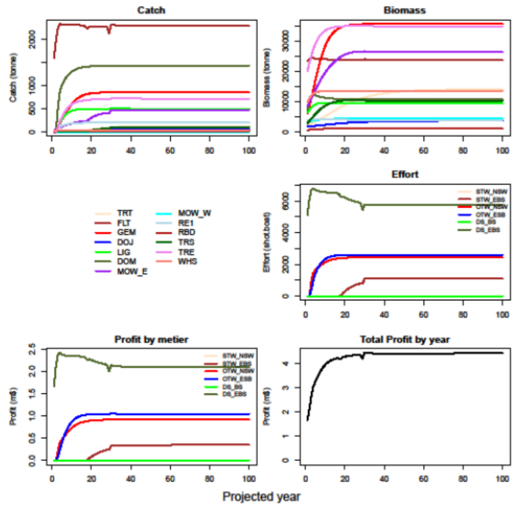
Scenarios 5a/b to 7a/b (see Table A. 1 and Table A. 2) were run to check if the results are sensitive to the timing of the transition to the constraint of constant effort (i.e. 20 years in Scenario 2a/b). The results indicate that an earlier transition (20 yrs) is optimal compared to 30, 50 or 80 years as the trend in the variables becomes more unstable – as the end of the time period is approached (where the so-called “bang-bang” solution would occur if not constrained). The NPVs are not significantly sensitive to where the transition occurs thus Scenario 2a/b still represent the most satisfying result.

Finally, Scenario 8a/b represents a simulation extension of the equilibrium solution. In this case computing NPV is not applicable as the values are not directly comparable with the other scenario runs. However the calculated NPVs are provided as an indication of their magnitude compared to the dynamic runs.

Table A. 1. Results for the Scenarios using either the Official cost data or Modified cost data including assumptions and comments

No	Assumptions	Comments	Original cost data	Modified cost data
1	Previous run – magnitude of effort change constrained	We did no continue with this way of constraining effort as NPV goes to zero and effort does not equilibrate	ConstantEffortChange 	ConstantEffortChange 
2	Effort constant after 20 years – **NO lower bound**	Small “kink” in transition	EffortChange20yrs 	EffortChange20yrs 

No	Assumptions	Comments	Original cost data	Modified cost data
3	Effort constant after 20 years – set to a lower bound	Profit is below ZERO for one fleet over the whole time period	EffortChange20yrs_fixLowBound 	EffortChange20yrs_fixLowBound 
4	Biomass begins at higher/different level	Biomass "returns" to same level as in current state	EffortChange20yrsBigBt0 	EffortChange20yrsBigBt0 

<table>
<tr><th>No</th><th>Assumptions</th><th>Comments</th><th>Original cost data</th><th>Modified cost data</th></tr>
<tr><td>5</td><td>Effort constant after 30 years – NO lower bound</td><td>Large “kink” in transition</td><td>EffortChange30yrs

</td><td>EffortChange30yrs

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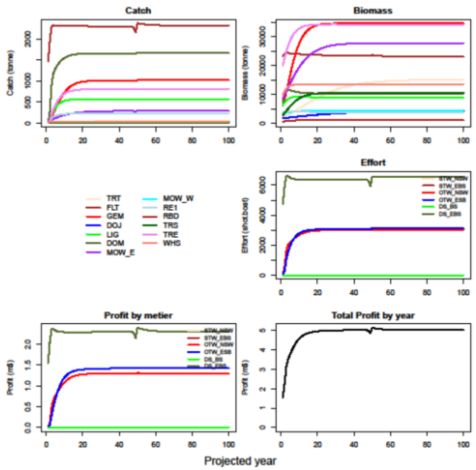
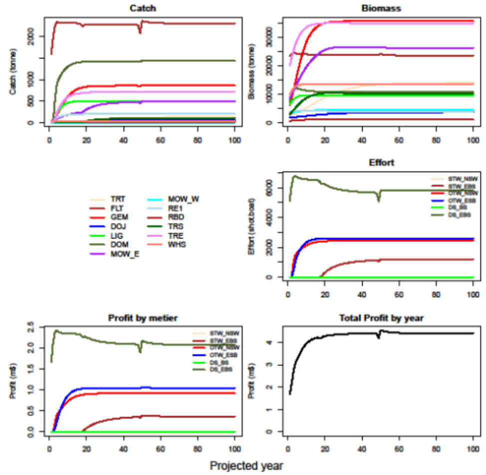
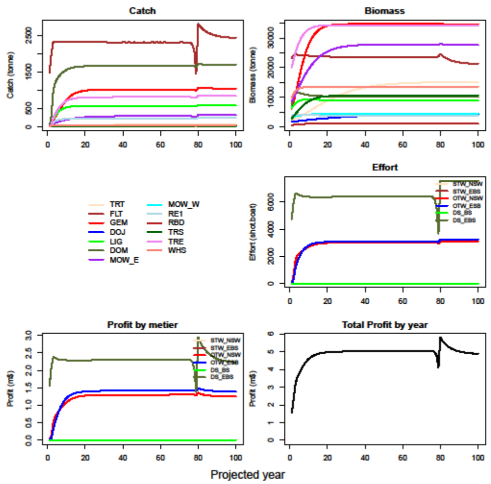
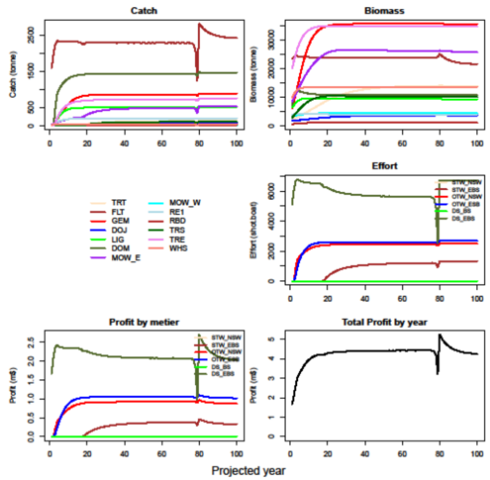
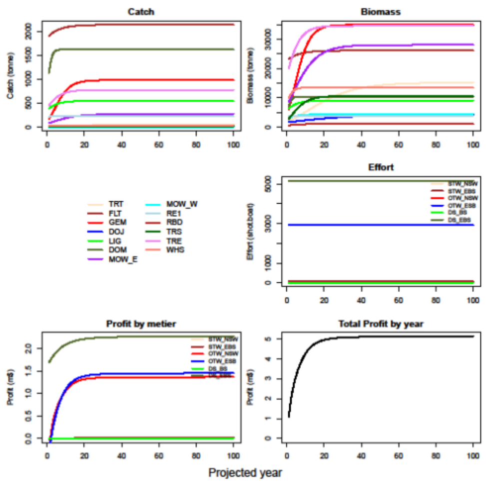
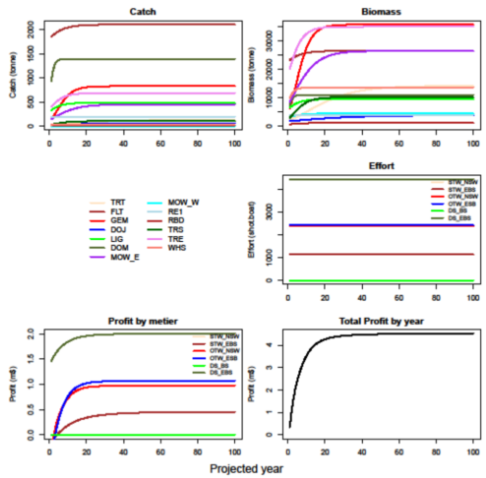
<tr><td>6</td><td>Effort constant after 50 years – NO lower bound</td><td>Larger “kink” in transition</td><td>EffortChange50yrs

</td><td>EffortChange50yrs

</td></tr>
</table>

• No	• Assumptions	• Comments	• Original cost data	• Modified cost data
• 7	• Effort constant after 80 years – **NO lower bound**	• Massive “kink” in transition	• EffortChange80yrs  •	• EffortChange80yrs  •
• 8	• Equilibrium	•	• EquilibriumEffortSimulationCost1  •	• EquilibriumEffortSimulationCost1  •

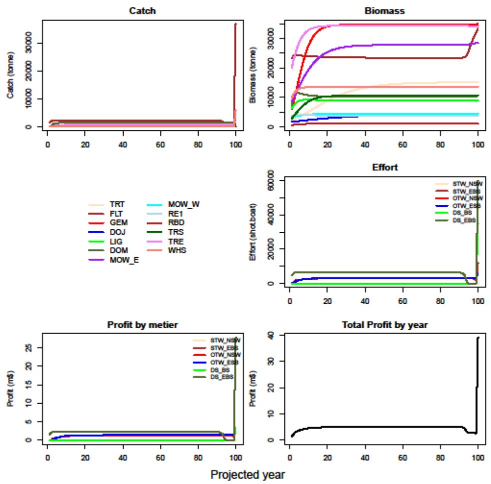
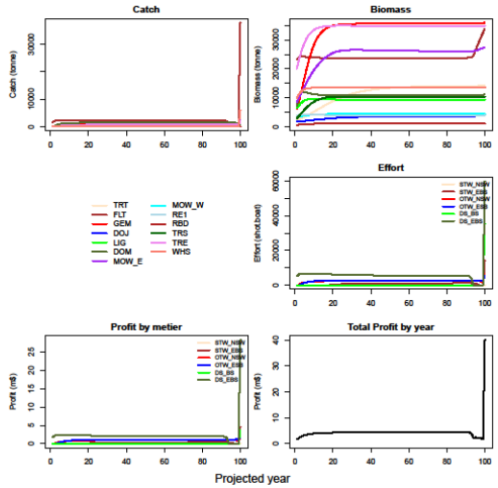
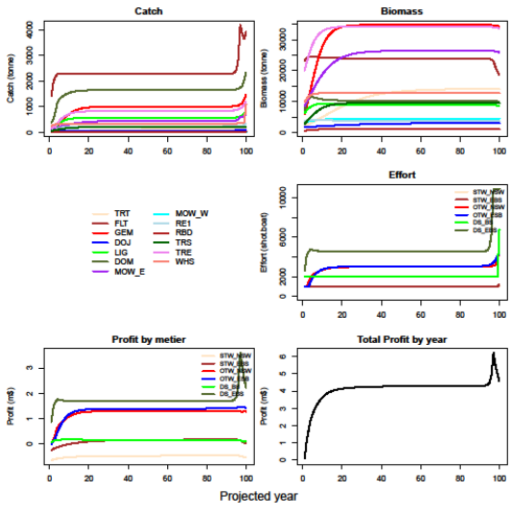
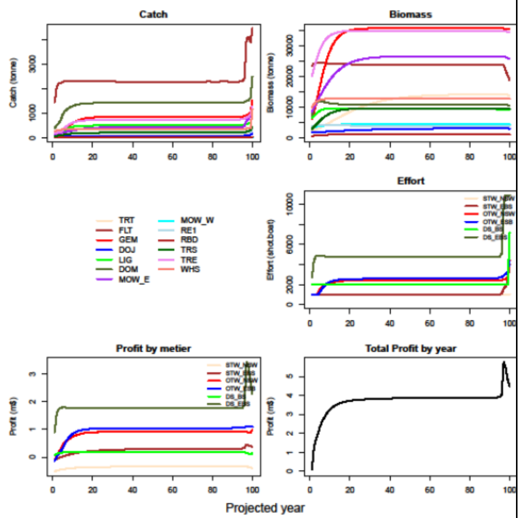
• No	• Assumptions	• Comments	• Original cost data	• Modified cost data
• 9	• Effort not constant at end	• "Bang-bang" at the end. That is optimal mathematical solution is for stock to be taken in total at end. •	• Optimised  •	• Optimised  •
• 10	• Two fleets (Trawl and DS) constrained at different levels	• Two "weakest" fleets end up at two different lower set constraints. • Profit is below ZERO for one fleet over the whole time period	• TwoGroupFleets  •	• TwoGroupFleets 

Table A. 2. The NPV values for the Scenarios (Table A.1) including detailed comments on rationale and results.

No	Assumptions	Cost data	NPV (AU$ Millions)	Comment/Observations
1a	Previous run – magnitude of effort change constrained	Official	82.62	Scenario was originally run to reduce effect of “bang-bang” (see year 100 in Scenario 9) however was replaced by Scenario 2 to 7 as in this scenario effort continues to increase (unrealistically) towards time T=100 (and Profit by Year goes to zero).
1b	Same as 1a	Modified	71.88	Same as 1a except costs higher and thus the NPV is lower.
2a	Effort constant after 20 years – NO lower bound	Official	91.18	The optimal solution, in that NPV is the maximum of all scenarios (excluding Scenario 4a which is not the current situation, and the “bang-bang” scenario – 9a/b). The only downside is that only 3 of the metiers remain (two otter trawl and one Danish Seine).
2b	Same as 2a	Modified	79.47	Same as 2a except costs higher and thus NPV lower. Except due to higher costs there is lower effort in some metiers and 4 of the metiers remain.
3a	Effort constant after 20 years – set to a lower bound	Official	70.09	• In order to reduce likelihood that effort goes to zero in 3 metiers (as in Scenario 2a/b) a lower bound was set on effort in any metier of 1000 shots per year. • The result is that the least efficient metiers remain in the fishery and experience negative profits.
3b	Same as 3a	Modified	63.48	Same as 3a except costs higher and thus the NPV is lower.

No	Assumptions	Cost data	NPV (AU$ Millions)	Comment/Observations
4a	Biomass begins at higher/different level	Official	(113.46)	Scenario run undertaken to test the stability of the model. B_0 values were set at 1.5 x the current levels in order to check if model run reaches the same solution state as Scenario 2-7 which it does. The NPV are positively exaggerated given higher starting B_0 values.
4b	Same as 4a	Modified	(99.95)	Same as 4a except costs higher and thus the NPV is lower.
5a	Effort constant after 30 years – NO lower bound	Official	91.18	Scenarios 5a/b to 7a/b were run to check if the results are sensitive to the timing of transition to constant effort (i.e. 20 years in Scenario 2a/b). The results indicate that an earlier transition (20 yrs) is optimal compared to 30, 50 or 80 years as the trend in the variables becomes more unstable – as the end of the time period is approached (where "bang-bang" would occur if not constrained. The NPV are not significantly sensitive to where the transition occurs thus Scenario 2a/b represent the most satisfying result.
5b	Same as 5a	Modified	79.48	
6a	Effort constant after 50 years – NO lower bound	Official	91.19	
6b	Same as 6a	Modified	79.49	
7a	Effort constant after 80 years – NO lower bound	Official	91.19	
7b	Same as 7a	Modified	79.50	
8a	Equilibrium	Official	n/a [82.41]	A simulation extension of the equilibrium solution. In this case computing NPV is not applicable as the values are not directly comparable with the other scenario runs. However the calculated NPVs are provided as an indication of the magnitude compared to NPV values computed from the dynamic runs.
8b	Same as 8a	Modified	n/a [78.49]	Same as 8a except costs higher and thus the NPV is lower.

No	Assumptions	Cost data	NPV (AU$ Millions)	Comment/Observations
9a	Effort not constant at end	Official	91.32	The classic “bang-bang” optimal (yet unrealistic) control theory solution. The maximum NPV is obtained in this manner; however the whole stock is caught in ~ time T = 100 (last time period).
9b	Same as 9a	Modified	79.63	Same as 9a except costs higher and thus the NPV is lower.
10a	Two fleets (Trawl and DS) constrained at different levels	Official	71.40	This scenario is a derivation of 3a except the lower bound constraint on effort is set at a different level for Danish seiners compared to otter trawlers. In the solution, profit is negative for one of the metiers over the whole time period and the NPV is lower than Scenario 2a.
10b	Same as 10a	Modified	64.30	Same as 10a except costs higher and thus the NPV is lower.

Appendix B. List of researchers

CSIRO

- Sean Pascoe
- Trevor Hutton
- Roy Deng
- Neil Klaer
- Olivier Thebaud
- Pierre Lelong (Student, Ecole Polytechnique, France).

ABARES

- Simon Vieira

Advisors/Reviewers

- Cathy Dichmont (CSIRO)
- Malcolm Haddon (CSIRO)
- Simon Boag (SETFIA)
- Diarmid Mather (AFMA)
- Robert Curtotti (ABARES)

References

ABARES (2011). Australian Fisheries Statistics 2010. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, pp 233.

Anderson, L.G. (1975). Analysis of Open-Access Commercial Exploitation and Maximum Economic Yield in Biologically and Technologically Interdependent Fisheries, *Journal of the Fisheries Research Board of Canada* 32, 1825-1842.

Anderson, L.G. (1986). *The economics of fisheries management*. Johns Hopkins University Press.

Bednarski, M., Cholewa, W. and Frid, W. (2004). Identification of sensitivities in Bayesian networks, *Engineering Applications of Artificial Intelligence* 17, 327-335.

Bevilacqua, M., Braglia, M. and Montanari, R. (2003). The classification and regression tree approach to pump failure rate analysis, *Reliability Engineering & System Safety* 79, 59-67.

Biseau, A. (1998). Definition of a directed fishing effort in a mixed-species trawl fishery, and its impact on stock assessments, *Aquatic Living Resources* 11, 119-136.

Bjørndal, T., Gordon, D. and Bezabih, M. (2012). Measuring potential profits in a bioeconomic model of the mixed demersal fishery in the North Sea, *Journal of Bioeconomics* 14, 147-166.

Borthwick, D. (2012). Review of Commonwealth Fisheries: Legislation, Policy and Management. Department for Agriculture, Fisheries and Forestry, Canberra.

Campbell, H.F., Hand, A.J. and Smith, A.D. (1993). A bioeconomic model for management of orange roughy stocks, *Marine Resource Economics* 8, 155-172.

Chae, D.R. and Pascoe, S. (2005). Use of simple bioeconomic models to estimate optimal effort levels in the Korean coastal flounder fisheries, *Aquatic Living Resources* 18, 93-101.

Chaudhuri, K. (1986). A bioeconomic model of harvesting a multispecies fishery, *Ecological Modelling* 32, 267-279.

Chen, S.H. and Pollino, C.A. (2012). Good practice in Bayesian network modelling, *Environmental Modelling & Software* 37, 134-145.

Christensen, A.-S. and Raakaer, J. (2006). Fishermen's tactical and strategic decisions: A case study of Danish demersal fisheries, *Fisheries Research* 81, 258-267.

Christensen, V. (2010). MEY = MSY, *Fish and Fisheries* 11, 105-110.

Clark, C.W. (1976). *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. John Wiley and Sons, USA.

Clark, C.W. and Kirkwood, G.P. (1979). Bioeconomic model of the Gulf of Carpentaria prawn fishery, *Journal of the Fisheries Board of Canada* 36, 1304-1312.

Clarke, R.P., Yoshimoto, S.S. and Pooley, S.G. (1992). A bioeconomic analysis of the Northwestern Hawaiian Islands lobster fishery, *Marine Resource Economics* 7, 115-140.

Da Rocha, J.-M., Gutiérrez, M.-J. and Cerviño, S. (2012). Reference points based on dynamic optimization: a versatile algorithm for mixed-fishery management with bioeconomic age-structured models, *ICES Journal of Marine Science: Journal du Conseil*.

DAFF (2007). Commonwealth fisheries harvest strategy: policy and guidelines. Department of Agriculture Fisheries and Forestry, Canberra.

DAFF (2013). Report on the review of the Commonwealth Fisheries Harvest Strategy Policy and Guidelines. Department of Agriculture, Fisheries and Forestry, Canberra.

De'ath, G. (2002). Multivariate regression trees: a new technique for modeling species–environment relationships, *Ecology* 83, 1105-1117.

De'ath, G. and Fabricius, K.E. (2000). Classification and regression trees: a powerful yet simple technique for ecological data analysis, *Ecology* 81, 3178-3192.

Dichmont, C.M., Pascoe, S., Kompas, T., Punt, A.E. and Deng, R. (2010). On implementing maximum economic yield in commercial fisheries, *Proceedings of the National Academy of Sciences* 107, 16-21.

Doyen, L., Thébaud, O., Bene, C., Martinet, V., Gourguet, S., Bertignac, M., Fifas, S. and Blanchard, F. (2012). A stochastic viability approach to ecosystem-based fisheries management, *Ecological Economics* 75, 32-42.

Duarte, C.C. (1992). Targeted versus nontargeted multispecies fishing, *Environmental and Resource Economics* 2, 259-281.

Dyson, R.G. and Thanassoulis, E. (1988). Reducing Weight Flexibility in Data Envelopment Analysis, *The Journal of the Operational Research Society* 39, 563-576.

Fonarow, G.C., Adams Jr, K.F., Abraham, W.T., Yancy, C.W. and Boscardin, W.J. (2005). Risk stratification for in-hospital mortality in acutely decompensated heart failure, *JAMA: the journal of the American Medical Association* 293, 572-580.

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, 233-249.

Fox, W.W. (1970). An Exponential Surplus-Yield Model for Optimizing Exploited Fish Populations, *Transactions of the American Fisheries Society* 99, 80-88.

Galeano, D., Langenkamp, D., Shafron, W. and Levantis, C. (2004). Australian Fisheries Surveys Report 2003: Economic Performance of Selected Fisheries in 2000-01 and 2001-02. ABARE, Canberra.

George, D. and New, R. (2013). Australian fisheries surveys report 2012: Financial and economic performance of the Eastern Tuna and Billfish Fishery, the Commonwealth Trawl Sector and the Gillnet, Hook and Trap Sector, *Australian fisheries surveys report*. ABARES, Canberra.

Georgeson, L., Stobutzki, I. and Curtotti, R. (2014). Fishery Status Report 2013-14. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Gordon, H.S. (1954). The economic theory of a common-property resource: The fishery *Journal of Political Economy* 62, 124–142

Gourguet, S., Macher, C., Doyen, L., Thébaud, O., Bertignac, M. and Guyader, O. (2013). Managing mixed fisheries for bio-economic viability, *Fisheries Research* 140, 46-62.

Grafton, Q.R., Kompas, T., Che, T.N., Chu, L. and Hilborn, R. (2012). BMEY as a fisheries management target, *Fish and Fisheries* 13, 303-312.

Grafton, R.Q., Kompas, T., Chu, L. and Che, N. (2010). Maximum economic yield, *Australian Journal of Agricultural and Resource Economics* 54, 273-280.

Guillen, J., Macher, C., Merzéréaud, M., Bertignac, M., Fifas, S. and Guyader, O. (2013). Estimating MSY and MEY in multi-species and multi-fleet fisheries, consequences and limits: an application to the Bay of Biscay mixed fishery, *Marine Policy* 40, 64-74.

Haapasaari, P., Michielsens, C.G.J., Karjalainen, T.P., Reinikainen, K. and Kuikka, S. (2007). Management measures and fishers' commitment to sustainable exploitation: a case study of Atlantic salmon fisheries in the Baltic Sea, *ICES Journal of Marine Science: Journal du Conseil* 64, 825-833.

Halls, A.S., Welcomme, R.L. and Burn, R.W. (2006). The relationship between multi-species catch and effort: Among fishery comparisons, *Fisheries Research* 77, 78-83.

Hamon, K. (2011). Bio-economic analysis of the response of a fishery to changes in access regulation: the case of individual transferable quotas in the Tasmanian rock lobster fishery, Université de Bretagne occidentale-Brest.

Hamon, K.G., Frusher, S.D., Little, L.R., Thébaud, O. and Punt, A.E. (2013). Adaptive behaviour of fishers to external perturbations: simulation of the Tasmanian rock lobster fishery, *Reviews in Fish Biology and Fisheries*1-16.

Hoff, A., Frost, H., Ulrich, C., Damalas, D., Maravelias, C.D., Goti, L. and SanturtÃºn, M. (2010). Economic effort management in multispecies fisheries: the FcubEcon model, *ICES Journal of Marine Science: Journal du Conseil* 67, 1802-1810.

Holland, D.S. and Maguire, J.-J. (2003). Optimal effort controls for the multispecies groundfish complex in New England: what might have been, *Canadian Journal of Fisheries and Aquatic Sciences* 60, 159-170.

Hoshino, E., Milner-Gulland, E.J. and Hillary, R.M. (2012). Bioeconomic adaptive management procedures for short-lived species: A case study of Pacific saury (Cololabis saira) and Japanese common squid (Todarodes pacificus), *Fisheries Research* 121-122, 17-30.

Hutton, T., Thébaud, O., Fulton, B., Pascoe, S. and Kulmala, S. (2010). *Ecosystem-Wide Impacts of Alternative Bycatch Reduction Strategies: An Ecological-Economic Assessment of the Australian Southern and Eastern Scalefish and Shark Fishery*, Proceedings of the AARES;Melbourne.

Ives, M.C., Scandol, J.P. and Greenville, J. (2013). A bio-economic management strategy evaluation for a multi-species, multi-fleet fishery facing a world of uncertainty, *Ecological Modelling* 256, 69-84.

Jensen, F.V. and Nielsen, T.D. (2007). *Bayesian networks and decision graphs*. Springer Verlag.

Jin, D.I., Kite-Powell, H., Hoagland, P. and Solow, A. (2012). A Bioeconomic Analysis of Traditional Fisheries in the Red Sea, *Marine Resource Economics* 27, 137-148.

Kennedy, J.O.S. and Pasternak, H. (1991). Optimal Australian and Japanese harvesting of southern bluefin tuna, *Natural Resource Modeling* 5, 213-238.

Klaer, N.L. and Smith, D.C. (2012). Determining primary and companion species in a multi-species fishery: Implications for TAC setting, *Marine Policy* 36, 606-612.

Kompas, T. and Che, N. (2006). A Stochastic Bioeconomic Model of a Multi-species and Multifleet fishery: An Application to the South East Trawl Fishery, *ABARE report to the Fisheries Resources Research Fund, Canberra*.
Kompas, T., Che, N., Chu, L. and Klaer, N. (2012). Transition to MEY Goals for the Great Australian Bight Trawl Fishery, *Report to Fisheries Research and Development Corporation* Australian Centre for Biosecurity and Environmental Economics, Crawford School of Public Policy, Australian National University, Canberra.
Kompas, T., Che, T.N. and Pham, T. (2009a). Maximum Economic Yield in the Southern and Eastern Scalefish and Shark Fishery, *ABARE Report to the Fisheries Resources Research Fund*. Commonwealth of Australia, Canberra.
Kompas, T., Dichmont, C.M., Punt, A.E., Deng, A., Che, T., Bishop, J., Gooday, P., Ye, Y. and Zhou, S. (2010a). Maximizing profits and conserving stocks in the Australian Northern Prawn Fishery, *Australian Journal of Agricultural and Resource Economics* 54, 281-299.
Kompas, T., Grafton, Q., Che, N. and Gooday, P. (2009b). Development of methods and information to support the assessment of economic performance in Commonwealth fisheries, *ABARE report for the Fisheries Research and Development Corporation Research report*. ABARES, Canberra, pp 79.
Kompas, T., Grafton, R.Q., Che, N. and Gooday, P. (2009c). Development of methods and information to support the assessment of economic performance in Commonwealth fisheries, *ABARE report for the Fisheries Research and Development Corporation*. ABARES.
Kompas, T., Grafton, R.Q. and Che, T.N. (2010b). Bioeconomic losses from overharvesting tuna, *Conservation Letters* 3, 177-183.
Korb, K.B. and Nicholson, A.E. (2003). *Bayesian artificial intelligence*. Chapman & Hall/CRC.
Lawrence, R.L. and Wright, A. (2001). Rule-based classification systems using classification and regression tree (CART) analysis, *Photogrammetric Engineering and Remote Sensing* 67, 1137-1142.
Lemon, S.C., Roy, J., Clark, M.A., Friedmann, P.D. and Rakowski, W. (2003). Classification and regression tree analysis in public health: Methodological review and comparison with logistic regression, *Annals of Behavioral Medicine* 26, 172-181.
Levontin, P., Kulmala, S., Haapasaari, P. and Kuikka, S. (2011). Integration of biological, economic, and sociological knowledge by Bayesian belief networks: the interdisciplinary evaluation of potential management plans for Baltic salmon, *ICES Journal of Marine Science: Journal du Conseil* 68, 632-638.
Lewis, R.J. (2000). *An introduction to classification and regression tree (CART) analysis*, Proceedings of the Annual Meeting of the Society for Academic Emergency Medicine in San Francisco, California. Citeseer.
Little, L.R., Kuikka, S., Punt, A.E., Pantus, F., Davies, C.R. and Mapstone, B.D. (2004). Information flow among fishing vessels modelled using a Bayesian network, *Environmental Modelling & Software* 19, 27-34.
Lorenzen, K., Almeida, O., Arthur, R., Garaway, C. and Khoa, S.N. (2006). Aggregated yield and fishing effort in multispecies fisheries: an empirical analysis, *Canadian Journal of Fisheries and Aquatic Sciences* 63, 1334-1343.
Mace, P.M. (1994). Relationships between Common Biological Reference Points Used as Thresholds and Targets of Fisheries Management Strategies, *Canadian Journal of Fisheries and Aquatic Sciences* 51, 110-122.
Marchal, P., Little, L.R. and Thébaud, O. (2011). Quota allocation in mixed fisheries: a bioeconomic modelling approach applied to the Channel flatfish fisheries, *ICES Journal of Marine Science: Journal du Conseil* 68, 1580-1591.
Mardle, S., Pascoe, S., Tamiz, M. and Jones, D. (2000). Resource allocation in the North Sea demersal fisheries: A goal programming approach, *Annals of Operations Research* 94, 321-342.
Martell, S. and Froese, R. (2013). A simple method for estimating MSY from catch and resilience, *Fish and Fisheries* 14, 504-514.
Matsuda, H. and Abrams, P.A. (2006). Maximal Yields From Multispecies Fisheries Systems: Rules For Systems With Multiple Trophic Levels, *Ecological Applications* 16, 225-237.
May, R.M., Beddington, J.R., Clark, C.W., Holt, S.J. and Laws, R.M. (1979). Management of multispecies fisheries, *Science* 205, 267-277.
Norman-López, A. and Pascoe, S. (2011). Net economic effects of achieving maximum economic yield in fisheries *Marine Policy* 35, 489–495.
Pascoe, S. (2000). Single species conservation in a multispecies fishery: the case of the Australian eastern gemfish, *Ecological Economics* 32, 125-136.

Pascoe, S., Battaglene, T. and Campbell, D. (1992). *A bioeconomic model of the southern shark fishery*. Australian Bureau of Agricultural and Resource Economics.
Pascoe, S., Dichmont, C.M., Vieira, S., Kompas, T., Buckworth, R.C. and Carter, D. (2013). A Retrospective Evaluation of Sustainable Yields for Australia's Northern Prawn Fishery: An Alternative View, *Fisheries* 38, 502-508.
Pascoe, S., Innes, J., Holland, D., Fina, M., Thebaud, O., Townsend, R., Sanchirico, J., Arnason, R., Wilcox, C. and Hutton, T. (2010a). Use of Incentive-Based Management Systems to Limit Bycatch and Discarding, *International Review of Environmental and Resource Economics* 4, 123-161.
Pascoe, S., Koundouri, P. and Bjorndal, T. (2007). Estimating targeting ability in multi-species fisheries: a primal multi-output distance function approach, *Land Economics* 83, 382-397.
Pascoe, S. and Mardle, S. (2001). Optimal fleet size in the English Channel: a multi-objective programming approach, *European Review of Agricultural Economics* 28, 161-185.
Pascoe, S., Proctor, W., Wilcox, C., Innes, J., Rochester, W. and Dowling, N. (2009). Stakeholder objective preferences in Australian Commonwealth managed fisheries, *Marine Policy* 33, 750-758.
Pascoe, S., Punt, A.E. and Dichmont, C.M. (2010b). Targeting ability and output controls in Australia's multi-species Northern Prawn Fishery, *European Review of Agricultural Economics* 37, 313-334.
Pascoe, S., Vieira, S. and Thebaud, O. (2014). Allocating repairs and maintenance costs to fixed or variable costs in fisheries bioeconomic models, *Applied Economics Letters*1-5.
Pearse, P.H. and Walters, C.J. (1992). Harvesting regulation under quota management systems for ocean fisheries: Decision making in the face of natural variability, weak information, risks and conflicting incentives, *Marine Policy* 16, 167-182.
Pelletier, D., Mahevas, S., Drouineau, H., Vermard, Y., Thebaud, O., Guyader, O. and Poussin, B. (2009). Evaluation of the bioeconomic sustainability of multi-species multi-fleet fisheries under a wide range of policy options using ISIS-Fish, *Ecological Modelling* 220, 1013-1033.
Penney, A., Moore, A., Flood, M., Georgeson, L. and Curtotti, R. (2014). Commonwealth Trawl and Scalefish Hook sectors. in Georgeson, L., Stobutzki, I. and Curtotti, R. (eds.), *Fishery Status Report 2013-14*. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.
Placenti, V., Rizzo, G. and Spagnolo, M. (1992). A bio-economic model for the optimization of a multi-species, multi-gear fishery: the Italian case, *Marine Resource Economics* 7, 275-295.
Plagányi, É., Deng, R., Dennis, D., Hutton, T., Pascoe, S., van Putten, I. and Skewes, T. (2012). An Integrated Management Strategy Evaluation (MSE) for the Torres Strait tropical rock lobster *Panulirus ornatus* fishery, *CSIRO/AFMA Final Project Report. AFMA Project number 2009/839*. CSIRO, Brisbane, pp 233.
Pollino, C.A., Woodberry, O., Nicholson, A., Korb, K. and Hart, B.T. (2007). Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment, *Environmental Modelling & Software* 22, 1140-1152.
Punt, A.E., Deng, R., Pascoe, S., Dichmont, C.M., Zhou, S., Plagányi, É.E., Hutton, T., Venables, W.N., Kenyon, R. and van der Velde, T. (2011). Calculating optimal effort and catch trajectories for multiple species modelled using a mix of size-structured, delay-difference and biomass dynamics models, *Fisheries Research* 109, 201-211.
Punt, A.E., Deng, R.A., Dichmont, C.M., Kompas, T., Venables, W.N., Zhou, S., Pascoe, S., Hutton, T., Kenyon, R., van der Velde, T. and Kienzle, M. (2010). Integrating size-structured assessment and bioeconomic management advice in Australia's northern prawn fishery, *ICES Journal of Marine Science* 67, 1785-1801.
Punt, A.E., Smith, A.D. and Cui, G. (2002a). Evaluation of management tools for Australia's South East Fishery. 1. Modelling the South East Fishery taking account of technical interactions, *Marine and Freshwater Research* 53, 615-629.
Punt, A.E., Smith, A.D.M. and Cui, G. (2002b). Evaluation of management tools for Australia's South East Fishery. 1. Modelling the South East Fishery taking account of technical interactions, *Marine and Freshwater Research* 53, 615-629.
R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Reid, C., Collins, P. and Battaglene, T. (1993). Torres Strait prawn fishery: an economic analysis, *ABARE Research Report 93.15*. ABARE, Canberra.
Sandberg, P., Bogstad, B. and RÃ¸ttingen, I. (1998). Bioeconomic advice on TACâ€“the state of the art in the Norwegian fishery management, *Fisheries Research* 37, 259-274.

Savina, M., Forrest, R.E., Fulton, E.A. and Condie, S.A. (2013). Ecological effects of trawling fisheries on the eastern Australian continental shelf: a modelling study, *Marine and Freshwater Research* 64, 1068-1086.

Schaefer, M.B. (1954). Some aspects of the dynamics of populations important to the management of commercial marine fisheries, *Bulletin of the Inter-American Tropical Tuna Commission* 1, 25-56.

Schaefer, M.B. (1957). A study of the dynamics of fishery for yellowfin tuna in the Eastern tropical Pacific Ocean, *Bulletin of the Inter-American Tropical Tuna Commission* 2, 247-285.

Scott, A. (1955). The Fishery: The Objectives of Sole Ownership, *The Journal of Political Economy* 63, 116-124.

Silliman, R.P. (1971). Advantages and Limitations of "Simple" Fishery Models in Light of Laboratory Experiments, *Journal of the Fisheries Research Board of Canada* 28, 1211-1214.

Silvert, W. and Smith, W.R. (1977). Optimal exploitation of a multi-species community, *Mathematical Biosciences* 33, 121-134.

Skirtun, M., Sahlqvist, P. and Vieira, S. (2013). Australian fisheries statistics 2012, FRDC project 2010/208. ABARES, Canberra.

Squires, D. (1987). Public regulation and the structure of production in multiproduct industries: an application to the New England otter trawl industry, *RAND Journal of Economics* 18, 232-247.

Squires, D. and Kirkley, J. (1991). Production quota in multiproduct pacific fisheries, *Journal of Environmental Economics and Management* 21, 109-126.

Stephan, M. and Hobsbawn, P. (2014). Australian fisheries and aquaculture statistics 2013, FRDC project 2010/208. ABARES, Canberra.

Thunberg, E.M., Bresnyan, E.W. and Adams, C.M. (1995). Economic Analysis of Technical Interdependencies and the Value of Effort in a Multi-Species Fishery, *Marine Resource Economics* 10, 59-76.

Tittonell, P., Shepherd, K.D., Vanlauwe, B. and Giller, K.E. (2008). Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya—An application of classification and regression tree analysis, *Agriculture, Ecosystems & Environment* 123, 137-150.

Tuck, G.N.e. (2010). Stock Assessment for the Southern and Eastern Scalefish and Shark Fishery 2009. Part 1. Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research, Hobart, pp 334.

Ulrich, C., Le Gallic, B., Dunn, M.R. and Gascuel, D. (2002). A multi-species multi-fleet bioeconomic simulation model for the English Channel artisanal fisheries, *Fisheries Research* 58, 379-401.

van Putten, I., Lalancette, A., Bayliss, P., Dennis, D., Hutton, T., Norman-Lopez, A., Pascoe, S., Plaganyi, E. and Skewes, T. (2013). A Bayesian model of factors influencing indigenous participation in the Torres Strait tropical rock lobster fishery, *Marine Policy* 37, 96-105.

Vayssières, M.P., Plant, R.E. and Allen-Diaz, B.H. (2000). Classification trees: An alternative non-parametric approach for predicting species distributions, *Journal of Vegetation Science* 11, 679-694.

Walters, C. (1998). Designing fisheries management systems that do not depend upon accurate stock assessment. in Pitcher, T., Pauly, D. and Hart, P.B. (eds.), *Reinventing Fisheries Management*. Springer Netherlands, pp 279-288.

Walters, C. and Pearse, P. (1996). Stock information requirements for quota management systems in commercial fisheries, *Reviews in Fish Biology and Fisheries* 6, 21-42.

Wang, Y.-G. and Wang, N. (2012). A Retrospective Evaluation of Sustainable Yields for Australia's Northern Prawn Fishery, *Fisheries* 37, 410-416.

Ward, J.M. (1994). The bioeconomic implications of a bycatch reduction device as a stock conservation management measure, *Marine Resource Economics* 9, 227-240.

Zhou, S., Pascoe, S., Dowling, N., Haddon, M., Klaer, N., Larcombe, J., Smith, A.D.M., Thebaud, O. and Vieira, S. (2012). Quantitatively defining biological and economic reference points in data poor and data limited fisheries, *Final Report on FRDC Project 2010/044*. CSIRO Marine and Atmospheric Research, Canberra, Australia. .

Ziegler, P.E. (2012). Fishing tactics and fleet structure of the small-scale coastal scalefish fishery in Tasmania, Australia, *Fisheries Research* 134–136, 52-63.