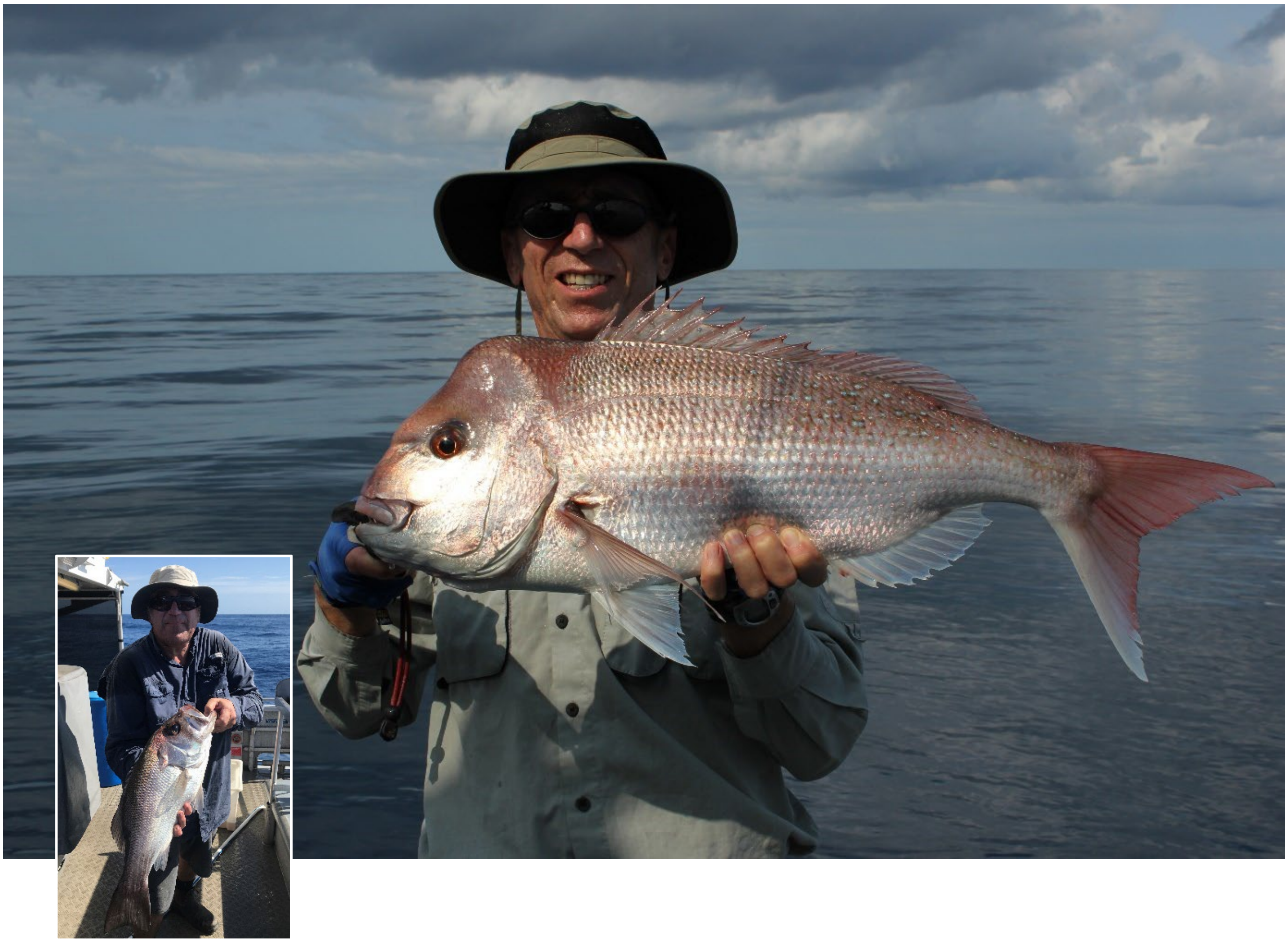

Development of a user-friendly MSE framework for Queensland's rocky reef fishery

Matthew Campbell, Michael F. O'Neill, Ken Taggart, Ali Khorsandian, Nils Krueck, Branko Dijkstra, Peter Brady, Syed Hussain

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Researcher Contact Details		**FRDC Contact Details**	
Name:	Matthew Campbell	Address:	25 Geils Court
Address:	Ecosciences Precinct, Level 1BEast,		Deakin ACT 2600
	41 Boggo Road, Dutton Park QLD 4102	Phone:	02 6285 0400
Phone:	07 3708 8329	Fax:	02 6285 0499
Fax:	07 3708 8429	Email:	frdc@frdc.com.au
Email:	matthew.campbell@daf.qld.gov.au	Web:	www.frdc.com.au

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Abbreviations

Abbreviation	Definition
BH-LHI	Beverton-Holt Life History Invariants
DAF	Department of Agriculture and Fisheries
FIS	Fishery-independent survey
FL	Fork length
FQ	Fisheries Queensland
MEY	Maximum Economic Yield
MLS	Minimum legal size
MSE	Management Strategy Evaluation
MSY	Maximum Sustainable Yield
PRS	Post-release survival
QFB	Queensland Fish Board
RRFF	Rocky Reef Finfish Fishery
RRWG	Rocky Reef Working Group
SAFS	Status of Australian Fish Stocks
SBR	Spawning biomass ratio (S_y/S_0)
TAC	Total allowable commercial catch
TL	Total length

Executive Summary

Researchers from the Queensland Department of Agriculture and Fisheries have developed a Management Strategy Evaluation (MSE) tool to test the effects of potential management changes on the spawning biomass of Snapper and Pearl Perch in Queensland. The MSE was developed in collaboration with a scientist from the University of Tasmania and software consultants from MathWorks® and Jundra. The MSE was built on stock assessment procedures to construct a virtual stock on which various management scenarios were imposed to determine their effect.

Snapper and Pearl Perch have been exploited since the late 1880s and are both currently assessed as depleted in Queensland. Previous stock assessments indicate the spawning biomass of both Snapper and Pearl Perch is currently at unsustainable levels and significant management intervention is required. The MSE confirms that significant increases in the minimum legal size that allows more animals to spawn before capture will have a positive effect on the spawning biomass of both species. This, combined with an increase in the length of the spawning closure, is likely to increase spawning biomass to acceptable levels in Queensland.

The MSE enables Fisheries Queensland to make evidence-based management decisions. Stakeholders are unlikely to support management intervention that significantly reduces catch if there is insufficient evidence that such measures will achieve fishery objectives. The MSE enables Fisheries Queensland to demonstrate the efficacy of management changes before their implementation. The MSE can also help guide the development of appropriate harvest control rules and/or harvest strategies.

Background

Snapper and Pearl Perch are popular table fish targeted by commercial, charter and recreational fishers in Queensland. Both species have a long history of exploitation, and both are currently categorised as depleted as defined by the Status of Australian Fish Stocks (SAFS). As such, Fisheries Queensland (FQ), the management agency within the Queensland Department of Agriculture and Fisheries (DAF), are obliged to implement management changes that improve the spawning biomass of these species.

To implement changes that achieve fishery objectives, FQ supported the development of a Management Strategy Evaluation (MSE) tool. An MSE allows FQ to assess the effects of management changes prior to their implementation by imposing the changes on a virtual stock. Stock assessment outputs, such as natural mortality and stock-recruitment relationships, are used to estimate the spawning biomass into the future. Management changes can then be imposed to assess their effect on spawning biomass. Such a tool, therefore, facilitates evidence-based management decisions that have demonstrable benefits to the stock. Where drastic changes are required, demonstrations of their benefits are necessary to ensure the support of stakeholders.

Aims/objectives

The aim of this project was to develop a Management Strategy Evaluation for Queensland's Rocky Reef Finfish Fishery, specifically Snapper and Pearl Perch.

Methodology

For each species, the MSE calculates the number of fish (N) in each age group (a) in each month (t) using stock assessment metrics such as growth, natural mortality and recruitment. The number of fish is decreased by the mean harvest rate (i.e., harvest/biomass) as a function of month ($t_{1\text{-}12}$), region ($k_{1,2}$) and fleet ($f_{1\text{-}7}$). Harvest rates were calculated in the stock assessment and are a function of the fishing mortality applied to each stock according to data inputs such as commercial harvest and recreational catch.

The MSE calculates the spawning biomass (S_t) and compares this to the spawning biomass prior to fishing (virgin spawning biomass, S_0) as an indication of population health. A spawning biomass ratio (SBR, S_t/S_0) of 40% is associated with maximum sustainable yield (MSY). To ensure maximum economic, social, and ecological benefit, Fisheries Queensland aim to achieve maximum economic yield (SBR ~60%) for all exploited fish stocks by 2027.

Harvest rates were adjusted according to changes to the minimum legal size, total allowable commercial catch, spawning closure duration and recreational bag limits. The effect of the changes was measured by comparing the resulting SBR to fishery objectives.

Results/key findings

The MSE indicates significant increases in minimum legal size would have a positive effect on the spawning biomass of both Snapper and Pearl Perch. Increasing the minimum legal-size results in the protection of more cohorts with the ability to spawn across multiple spawning seasons before recruiting to the fishery. Further, the larger, older fish are more productive than smaller, younger fish resulting in an increase in egg production. This result was demonstrated for published discard mortality rates of around 10% for each species.

The current one-month spawning closure had only a small effect. This was due to fishing efforts prior to and after the closure period largely negating its intended effect. Increasing the length of the closure had a positive effect on the spawning biomass of both species.

Any strategy that increases the spawning biomass of Snapper and Pearl Perch is likely to lead to an increase in the number of fish released. Although these species exhibit high post-release survival, the effect of predation on released fish by sharks and dolphins is unknown but commonly reported by commercial and recreational fishers. Similarly, depredation by sharks is possibly a significant source of fishing mortality. Both predation of released fish and depredation could adversely affect the intended benefits to stocks from fishery management changes. Climate-driven decreases in recruitment are likely to occur for Snapper, potentially inhibiting the level of recovery of this long-lived species in Queensland.

Implications for relevant stakeholders

The provision of evidence-based management of Snapper and Pearl Perch is the primary implication of this research. The MSE allows Fisheries Queensland to measure the efficacy of proposed management strategies before their implementation. The MSE can also provide stakeholders with confidence that the proposed management intervention will be effective should significant reductions in harvest be implemented.

The MSE has been developed so that species other than Snapper and Pearl Perch can be assessed. Management changes for those line-caught species subject to formal stock assessments can be assessed using the MSE developed in the current project.

The management changes imposed to increase spawning biomass will necessarily result in the release of captured individuals. Given the number of fish released, significant efforts will be required to educate fishers on methods that maximise the survival of released fish. Further, empirically derived estimates of depredation and predation will increase the accuracy of MSE (and stock assessment) outputs and enable assessment of their impacts on the future recovery of the respective stocks. Similarly, increasing sea temperature is likely to delay recovery of the Snapper spawning biomass in Queensland, by adversely affecting future recruitment and the timing/length of spawning season.

Recommendations

1. DAF (both Fisheries Queensland and Animal Science) should provide the resources to update the required data inputs used in the MSE at the completion of future stock assessments for Snapper and Pearl Perch.

2. The MSE should be used to assess potential management changes for other species, particularly those species where significant management interventions are necessary to rebuild spawning biomass. Fisheries Queensland and Animal Science should dedicate resources to this task where required, such as Spanish Mackerel.

3. The current iteration of the MSE achieves the objectives of this project. However, significant improvements are possible in the future. One improvement would be the inclusion of harvest rules for future SBRs following the hockey stick approach consistent with the harvest control rules and preferred harvest strategy approach for other fisheries in Queensland such as the Reef line harvest strategy[1]. A SBR of 60% could trigger a predetermined harvest rule that allows for an increase in the TAC and/or the recreational bag limit to maintain SBR at that level. Similarly, an SBR of 20% would trigger a harvest strategy that restricts fishing mortality in order to increase SBR from that point forward. This would allow future decision making under the harvest strategy transparent, and accessible by fishery managers, the working group, and broader stakeholders

4. Resources should be dedicated to educating fishers about maximising the survival of released fish. The RRWG should be engaged to discuss the most efficient methods of extending information to fishers.

5. Following from 4, above, the mandatory use of tools that mitigate the effects of barotrauma, such as release weights, venting tools or Coucum's Cages, should be considered by fishery managers and the working group.

6. The depredation of rocky reef fish should be quantified to increase the accuracy of MSE (and stock assessment) outputs. Fishers are reporting increasing numbers of sharks depredating catches in the RRFF.

7. Following from 4 – 6, above, although the post-release survival of released Snapper and Pearl Perch is quantified, these estimates excluded predation after release. There is a need, therefore, to quantify predation of released fish by sharks and dolphins in time and space to improve post-release survival estimates. Further, there is an urgent need to research methods to best avoid depredation and the predation of released fish.

8. Fishing power has been quantified for the RRFF. However, fishing power change was based on subjective estimates of the effects of a range of technological changes on catches between 1982 and 2012 provided by fishers. There is a need, therefore, to derive empirical estimates of fishing power, particularly with the advent of spot-lock electric motors and digital steering for outboard motors, both of which allows the fisher to maintain position without the need to deploy an anchor. Similarly, the effect of powerful sonar equipment that identify fishable locations when fishers are moving at steaming speed remains unquantified.

[1] https://www.daf.qld.gov.au/__data/assets/pdf_file/0007/1481920/Reef-line-harvest-strategy.pdf

9. The larval dispersion model outputs would benefit from the incorporation of spatial layers of rocky reef habitat. Further, knowledge of true spawning aggregation areas is currently incomplete and could not be represented in the model. Efforts should be made to quantify these potential inputs to future larval dispersion models.

Keywords

Snapper, *Chrysophrys auratus*, Pearl Perch, *Glaucosoma scapulare*, management strategy evaluation, MSE, stock assessment, minimum legal size, spawning closure, total allowable catch, bag limit, forecast, spawning biomass ratio

1. Introduction

The Queensland rocky reef finfish fishery (RRFF) is a multi-sector line fishery accessed by commercial, recreational and charter fishers. The fishery extends from ~22°S to the New South Wales-Queensland border (28°10.218 S, 153°31.830 E). Fishers primarily target Snapper (*Chrysophrys auratus*) and Pearl Perch (*Glaucosoma scapulare*), while Teraglin (*Atractoscion atelodus*), Samsonfish (*Seriola hippos*), Amberjack (*Seriola dumerili*), Yellowtail Kingfish (*Seriola lalandi*), Mahi Mahi (*Coryphaena hippurus*), Grass Emperor (*Lethrinus laticaudis*) and Cobia (*Rachycentron canadum*) are also caught (Sumpton *et al.*, 2013a).

The Snapper and Pearl Perch populations in southern Queensland have a long history of exploitation. Newspaper articles suggest Snapper were caught in southern Queensland as early as 1878, at which time groups of fishers on-board chartered vessels were reported to catch in excess of 100 Snapper per hour (Thurstan *et al.*, 2016). State-wide Snapper catches from both recreational and commercial fishers were recorded by the Queensland Fish Board (QFB) from the mid-1940s.

Although Pearl Perch were not mentioned specifically in the early newspaper reports, it is likely that some Pearl Perch were caught during the 1880s. Very few Pearl Perch catches were distributed/identified through the QFB: however, commercial fishers were catching Pearl Perch for sale in the 1950s (Sumpton *et al.*, 2017). At this time, fishers recorded catches more than 500 kg per day.

Historically fishers targeted Snapper and Pearl Perch in the areas adjacent to the population centres of the Sunshine Coast, Brisbane, and the Gold Coast. Vessels were generally small (<6 m) and powered by two-stroke outboard engines. This, along with the need to use landmarks to locate fishing spots, largely restricted fishing effort to inshore reef systems (Sumpton *et al.*, 2013a; Sumpton *et al.*, 2017). The adoption of increasingly powerful sonar and global positioning systems (GPS, Sumpton *et al.*, 2013a) in the 1990s, along with declines in Snapper catch rates (Wortmann, 2020), drove the expansion of the fishery into areas to the east and north of traditional fishing grounds.

Since 2005, Snapper and Pearl Perch catches have declined significantly (Wortmann, 2020). Three previous stock assessments categorised the Queensland Snapper stock as depleted (Allen *et al.*, 2006; Campbell *et al.*, 2009; Wortmann *et al.*, 2018b), as defined by the Status of Australian Fish Stocks (SAFS[2]). Similarly, the most recent Pearl Perch stock assessment indicated the exploitable biomass is likely below sustainable levels (Sumpton *et al.*, 2017). As such, increasingly stringent management measures have been applied to arrest the decline in the respective stocks.

The Queensland government have employed a range of input and output controls to regulate the catch of Snapper and Pearl Perch. Commercial line fishers endorsed with an L1 symbol can effectively fish in all state-managed coastal and offshore waters south of the Great Barrier Reef and are restricted to using rod-and-reel or hand line fishing gear, including mechanical or electrical reels. Multi-hook commercial fisheries (longline) and trapping are prohibited methods in Queensland.

Prior to 1993, the only restriction on Snapper catch was a minimum legal size (MLS) of 25 cm total length (TL), which applied to all sectors, whereas no restrictions applied to the catch of Pearl Perch (Table 1). In 1993, an MLS of 30 cm TL was introduced for both Snapper and Pearl Perch, along with recreational bag limits of 30 and ten, respectively. In December 2002, the MLS and bag limit were changed to 35 cm and five, respectively, for both Snapper and Pearl Perch.

[2] https://www.fish.gov.au/

It should be noted that, prior to 1984, recreational fishers were permitted to sell any quantity of Snapper and Pearl Perch. In 1984, recreational fishers were restricted to the sale of a maximum of 600 kg per annum. Legislation in 1990 prohibited the sale of fish by recreational fishers.

Table 1: Timeline of Queensland management arrangements for Snapper and Pearl Perch. MLS is the minimum legal size, in cm, bag limit is the recreational in-possession limit, TAC is the total allowable commercial catch, closure is the period of no-take where fishers must release incidentally caught fish immediately, and the boat limit is the number of individuals permitted per vessel where the number of fishers is 3 or more.

	Snapper					**Pearl Perch**			
Date	MLS	Bag limit	TAC	Closure	Boat limit	MLS	Bag limit	TAC	Closure
Pre-1900									
1900	25								
1993	30	30				30	10		
Dec, 2002	35	5				35	5		
Sep, 2011	35	4†		15/2/12-31/3/12		35	5		15/2/12-31/3/12
Sep, 2019	35	4†	42 t	15/7-15/8⁋	8‡	38	4	15 t	15/7-15/8⁋

† with 1 >70 cm TL, ‡ with 2 >70 cm TL, ⁋ on-going annually

In response to the stock assessment undertaken by Campbell *et al.* (2009), Fisheries Queensland established a Snapper Working Group to seek stakeholder views regarding management measures to rebuild Snapper stocks in Queensland. At the end of this process, a number of management options were developed, including various combinations of commercial quota, seasonal closures and reduced recreational bag limits.

All options were criticised by stakeholders outside of the working group. After extensive consultation, the government opted for a reduction in the recreational bag limit for Snapper from five to four with one fish >70 cm TL. Further, a six-week no-take period for Snapper, Pearl Perch and teraglin, commencing on 15 February 2011, was introduced for one year to reduce effort by ~14% at a time when fishers could target other species such as mackerel (*Scomberomorus* spp.) to reduce the impact of the no-take period. No further management action was taken at this time, despite the stock assessment indicating fishery performance was poor. The addition of Pearl Perch and teraglin to the no-take species list was designed to discourage fishers from targeting these species and causing incidental mortality of Snapper during the closure period. However, the no-take period was removed the following year, after confusion from stakeholders regarding the efficacy of such a closure outside of the known Snapper spawning season (June to September).

In 2018, as part of the *Sustainable Fisheries Strategy (2017 – 2027)*, Fisheries Queensland established the Rocky Reef Working Group (RRWG) to assist with reviewing the management of the RRFF and to develop future harvest strategies. In the absence of a dedicated management strategy evaluation (MSE) tool, the RRWG considered a suite of measures to reduce the total harvest of Snapper and Pearl Perch, considered to be appropriate to enhance spawning fish stocks, and cease the ongoing decline in stocks. Following a round of consultation (February 2019[3]), Fisheries Queensland announced changes to the regulations in September 2019. Commercial fishers were restricted to a maximum of 42 and 15 t of Snapper and Pearl Perch respectively, a recreational boat limit of eight Snapper (with 2 or more people on board) was implemented, the MLS of Pearl Perch was increased from 35 to 38 cm TL, the Pearl Perch recreational bag limit was reduced from five to four, and an

[3] https://www.daf.qld.gov.au/business-priorities/fisheries/sustainable/fishery-working-groups/rocky-reef-working-group/communiques/communique-4-5-february-2019

annual one month no-take period for Snapper and Pearl Perch commenced on 15 July (Table 1). Further, the harvest of Snapper using any netting apparatus was prohibited.

Fisheries Queensland aim to achieve maximum economic yield, which is notionally a target reference point of 60% of the unexploited spawning biomass (i.e., S_{60}) for key target species, including Snapper and Pearl Perch. To achieve this reference point, sustainable catch limits will be established through harvest strategies developed via stakeholder engagement and public consultation. The efficacy of the harvest strategies will be determined by comparing biomass estimates, based on stock assessment outputs, to target levels.

Harvest strategies can also be tested within a MSE framework. Computer simulation allows fishery managers to determine which measures are more likely to achieve specified management objectives (Butterworth and Punt, 1999). Building on previous stock assessments, the MSE produced as part of this project enables fishery managers to determine the future status of Snapper and Pearl Perch stocks and make evidence-based management decisions. This project was developed to demonstrate the effectiveness of management changes to RRWG members when developing future harvest strategies. The MSE was designed with the flexibility to allow for additional stocks to be included in future analyses.

2. Objectives and scope

The aim of the project was to develop a management strategy evaluation (MSE) for Queensland's RRFF. Specifically, the MSE was developed to assess changes in the harvest strategies for Snapper and Pearl Perch, both of which were subject to high levels of fishing mortality (Sumpton *et al.*, 2017; Wortmann *et al.*, 2018a).

The initial MSE focused on developing the biological and fishery components of the operating-model, with options for testing various management procedures fixed in time (Figure 1). Staff from MathWorks and Jundra were engaged to generate MATLAB® (MathWorks, 2021) code for the MSE and develop a simple web user interface for use by fishery managers in a working group setting.

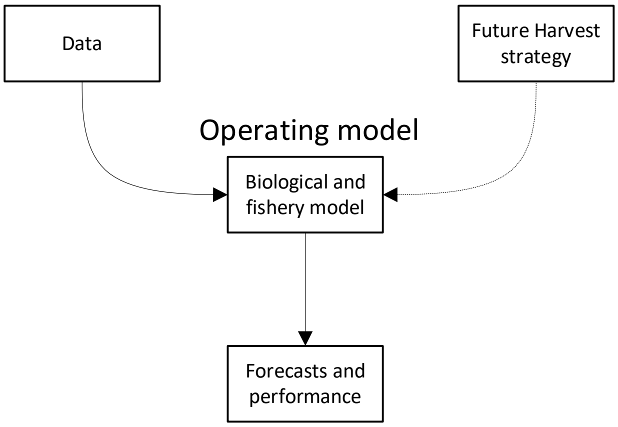


Figure 1: Conceptual overview of the initial MSE model.

Beyond this project, the flexibility of the MSE facilitates the inclusion of additional species. It is also possible to add stock assessment and monitoring components into Figure 1 to simulate more innovative time-varying management procedures. For example, should the forecasted biomass of a species reach S_{60}, the modified MSE could initiate pre-determined management changes to maintain biomass at this level by easing catch restrictions. Similarly, should forecasted spawning biomass reach S_{20}, the modified MSE could introduce increasing restrictions on catch and/or effort to re-build the stock. However, the time-varying aspect was out of scope for the current project and management need.

The MSE was coded such that parameters from the most recent stock assessment are incorporated into the forecast phase. As future stock assessments are completed, the parameters can be updated to ensure the calibration phase of the MSE corresponds to stock assessment outputs. This, combined with updated input data (harvest, catch rate, etc.) and modelling support, enables evidence-based management decisions to be made by Fisheries Queensland and their working groups. It could also be applied nationally in other fisheries.

It should be noted that the aim of the project was to provide a forecasting tool for use by stakeholders and fishery managers rather than a tool solely for scientists. The web application was designed to provide a simple interface between the user and the complex mathematical modelling required to forecast biomass into the future. Further, project staff have compiled this report to reflect the intended audience: fishery managers, fishers and other stakeholders. Technical methodology concerning the modelling undertaken has been minimised to ensure the reader is not discouraged by the jargon typically found in reports such as this.

3. Method

3.1 Biological information

Below is a summary of the known biological information relevant to the MSE. The parameters used in the MSE are presented in Table 11, on page 31.

3.1.1 Snapper

Snapper caught in Queensland are part of the larger east coast stock, which is distributed between Eden (37°04' S, 149°54' E) and Townsville (19°15′23″S, 146°49′6″E) (Morgan *et al.*, 2019). Snapper are found from shallow inshore areas, such as bays and estuaries, to offshore areas in depths to 200 m (Kailola *et al.*, 1993). In Queensland, Snapper grow to >1 m TL and in excess of 10 kg in weight (Grant, 2002). Stewart *et al.* (2001) reported age-at-maturity for Snapper in New South Wales at 2.5 yr. Age-at-maturity is unknown in Queensland: however, Ferrell and Sumpton (1997) reported that some Snapper in Queensland matured at an age of 22 months, although some fish as old as five years had not yet spawned. All fish >5 yr (~39 cm TL) were found to be mature. Snapper growth varies with latitude, with the specific growth rate of tagged fish (Δ length/time-at-liberty) inversely proportional to latitude (Stewart *et al.*, 2020). Spawning occurs throughout winter (~19 – 21°C, Scott and Pankhurst, 1992), with post-spawn female gonads occurring during June – September (Ferrell and Sumpton, 1997). The highest proportion of post-spawn ovaries were present in September, indicating the end of the spawning season. Using the empirical formula developed by Ferrell and Sumpton (1997), the fecundity of a legal-sized female (35 cm TL) is approximately one million eggs.

3.1.2 Pearl Perch

Pearl Perch are endemic to the east coast of Australia between Mackay (21°S) and Newcastle (33°S). Unlike Snapper, Pearl Perch generally occur only in oceanic waters >20 m water depth. The species occurs close to submerged rocky reefs (McKay, 1997) to depths of at least 200 metres. In Queensland, previous research has shown that Pearl Perch are a slow growing and long-lived species (Stewart *et al.*, 2013; Sumpton *et al.*, 2013a). In Queensland, fishery-dependent sampling indicate that Pearl Perch grow to at least 75 cm TL and 20 years of age. Stewart *et al.* (2013) reported that growth rate is higher in Pearl Perch sampled from Queensland (k = 0.24 yr^{-1}), compared to those sampled in New South Wales (k = 0.13 yr^{-1}). In contrast to Snapper, relatively little is known about the reproductive biology of Pearl Perch. Prior to 2009, no spawning Pearl Perch had been sampled from the traditional fishing grounds in south-east Queensland and northern New South Wales. Spawning females have since been found on grounds that traditionally received low levels of fishing effort: spawning fish have been found in locations off the Sunshine Coast and Fraser Island in depths >180 m, and in waters adjacent to the Swain's Reef area at the southern end of the Great Barrier Reef. Age-at-maturity is currently unknown and will be quantified in a concurrent FRDC-funded research project (2018/074). This research has shown that Pearl Perch spawn between March and May in southern Queensland, and in the summer months in the Swain's Reef area. Stock structure will be quantified using genetics as part of 2018/074: however, the Pearl Perch occurring in Queensland and New South Wales are currently considered a single biological stock (Stewart *et al.*, 2013). At the legal size of 38 cm TL, a female Pearl Perch produces ~300,000 eggs (see page 48 of Sumpton *et al.*, 1998 for relevant data).

3.2 Reference Points

The objectives for the MSE followed those from Queensland's *Sustainable Fisheries Strategy (2017–2027*). The objectives were operational, so that statistics can evaluate the biological performance of different management procedures (Punt *et al.*, 2016). The primary performance measure was to evaluate spawning biomass (S) against a target reference point for each species, s. This measured the sustainability and health of the fish populations. The Sustainable Fisheries Strategy identifies reform areas and specific management actions to be implemented by 2027. These include achieving maximum economic yield through harvest strategies that ensure sustainable, evidence-based catch limits.

Table 2: Relevant features of the current MSE operating model.

Feature	Description
Software	MATLAB® operated by a free web-based user interface
Number of species (s)	2
Time spans years (y)	Snapper 1880–2016; Pearl Perch 1938–2013
Time step (t)	Monthly
Fish ages (a)	In months up to the maximum fish ages
Number of regions (k)	2; State waters of New South Wales and Queensland
Fish movement (**T**)	Regional movements – probability transition matrix **T**
Number of fleets per region (f)	4; commercial trap, commercial line, charter line, and recreational line
Natural mortality (M)	Constant rate per t per s
Stock recruitment ($R_{a=1,k,t}$)	Beverton-Holt function using R_0 and steepness parameters; Yearly whole-stock recruitment split into regions and months
Recruitment deviations (η_y)	Yearly for the whole-stock; Log-normal deviations
Vulnerability ($v_{a,t,f}$)	Domed shaped for the trap fleet and logistic for the line fleets; varies with time changes in fish minimum legal sizes
Tuning data	Historical whole-stock spawning biomass ratios (S_t/S_0) and MSY tonnes
Harvest rates ($u_{k,t,f}$)	Fractions of exploitable sized fish harvested per month-fleet-region
Stock assessment data	The MSE loads and calibrates to current annual-whole-stock assessments. The calibration splits annual dynamics into regions and months. The last published stock assessment for Snapper was in 2016 and Pearl Perch in 2014. MCMC parameter samples and data inputs were used.

The Queensland Government aims to identify a harvest strategy to limit the catch of Snapper and Pearl Perch to rebuild these stocks to sustainable levels (around 40-50% spawning biomass). Furthermore, catch limits that lead to spawning biomass levels associated with maximum economic yield by 2027(MEY, B_{60}; see Punt *et al.* (2014) are desirable.

3.3 Simulation

Management strategy evaluation (MSE) involves using computer simulations to compare the relative effectiveness for achieving management objectives for different combinations of data collection schemes, methods of analysis and management actions (Punt *et al.*, 2016). MSE can identify the management strategy among a set of candidate strategies that achieves a pre-determined goal, or to determine how well an existing strategy has performed (Punt *et al.*, 2016).

The MSE herein assessed the proposed management procedures within a virtual simulation of the Snapper and Pearl Perch fisheries. The algorithm driving the MSE used projection methodology similar to that described by Richards *et al.* (1998). The population dynamics simulated numbers (N) of fish by species (s), region (k), age groups (a) and month (t) (Table 2, Table 3, and Table 10), using a sample of parameter values shown in Table 11, on page 31.

The historical years of the MSE were tuned to the annual whole-stock dynamics from separate stock assessment results. This MSE converts the stock assessment outputs from annual spawning biomass to spawning biomass as a function of month (t), region (k) and fleet (f). The population parameters were set for the low natural mortality and slow growth characteristics of Snapper and Pearl Perch and tested the performance of the management strategies outlined in section 3.5, below.

Regional harvest data further tuned the hypotheses for the historical stock-status in each jurisdiction (k), based on the simulation settings. The model projected around 20 years to cover approximately half the potential life cycle of Snapper and Pearl Perch. This was to quantify short-term (2027) and longer-term management performance. For each scenario, the projection process from selecting sample parameters to drive the fish population dynamics (Table 3), to management and harvest, was performed in MATLAB® (MathWorks, 2021).

3.4 Operating model

The MSE operating model (OM) provides the mathematical equations to simulate the rocky reef finfish fishery for Snapper and Pearl Perch. This represents a virtual reality that sufficiently matches the historical data, stock assessment and population abundance settings. The OM includes the biological, fishing and management components of the finfish fishery. The operating model includes the following components:

- Table 10 – Equations for fish population dynamics (page 31).
- Table 11 – Parameters for the population equations (page 31).
- Table 12 – Key elements for forecasting (page 33).

Further details on the population dynamics and equations are described in the relevant past reports (O'Neill *et al.*, 2014; Sumpton *et al.*, 2017; Wortmann *et al.*, 2018b).

3.5 MSE setup

It should be noted that the MSE forecasts the biomass of Snapper and Pearl Perch across the distribution of the respective biological stocks. However, this report will focus solely on the forecasts of the Queensland portion of the biological stocks.

Once a fish species has been selected, the MSE is calibrated to that species' stock assessment outputs. The user is required to choose the starting point of the forecast period based on the outputs from the respective stock assessment. In the case of the stock assessments on which the MSE in the current study is based, two starting points for the forecasts are possible for the Queensland portion of the respective stocks (Figure 2). For both species, the most optimistic scenarios from Figure 2 were the starting point of the forecast period to generate the spawning biomass estimates throughout the remainder of this report.

The current iteration of the MSE forecasts harvest by seven fleets (f, Table 2). Three fleets are common to both states: commercial line, recreational line and charter line. A seventh fleet, commercial trap, only occurs in New South Wales. Monthly harvest rate for each fleet is calculated from the last 24 years of data used in the respective stock assessments. The mean (± S.D.) monthly harvest rate is then projected forward for 24 years.

The user is required to provide a suite of management strategies for each region, k. Currently, New South Wales has an MLS for Snapper and Pearl Perch of 30 cm TL, in-possession limits of 10 and five, respectively, and no spawning closure. For the purposes of this report, these management strategies will be applied for the New South Wales portion of the respective stocks for the duration of the forecast period.

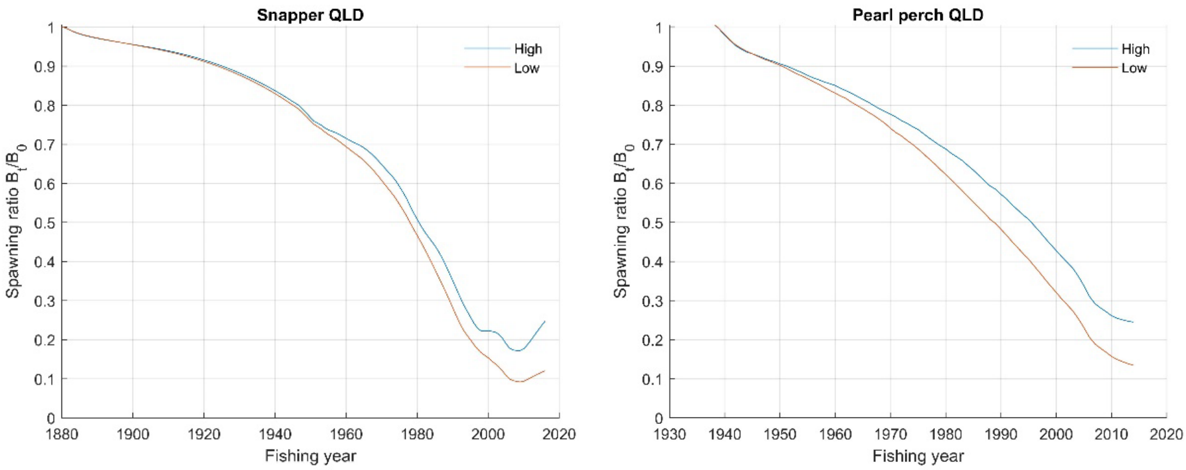
Table 3: Algorithm for the MSE.

MSE steps	Description
1. Read data inputs	Data for harvest strategy variables, biological parameters, age-based maturity, annual harvests, monthly harvest patterns, monthly spawning patterns, fish movement transition-matrix and historical changes in fish minimum legal sizes (MLS). The data are read from a MS Excel file, and the format defines the number of regions and fishing sectors/fleets to simulate.
2. Base data store	In MATLAB® (MathWorks, 2021), the data inputs are reshaped into structures for storing information on the respective species, biology, and management strategies. Each structure groups all the related data into a neat usable form.
3. Setup a fish species	Select a fish species and stock-assessment scenario for MSE simulation and transfer the data into the structure MyFish. Each variable's data can be accessed using dot notation of the form MyFish(1).Region(2), which specifies a species and region setup.
4. Run a calibration	This is performed within the function MyFish.runCalibration. This loads the stock-assessment scenario-data and performs the MSE calibration (tuning). The calibration adjusts the stock-assessment annual-whole-stock information into monthly, regional, and fleet aspects. The calibration fits to the selected spawning biomass time series and the MSY. Once complete, all data and parameters inform the forecasts (future simulations at a finer spatial-temporal scale than possible in annual whole-stock assessment).
5. Run a forecast	This is performed within MyFish.forecast. To enable a forecast for a species in a region, the MSE will run each region's management settings for MLS, recreational bag limit, TAC, closure time, fishing power growth, fishing effort growth, shark depredation, fish recruitment and deviation, and discard mortality.

3.6 Management strategies

Management strategies developed by the RRWG in 2019 were evaluated. These strategies form the basis of the results discussed in the remainder of this report. The RRWG were directed by Fisheries Queensland to provide a strategy with aims of decreasing the harvest of both Snapper and Pearl Perch. RRWG members discussed a range of options to reduce total catch and used a combination of increased MLS, reduced recreational bag limits, reductions in commercial catch and increasing the spawning closure period. The result of these discussions is presented in Table 4 and Table 5. The RRWG also indicated other sources of fishing mortality, such as depredation and discard mortality, are likely to effect biomass.

It should be noted that, where possible, published parameters will be used to inform metrics of discard mortality, depredation and fishing power. At present, discard mortality rates have been published for both snapper (McLennan *et al.*, 2014) and pearl perch (Campbell *et al.*, 2014). Some preliminary information regarding the fishing power changes that occurred in the RRFF in the period 1972 – 2002 was reported by Sumpton *et al.* (2013b). There are currently no published depredation rates for snapper or pearl perch. Further, in response to results reported by concurrent research (FRDC Project No. 2019/013), the user can specify recruitment deviations as a proxy for climate-driven changes in recruitment (Table 6).



(a) (b)

Figure 2: Predicted (a) Snapper and (b) Pearl Perch spawning biomass ratios from 1880 – 2016 and 1938 – 2013, respectively.

Advice on the commercial line TAC was provided by the RRWG. While the current iteration of the MSE includes a TAC for the commercial line fleet only, catch limits can be applied to all fleets. Where a fleet is subject to a TAC and the TAC is achieved part-way through a fishing year, the harvest rate for the fleet is set to zero until the start of the following fishing year.

Table 4: Nine strategies developed for Queensland Snapper by the Rocky Reef Working Group in 2019. All terms are defined as per Table 1. *Note, where the bag limit is >0, only one individual >70 cm TL is permitted.

Strategy	MLS	Bag Limit*	TAC	Closure
1	35	4	42	1 month
2	45	4	42	1 month
3	50	4	42	1 month
4	45	2	42	1 month
5	35	4	42	2 months
6	45	2	30	2 months
7	35	4	30	3 months
8	45	2	20	3 months
9	-	0	0	12 months

The starting date for the closure periods specified in the harvest strategies is contingent on the length of the closure period. Where the closure period is less than three months, the starting date is 15 July, annually, the current start of the closure period. A longer closure (≥3 months) is programmed to start on 15 June, annually. For the purposes of this report, the closure applies to both species at the same time and is the preferred management approach, to reduce regulatory complexity for stakeholders: however, the MSE has been coded to allow for closures to apply to each species such that closure times can be tailored for each species. For example, according to research from 2018/074, Pearl Perch appear to spawn in the months March to May in southern Queensland and the MSE has the flexibility to apply a closure during this period to assess its efficacy.

Table 5: Nine strategies developed for Queensland Pearl Perch by the Rocky Reef Working Group in 2019. All terms are defined as per Table 1.

Strategy	MLS	Bag Limit	TAC	Closure
1	38	4	15	1 month
2	45	4	15	1 month
3	50	4	15	1 month
4	45	2	15	1 month
5	38	4	15	2 months
6	45	2	10	2 months
7	38	4	10	3 months
8	45	2	5	3 months
9	-	0	0	12 months

In the current iteration of the MSE, the management strategies are contained in a design matrix in MATLAB® of dimensions *n* x 12, where *n* is the number of strategies to be tested.

Project staff contacted several recreational fishing groups by phone and email in December 2020 to obtain management strategies to increase Snapper and Pearl Perch biomass in Queensland. These groups were approached to provide 4 – 5 strategies. A moderator of the online recreational fishing forum, Ausfish (http://www.ausfish.com.au/), was approached to work with forum members to provide strategies they felt would be appropriate "to recover these stocks into the future". This engagement resulted in two strategies which supplement those provided by the RRWG. Further, an engaged recreational fisher offered another option to test. In both instances, only strategies to reduce Snapper fishing mortality were tested. These strategies are shown in Table 7.

Table 6: Matrix of Snapper management strategies, specified in Table 4, for testing in the MSE framework. The 12 columns are: 1) strategy number, 2) MLS in cm, 3) recreational bag limit, 4) TAC in tonnes, 5) closure period in months, 6) growth in fishing power as a proportion, 7) growth in fishing effort as a proportion, 8) shark depredation as a proportion, 9) mean recruitment deviation, 10) epsilon, the recruitment deviation standard deviation, 11) discard mortality as a proportion and 12) region label, *k*.

1	35	4	42	1	1	1	0	0	eps	0.12	2
2	45	4	42	1	1	1	0	0	eps	0.12	2
3	50	4	42	1	1	1	0	0	eps	0.12	2
4	45	2	42	1	1	1	0	0	eps	0.12	2
5	35	4	42	2	1	1	0	0	eps	0.12	2
6	45	2	30	2	1	1	0	0	eps	0.12	2
7	35	4	30	3	1	1	0	0	eps	0.12	2
8	45	2	20	3	1	1	0	0	eps	0.12	2
9	35	0	0	12	1	1	0	0	eps	0.12	2

The effects of discard mortality, depredation, fishing power and recruitment on SBR were also demonstrated. This was achieved through applying the values, shown in Table 8, to each of the strategies from Table 4 and Table 5 that produced the highest snapper and pearl perch SBRs, respectively. The values for depredation, discard mortality and fishing power were informed from discussions with RRWG members, while the change in recruitment deviation was informed by research conducted as part of FRDC Project 2019/013. These values are preliminary and will be updated once published values are available. However, the changes outlined in Table 8 demonstrate the effect of small changes in these metrics on SBR forecasts.

Table 7: Supplementary strategies to rebuild Snapper biomass in Queensland as supplied by recreational fishers. Note the first strategy is the status quo management strategy for contrast.

Strategy	MLS	Bag Limit	TAC	Closure
1	35	4	42	1 month
2	40	5	42	1 month
3	40	4	42	1 month
4	45	2	42	1.5 months

3.7 Web Application

Project staff developed a web application that allowed fishery managers to utilise the MSE without the need to learn MATLAB® or install the software on the user's machine. This used the MATLAB® Production Server software, which was installed on a DAF server. The web application provides a simple interface between the complex mathematical modelling associated with stock assessment and the user. Once the user inputs the relevant information, the modelling is undertaken within the Production Server software and SBR is displayed via a simple line graph on the web interface.

Table 8: Levels of depredation rate, discard mortality, fishing power and recruitment deviations used to illustrate their effect on spawning biomass ratio in the MSE.

Metric	Status quo	Indicative value
Depredation rate	1	1.2
Discard mortality	1.12	1.2
Fishing power	1	1.005
Recruitment deviation	0	-0.05

3.8 Larval dispersion

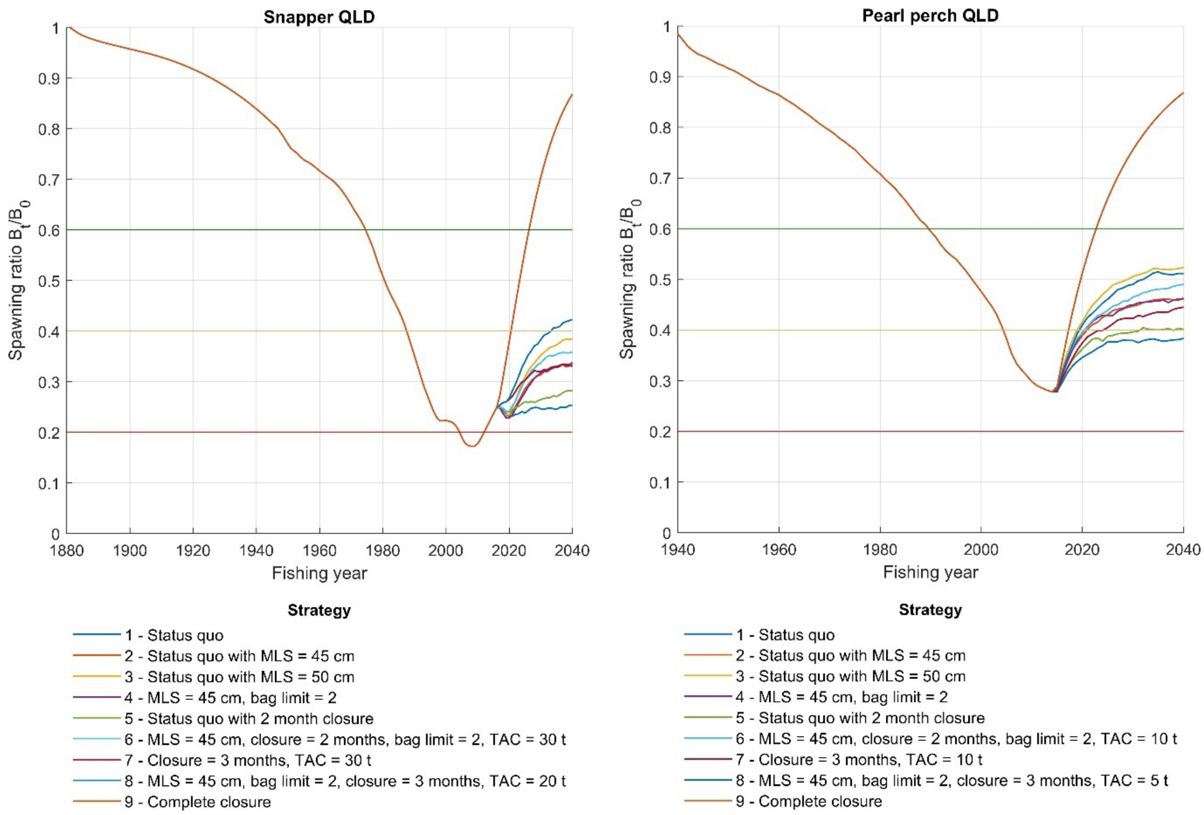
Larval dispersal was simulated using a widely tested biophysical model (Treml *et al.*, 2015; Treml and Halpin, 2012; Treml *et al.*, 2008; Treml *et al.*, 2012), which incorporated HYCOM ocean current data at a spatial resolution of 10 x 10 km and a temporal coverage of 16 years (1997-2012). To simulate dispersal events, larvae were released from 67 putatively representative locations distributed along the coast from northern QLD to southern NSW (see Figure 10). From each of these locations, larvae were released five times in two-week intervals over the assumed peak spawning period of Snapper in Queensland (June 15 to August 15) inferred from measurements of the Gonadosomatic Index (QLD Fisheries, unpublished data). Larvae were assumed to then drift passively with surface currents over a maximum pelagic duration of 32 days (Francis, 1994), and assuming a daily larval mortality rate of 10% (White *et al.*, 2014). Competency of larvae to settle was inferred from a Gamma probability density distribution, which assumed a pre-competency period of 16 days (no settlement) and a subsequent increase to 50% (24 days) and 100% (32 days) settlement competency. The model was otherwise parameterized as detailed in previous studies focusing on the same region along the eastern Australian coastline (Matz *et al.*, 2018). Key outcomes from the modelling were quantitative estimates of the probability of larval exchange among all 67 release locations across the study area.

4. Results, discussion and conclusion

4.1 Spawning biomass ratio

The MSE indicated significant management intervention was required for the respective SBRs to reach the target of 60% required under the Sustainable Fisheries Strategy (Figure 3). Only a full closure of the fishery (Strategy 9, Figure 3) achieved the objective for both species within the timeframe outlined in the Sustainable Fisheries Strategy. The level of spawning rebuild in Queensland was limited by the assumed (status quo) amount of fishing in NSW, given the stock recruitment dynamics was dependent on the level of whole-stock egg production produced in both jurisdictional waters.

Total fishery closures attract significant stakeholder concern and criticism. The South Australian government prohibited the take of Snapper by all sectors in 2020 after significant reductions in spawning biomass. A 2019 stock assessment (Fowler *et al.*, 2019) indicated the reduced spawning biomass was a result of an extended period of poor recruitment, especially in Spencer Gulf. Both fishery dependent and fishery independent indices indicated significant declines in biomass, warranting such a significant management response.



(a) (b)

Figure 3: Spawning biomass ratio estimates based on the nine strategies developed by the Rocky Reef Working Group for the period 1880 – 2040 for a) Snapper and b) Pearl Perch. Descriptions of each strategy are shown in Table 4 and Table 5. Status quo values for depredation, discard mortality, fishing power and the recruitment deviation are shown in Table 8.

A similar situation exists for Snapper and Pearl Perch in Queensland. Declining commercial catch rates of Snapper and Pearl Perch (Wortmann, 2020) and low densities of juvenile Snapper (Bessell-

Browne *et al.*, 2020) are evident in Queensland. Although it is likely that a changing climate is adversely affecting recruitment (Filar *et al.*, 2021), reductions in harvest and effort are required before spawning biomass increases (e.g. Wortmann *et al.*, 2018b). Although a total fishery closure would increase the SBR of these species, there would be little stakeholder support for such an approach.

The development of the MSE tool provides FQ a means to demonstrate the efficacy of a strategy prior to its implementation. Providing the outputs through this tool will allow stakeholders to explore the impacts from different levels of management intervention and enable them to understand if a particular management approach is likely to have the desired effect on stock recovery. Being more transparent through an interactive tool that can be explored by stakeholders may reduce their angst and suspicion around the management changes proposed. While a MSE will not satisfy all stakeholders, it will assist in unpacking the complex factors, influence and impact of management actions that are assessed by fishery managers and stock assessment scientists in developing a rebuilding strategy for a depleted stock.

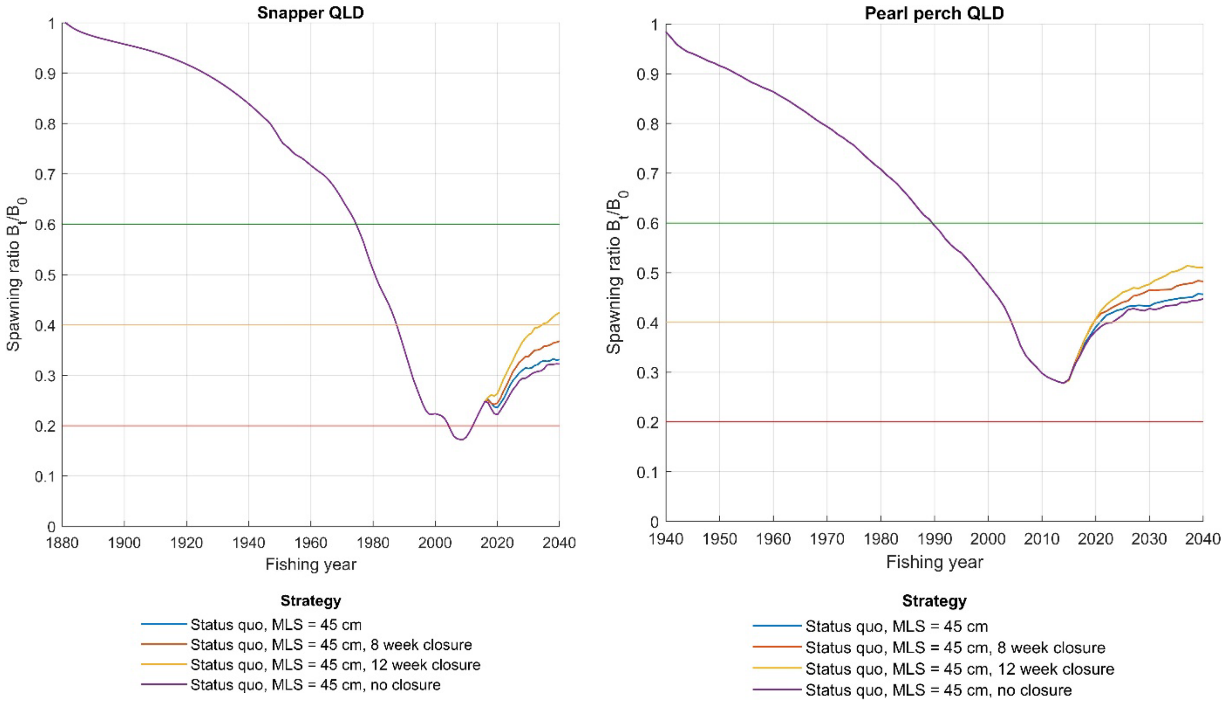
Most fishers understand the need for some protection of a species during spawning, particularly if the species aggregates to spawn. These temporary aggregations often consist of large numbers of fish with the sole purpose of reproduction (Domeier, 2012). The aggregating strategy allows for adults that are dispersed across large areas to come together to maximise fertilisation rates (de Mitcheson, 2016). Further, large volumes of fertilised eggs likely result in lower per capita egg predation rates (de Mitcheson, 2016). However, given the aggregations are predictable in time and space, this reproductive strategy results in increased catchability during the spawning period which may lead to overexploitation or localised depletion (Crisafulli *et al.*, 2019; Sadovy and Domeier, 2005).

In Queensland, many commercially and recreationally important species aggregate to spawn. Species such as Tailor (*Pomatomus saltatrix*), Barramundi (*Lates calcarifer*) and Coral Trout (*Plectropomus* spp.) have spatial and/or temporal spawning closures in place as protection from overexploitation during spawning periods. Where spawning locations are known and discrete, spatial spawning closures may be effective: examples of this include Tailor on Fraser Island and Snapper in Shark Bay, Western Australia. Such a strategy would be inappropriate for Snapper in Queensland, given the geographic and temporal range over which the species spawns (Sumpton and Jackson, 2010).

Pearl Perch exhibit a similar spawning strategy to Snapper in Queensland. Sampling undertaken as part of concurrent FRDC-funded research (2018/074) has demonstrated that Pearl Perch spawn across much of the northern extent of the species' distribution. Although preliminary at this stage, spawning appears to occur in deep water (>150 m) areas offshore of the Sunshine Coast and Fraser Island, as well as areas around the Swains Reef at the southern end of the Great Barrier Reef (M. Campbell, unpublished data).

Although the imposition of spatial closures to protect spawning animals may not be effective in this case, there is evidence that the implementation of marine protected areas (MPAs) has a positive effect on fish abundance and size. In the Solitary Islands Marine Park, offshore from Coffs Harbour in northern NSW, Snapper and Pearl Perch were more abundant and larger in sanctuary zones (i.e., no-take areas) compared to adjacent fished areas (Malcolm *et al.*, 2018). Similarly, Harasti *et al.* (2018) reported an increase in the abundance and size of Snapper within sanctuary zones compared to adjacent partially protected and unprotected areas off the central coast of New South Wales. A number of sanctuary zones were implemented in southern Queensland as part of the Moreton Bay Marine Park review in March 2009, including areas where Snapper are found: however, very little research has been conducted in these areas to assess their efficacy.

Temporal spawning closures are a logical management strategy to protect spawning aggregations. This approach may allow fishers to target other species during the spawning period in areas where Snapper and Pearl Perch spawn such as Grass Emperor and Cobia. The spawning behaviour of Snapper is well-known: sampling undertaken between 1992 and 1995 indicates that Snapper spawn during the period June to September annually (Sumpton and Jackson, 2010). In contrast, very little is known about the spawning behaviour of Pearl Perch. Research undertaken as part of 2018/074 indicates spawning occurs in from March to May off the Sunshine Coast and September to December at the southern end of the Great Barrier Reef. As such, implementing temporal spawning closures for Snapper and Pearl Perch would necessitate separate periods for each species which is not necessarily an easy option to maximise stakeholder understanding and compliance to promote voluntary uptake and support.



(a) (b)

Figure 4: Spawning biomass ratio estimates based on an MLS of 45 cm TL and an increasing spawning closure. All other variables are status quo as shown in Table 4 and Table 5. Status quo values for depredation, discard mortality, fishing power and the recruitment deviation are shown in Table 8. Note the status quo closure duration is four weeks.

Currently, an annual spawning closure is in place for the two species between 15 July and 15 August. This strategy was primarily implemented as a short-term measure to immediately reduce the fishing mortality of Snapper and halt the decline in SBR. This closure is unlikely to protect spawning Pearl Perch: however, given Pearl Perch are caught by both recreational and commercial fishers when targeting Snapper, it will reduce fishing mortality of this species. The MSE indicates that increasing the length of the spawning closure has a positive effect on SBR (Figure 4). The MSE also indicated that the effect of a one-month closure had only a negligible effect on the SBR of both species. This is due to assuming pulse fishing, characterised by increased harvest rates in the weeks prior to, and after, the spawning closure (Table *12*). In the MSE, this pulse fishing is approximated by adjusting harvest rates by $\sqrt{1 + closureMonthFraction}$. That is, the current spawning closure starts on 15 July and, therefore, only 0.5 of the July harvest rates are applicable in that month. However, using the adjustment above, the harvest rate for July in the forecast period is actually $\sqrt{1 + 0.5} \times 0.5 = 0.612$ to represent the effects of pulse fishing prior to the spawning closure. The same applies for the period immediately after the spawning closure ends on 15 August. The actual effect of pulse fishing is difficult to quantify empirically and there is no independent assessment available. Should calm weather occur in the weeks prior to a spawning closure, effort (and harvest rate) is likely to significantly increase. Conversely, poor weather may result in decreased harvest rates prior to the closure.

The MSE indicated that reductions in the recreational bag limit had minimal effect on SBR (Figure 3, Table 13, Table 14). For example, the SBR forecast for Strategy 2 and Strategy 4 were similar for both species despite a 50% reduction in the recreational bag limit. The MSE simulated the application of fish in possession (bag) limits per person in managing Snapper and Pearl Perch: however, further modelling is required to better relate the management benefits of bag limits to changes in recreational fishing effort resulting from adjustments in bag settings and fish abundance. This relationship is undefined and might also be influenced by a range of social and economic factors. Open access fisheries can respond to increases in fish abundance with strong effort responses (Cox and Walters, 2002). Therefore, the management success of changing bag limits may depend on levels of fishing effort. This was not modelled within the current MSE, and initial small bag limit effects might be underestimated given levels of effort were not adjusted accordingly when forecasting procedures were undertaken.

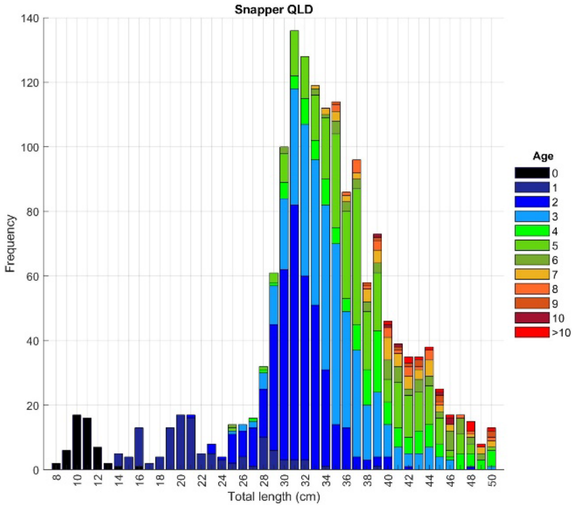
The design of a management framework to better control fishing effort needs more clarity for MSE coding. There is a particular need to consider more regional scales that address fishing quality for both remote and non-remote areas. Failure to recognise open access fishing, such as recreational fishing in Queensland, is a critical oversight in many fisheries' management plans (Cox and Walters, 2002). Improved effort control and allocation might be needed where angling quality or sustainability of fish populations are the main objectives (Cox and Walters, 2002). If a level of effort control can be achieved in the recreational fishery, and simulated in the MSE, the benefits to spawning biomass can be quantified via adjustments of the effort growth parameter (see Table 6).

Recreational fishing is now the primary source of fishing mortality for many Queensland fish stocks, particularly in and around the population areas of the Sunshine Coast, Brisbane, and the Gold Coast. With increasing recreational capacity, open-access recreational fisheries now respond to fish abundance increases with strong effort responses that reduce potential gains in quality of fishing for individual fishers. In Queensland, demand for recreational angling opportunities is likely to increase with human population increase.

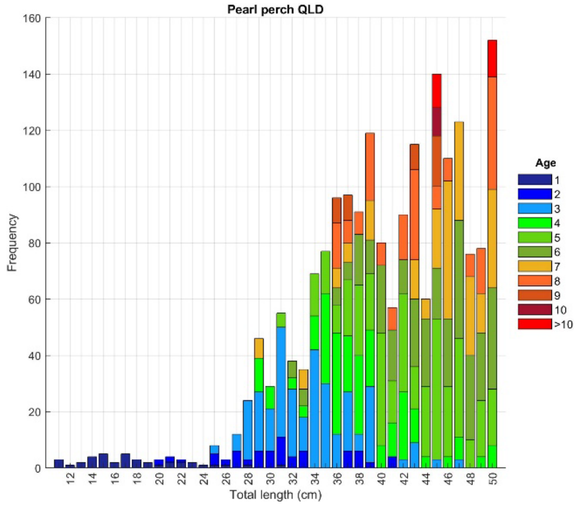
Historically, the usual methods of catch and size limit regulation have not been effective at achieving the simplest management objectives, such as MSY. Policies based on the regulation of individual angler harvests are ineffective as bag and size limits tend to be unrealistically high and low, respectively, and most recreational anglers rarely catch the maximum number of fish allowed. Given the levels of fishing effort applied to some stocks, the actual limits on both catch and size needed to protect fish populations are typically severe and attract significant opposition from stakeholders. Further, the response of recreational fishing effort to fish abundance is problematic. The increase in recreational fishing effort, as a response to perceived increases in abundance, can result in a "success breeds failure" paradigm (Cox and Walters, 2002): short-term increases in fish abundance result in higher effort and potentially higher exploitation until catch rate and angling quality (per angler) declines to the point where no further effort is attracted. As such, management strategies that do not address the open-access nature of recreational fisheries directly, may ultimately fail where angling quality is an objective of management changes.

Direct effort control is needed where angling quality or the conservation of wild fish populations are fishery objectives. However, the implementation of effort control policies is difficult due to: 1) intensive monitoring and enforcement is necessary, 2) access restrictions necessary to improve the quality of angling or protect wild stocks may be severe in some areas, and 3) the sociological and political conflicts that will ultimately arise when effort controls are proposed.

A more practical and acceptable management strategy is an increase in MLS, which had a positive effect on the SBR of both species (Figure 3). This was particularly the case for the Pearl Perch SBR which increased from 27.5% to 48.6% in the 14 years after an increase in MLS to 50 cm (Table 15, page 36). Increasing the MLS results in the protection of more cohorts with the ability to spawn across multiple spawning seasons before recruiting to the fishery (Figure 5). Further, an increased MLS results in the protection of larger, older animals which exhibit exponentially higher fecundity than smaller size classes (Figure 6). An increase in MLS, therefore, results in a larger number of animals spawning a larger number of eggs (Hill, 1990). For example, Ferrell and Sumpton (1997) estimated significant increases in eggs-per-recruit with increasing MLS for Snapper: these authors reported a ~two-fold increase in eggs-per-recruit when MLS increased from 25cm to 35cm, a four-fold increase with an MLS of 45 cm and a six-fold increase with an MLS of 50cm.



(a)



(b)

Figure 5: Length frequency of a) Snapper and b) Pearl Perch from sampling undertaken by Ferrell and Sumpton (1997) and Sumpton *et al.* (2013a), respectively, as a function of age. Note the length frequencies are for fish ≤50 cm TL only. An MLS of 30 cm TL applied to Snapper and an MLS of 35 cm TL applied to Pearl Perch when the respective sampling was undertaken.

An increase in the MLS to, for example, 45 cm for both species will have a significant initial impact on harvest by all sectors in Queensland. Increased size limits will result in fewer animals available for harvest and lower catch-per-unit-effort (Hill, 1990). This is demonstrated by the length frequency distributions of the respective species, both of which are skewed toward the MLS of 35 cm and 38 cm, respectively, particularly for the recreational sector (Figure 7). Fishery-dependent monitoring indicated that 55% of the Snapper caught by recreational fishers in Queensland in 2019 were between the MLS of 35 cm, and 44 cm. Similarly, 31.5% of Pearl Perch caught by recreational fishers in 2019 were between the MLS of 38 cm, and 44 cm. Further, approximately 29% and 28% of commercially harvested Snapper and Pearl Perch, respectively, were between the current MLS and 44 cm in 2019.

Ferrell and Sumpton (1997) showed that modest increases in MLS would result in short-term reductions in yield. For example, these authors estimated that there was a 60% probability of total harvest returning to that in the period prior to an increase in MLS from 25 to 36 cm in two years. This is due to the time required for the population to grow to the new MLS. However, for every year required to reach the new MLS, the number of fish in each age class decreases by approximately 19% as a result of natural mortality (M), where $M = 0.2$, along with an unknown, unavoidable amount of incidental fishing mortality. As such, fewer numbers of larger fish will be caught when the increased MLS is applied.

Recreational fishers generally prefer harvesting a smaller number of larger fish (Beardmore *et al.*, 2015; Ormsby, 2004; Sutton, 2006). For example, recreational anglers surveyed by Ferrell and Sumpton (1997) reported a preference to catch three Snapper weighing one kilogram each rather than six weighing 500 g each. Recreational stakeholders were concerned by proposals to increase the Snapper MLS in response to the Campbell *et al.* (2009) stock assessment. Fishers accessing Moreton Bay, adjacent to Brisbane, felt that they would find it difficult to retain any legal-sized fish for several years if the MLS was significantly increased. In areas where fishing pressure is high, there is significant competition for fish larger than the MLS and increasing the MLS will result in even fewer legal-sized fish being available as a result of natural mortality. In contrast, commercial fishers tend to catch a higher proportion of larger fish (Figure 7).

The harvest of larger fish by commercial fishers is a direct result of increasing fishing power facilitating access to remote areas (Sumpton *et al.*, 2013a). Fishing power is an important factor affecting forecasts of SBR (Figure 8). Sumpton *et al.* (2013b) estimated increases in fishing power in the RRFF between 1982 and 2012 using interviews with commercial fishers. The fishers provided subjective estimates of the effects of a range of technological changes on catches over 30 years. No empirically derived estimates of fishing power in the RRFF are published in the primary literature.

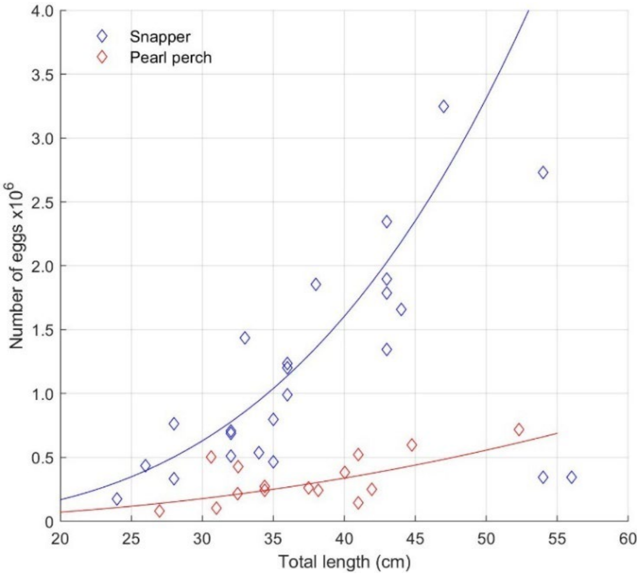
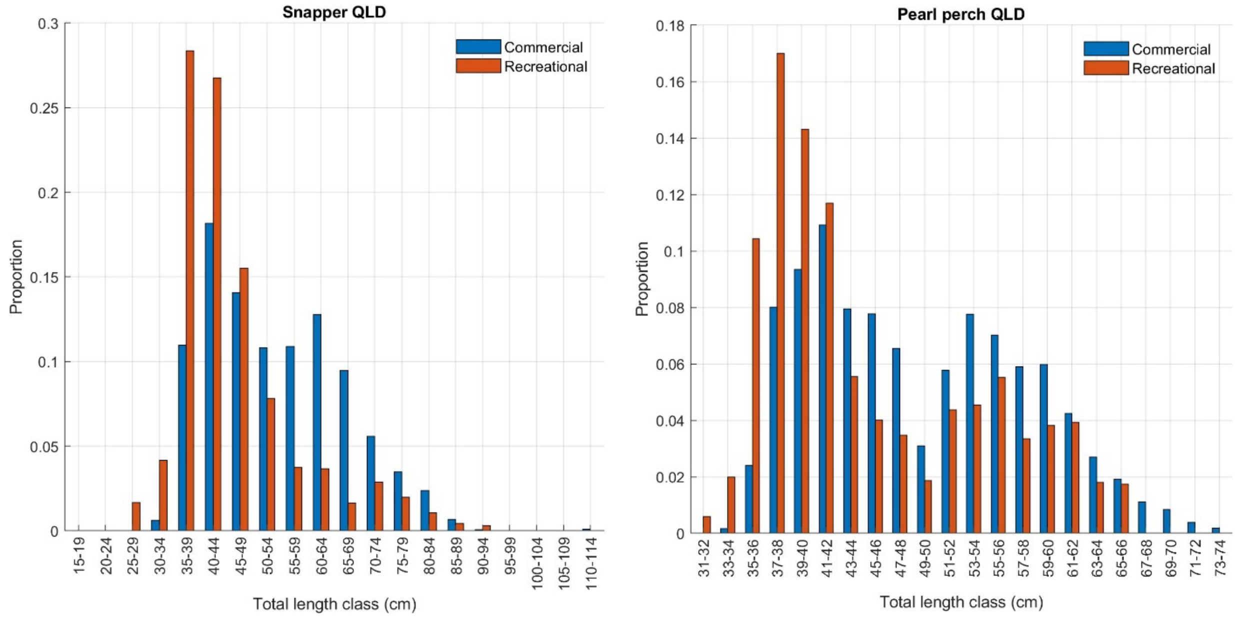


Figure 6: Fecundity of Snapper and Pearl Perch using data obtained by Ferrell and Sumpton (1997) and Sumpton *et al.* (1998), respectively. Solid lines represent mean fecundity as a function of total length.

The change in the length frequency distribution of Pearl Perch harvested by commercial fishers demonstrates the increase in fishing power in the RRFF. Historically, fishers targeted Snapper and Pearl Perch on inshore grounds in southern Queensland. In the mid-1990s, very few (<1%) Pearl Perch >55 cm TL were found in commercial catches (Figure 1a in Stewart *et al.*, 2013). In contrast, 38% of all Pearl Perch caught by commercial fishers in 2019 were >55 cm (Figure 7b). This is a result of fishers accessing grounds to the east and north of traditional fishing grounds. Larger vessels, four-stroke engines, GPS, and increasingly powerful fish-finding equipment have facilitated the shift to these more remote, lightly fished areas. For example, current sonar technology allows fishers to identify likely fishing locations, such as isolated rocks or wrecks, while steaming. Further, the effect of spot-lock electric motors and digital steering for outboard motors, both of which allows the fisher to maintain position without the need to deploy an anchor, remain unquantified. There is a need to empirically derive estimates of fishing power to improve the uncertainty around stock assessment and MSE outputs for Snapper and Pearl Perch.

An increase in MLS is only effective in conserving fish stocks if released fish survive capture and subsequent release (Broadhurst *et al.*, 2005). The published post-release survival (PRS) of Snapper (McLennan *et al.*, 2014) and Pearl Perch (Campbell *et al.*, 2014) are ~90%, suggesting that an increase in MLS is likely to be effective. However, at the most recent RRWG meeting, convened July 13-14 July 2021, members reported an increasing number of sharks predating released fish. Recreational fishers have also reported predation of released fish by dolphins, particularly in Moreton Bay. Predation was excluded from the results reported by McLennan *et al.* (2014) and Campbell *et al.* (2014) and, as such, these results likely overestimate the true discard survival of Snapper and Pearl Perch, respectively. Predation of discarded fish is likely to vary spatially and temporally, making it difficult to quantify a representative value for this metric for use in the MSE. The incorporation of a discard mortality parameter in the MSE allows the user to assess the effect on SBR across a range of discard mortality estimates (Figure 8).



(a) (b)

Figure 7: Length frequency distributions of a) Snapper and b) Pearl Perch harvested by Queensland commercial and recreational fishers in 2019. These data were supplied by Fisheries Queensland's Fishery Monitoring group. Note the Pearl Perch MLS in 2019 was 35 cm TL until September, when the MLS was increased to 38 cm (Table 1).

The RRWG members also reported an increasing number of sharks depredating catches at increasing rates. Depredation is defined as the partial or complete consumption of an animal caught by fishing before it can be landed (Mitchell *et al.*, 2018b). There are no published estimates of depredation rate in the RRFF. As with predation of released fish, estimates of depredation are likely to vary significantly across the fishery making it difficult to quantify a single value of this important metric. While depredation has been studied in other Australian line fisheries (e.g. Mitchell *et al.*, 2019; Mitchell *et al.*, 2018a) further research is required to generate reasonable estimates of depredation rate in the RRFF. Again, the MSE has the flexibility to use a range of values of depredation to assess its effect on SBR (Figure 8).

The long-term sustainability of Snapper and Pearl Perch is likely to be adversely affected by climate-driven reductions in recruitment. Filar *et al.* (2021) recently quantified the effects of environmental variables on the density of pre-recruit Snapper (≤13 cm FL, 3 – 6 months old) caught during Fisheries Queensland's annual fishery independent trawl survey (FIS) conducted in Moreton Bay throughout November and December (see Bessell-Browne *et al.*, 2020 for details). Figure 30 from Filar *et al.* (2021) indicates a significant negative relationship between June sea surface temperature (SST) in the area between Indian Head on Fraser Island and Point Lookout on Stradbroke Island and the density of Snapper pre-recruits caught during the FIS later that year. This, combined with the estimated increase in SST of 0.15ºC per decade (Figure 85 and Table 26 from the same report), will result in a 3.3% decrease in the density of pre-recruit Snapper per decade on current SST trajectories. This is likely due to the optimal temperature at which Snapper spawn: Scott and Pankhurst (1992) reported the optimal temperature range for spawning was 19 – 21ºC. Further, larval survival is likely to be affected by increasing SST (Fielder *et al.*, 2005). Increasing SST will result in a reduction in the period in which the optimal temperature range will occur with concomitant reductions in recruitment. Interestingly, Filar *et al.* (2021) reported that a SST range of 19.8 – 21.8°C in the area between Indian Head on Fraser Island and Point Lookout on Stradbroke Island results in higher densities of pre-recruit Snapper in the FIS. The recruitment of Pearl Perch is likely to be similarly affected: however, this is speculative without FIS data such as those reported by Bessell-Browne *et al.* (2020).

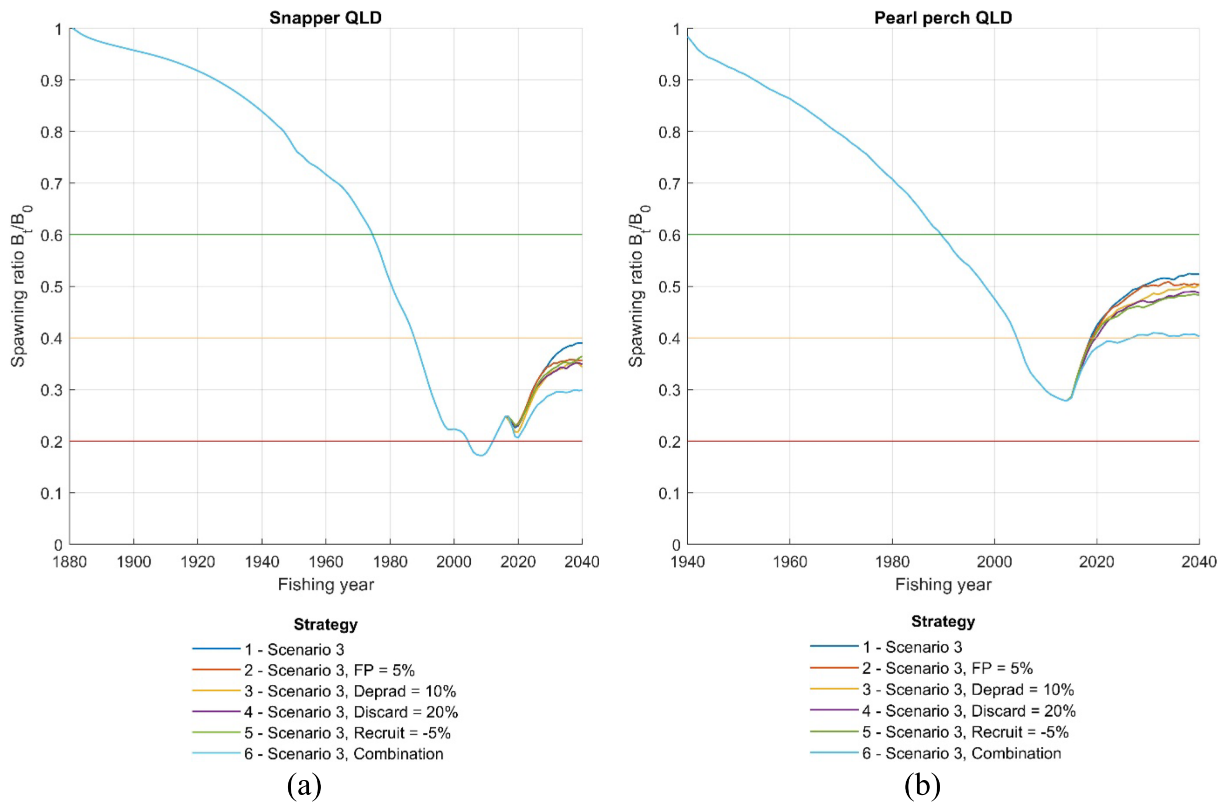


Figure 8: Spawning biomass ratio estimates for the period 1880 – 2040 for a) Snapper and b) Pearl Perch, each with an MLS of 50 cm. The outputs are based on varying the values of fishing power, discard mortality, depredation and recruitment variation shown in Table 8.

Filar *et al.* (2021) reported a significant positive relationship between the density of pre-recruit Snapper and the catch rate of commercially caught Snapper in Queensland four years later. The four-year-old age class is the most abundant cohort in the fishery-dependent sampling undertaken by the Fisheries Queensland's fishery monitoring program[4]. As such, the findings published by Filar *et al.* (2021) indicate that increasing SST will result in decreasing densities of pre-recruit Snapper in Moreton Bay which are indicative of lower catch rates and, by definition, lower abundance of Snapper in southern Queensland.

The decrease of 5% in recruitment tested in the MSE (Figure 8) is clearly an overestimate and we recommend a value of -0.33% per annum for use in future work.

The lack of fishery-independent sampling precludes similar analyses for Pearl Perch. However, it is likely that climate is affecting the Pearl Perch population in Queensland. Historically, the southern-most limit of Pearl Perch was Port Jackson in southern Sydney, New South Wales (McKay, 1997). Recently, Pearl Perch have been observed off the south coast of New South Wales[5,6]. Climate-driven shifts to higher latitudes are well-documented (Gervais *et al.*, 2021; Wernberg *et al.*, 2016) and it is reasonable to expect changes in the distribution of Snapper and Pearl Perch as a result of climate change trends.

Unpublished stock assessments of both Snapper and Pearl Perch indicate a modest recovery of Snapper and Pearl Perch spawning biomass in New South Wales (Fisheries Queensland, unpublished data). The Sustainability of Australian Fish Stocks currently lists Snapper as sustainable in New south Wales and depleted in Queensland, despite the determination that Snapper caught in both jurisdictions are from the same biological stock. Increasing Snapper catch rates in the trap sector, reduced harvest,

[4] https://www.daf.qld.gov.au/business-priorities/fisheries/monitoring-research/monitoring-reporting/commercial-fisheries/species-specific/snapper
[5] https://www.redmap.org.au/sightings/2730/
[6] https://www.naroomanewsonline.com.au/story/3506148/two-very-lost-pearl-perch-show-up-at-narooma/

and increases in the age and size of harvested fish from the commercial sector and increasing age ranges within any given size class, particularly those sizes vulnerable to capture by traps, led to the conclusion that fishing mortality is within sustainable limits.

In a previous FRDC-funded research project (Wortmann *et al.*, 2018a), Queensland and NSW researchers collaborated to, in part, develop protocols for inter-jurisdictional decision-making processes for the east coast Snapper stock. This was proposed to address stakeholder confusion regarding the inconsistent management arrangements employed by the respective jurisdictions despite fishers accessing a shared biological stock. Project staff expected to devise a consistent management strategy across both jurisdictions. However, the diverging trajectories of the stock in the respective jurisdictions, as quantified by the stock assessment conducted during the project (Wortmann *et al.*, 2018b), necessitates the increasingly stringent management measures employed by Queensland fishery managers in recent years.

Similar reasoning will be used to classify Pearl Perch in New South Wales as sustainable in future SAFS reports, despite a shared biological stock. Although improvements in stock metrics indicate a distribution shift for Snapper and Pearl Perch to higher latitudes, this hypothesis is currently unfounded.

4.2 Web Application

Budget savings accrued during the Covid-19 pandemic facilitated the development of a web application (WebApp). The WebApp provided a simple, user-friendly interface with which to conduct the MSE modelling. Unfortunately, the development of the WebApp was hindered significantly due to problems associated with access by Jundra and MathWorks staff to DAF servers and IT protocols. However, the WebApp is a logical enhancement in the MSE modelling process. The WebApp allows users without an expertise in MATLAB® to test a variety of management measures, without the need for statistical modelling, stock assessment and coding knowledge.

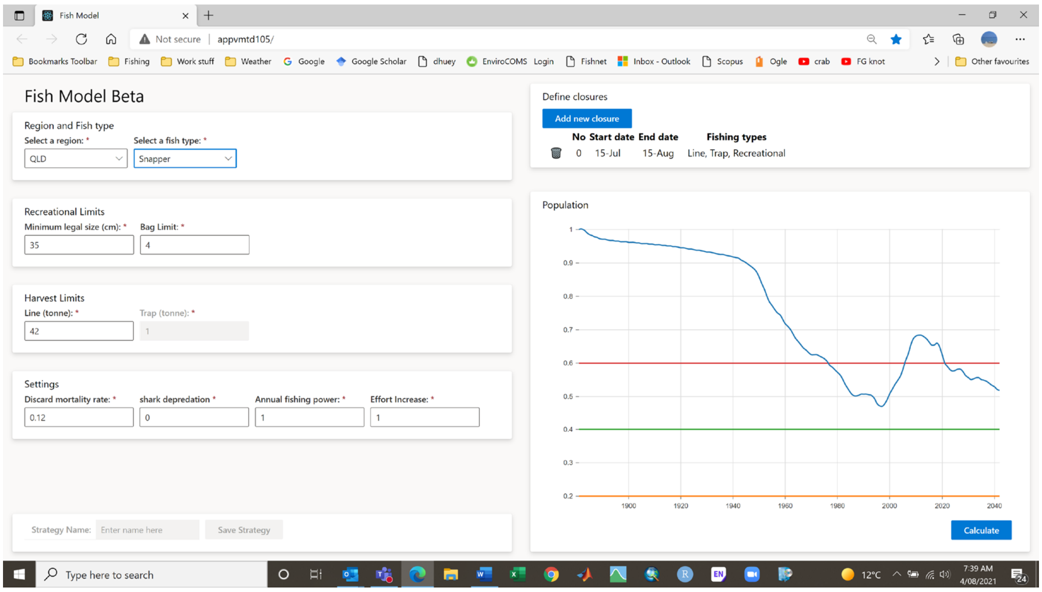


Figure 9: Screenshot of the web application.

The purchase of Production Server™ software facilitated the use of the modelling undertaken in MATLAB® to be utilised by the user with the WebApp as an interface. The WebApp is designed to be simple and self-explanatory (Figure 9). The user is required to choose the region of interest and a species. Various management measures can then be entered into the respective fields. Once the user clicks the calculate button, the MSE is calibrated to the outputs of the stock assessment on which the model parameters are based. All calculations are performed in MATLAB® using its algorithms and functions within the Production Server™ software. The output is a simple line graph displaying the SBR.

Project staff have developed the web application with the built-in flexibility to include species other than Snapper and Pearl Perch. Two species of interest are Spanish Mackerel and Grass Emperor.

4.3 Larval Dispersion

Based on modelling outcomes, we investigated patterns of potential larval connectivity across a selection of distinct areas routinely monitored by QDAFs Long-Term Monitoring Program, which covered the state's entire Snapper fishing ground and more (QLD monitoring areas are highlighted by black polygons in Figure 10). The results for all these 11 different regions indicated that larval dispersal is likely to be widespread, potentially extending beyond the continental shelf edge as indicated by the 200 m depth contour. Similarly, the probability of larval dispersal along the coast might be extensive and bi-directional, such that fish stocks in QLD must be expected to supply recruits to stocks in NSW and vice versa. While the area around Fraser Island might serve as a natural barrier of connectivity (particularly in terms of larval supply from more southern locations to more northern locations), connectivity between South-East QLD and northern NSW is likely to be considerable.

Table 9: Matrix of estimated larval dispersal probability (means ± standard deviations) among Queensland and New South Wales.

	QLD	NSW
QLD	0.023 ± 0.016	0.003 ± 0.001
NSW	0.001 ± 0.002	0.018 ± 0.008

Attempting to clarify potential directional strengths of larval dispersal across state boundaries for consideration in stock assessment models, we calculated mean annual probabilities of larval exchange between 18 putatively representative release locations within 200 m from the coast between Fraser Island, QLD (24.5 degrees South) and central NSW (30 degrees South). We then calculated (1) average proportions of larvae retained at selected release locations within each state, and (2) proportions of locally released larvae that were exported to selected locations in the other state (QLD or NSW).

For future consideration in management strategy evaluation modelling, the resulting mean annual probabilities of larval exchange across dispersal events within a year can be row-normalized and used in sequence or at random, or they can be averaged further across simulation years (from 1997-2012) and row-normalized for use of a single larval dispersal matrix. Results indicated that, on average, local retention of larvae in QLD was 1.2 times higher than in NSW, and that probabilities of larval export from QLD to NSW was 2.4 higher than from NSW to QLD (Table 9). These results are consistent with expectations according to the dominant southward flow direction of the East Australian Current (EAC). However, we note that our estimates of larval dispersal probabilities across state boundaries are based on a putatively biased selection of larval release locations (14 in QLD and 4 in NSW), primarily because (1) spatial layers of rocky reef habitat were unavailable and (2) knowledge of true spawning aggregation areas is incomplete and could not be represented in the model.

4.4 Conclusion

This research allows Fisheries Queensland to make evidence-based decisions regarding the future management of Snapper and Pearl Perch in Queensland. The MSE allows fishery managers to test a range of management approaches on a virtual stock to determine the suite of measures that are most likely to achieve fishery objectives.

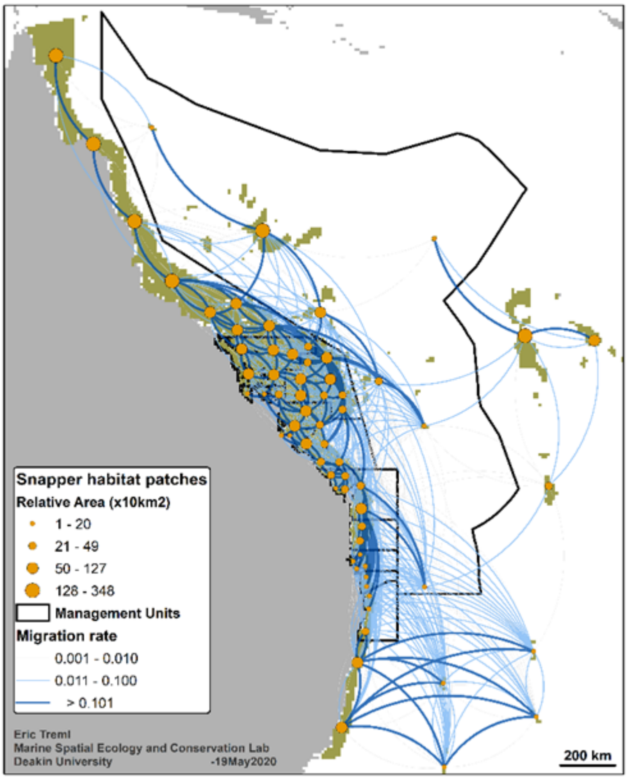


Figure 10: Potential connectivity among 67 hypothetical release locations through the dispersal of fish larvae during the peak spawning period of Snapper in Queensland.

The measures developed by the RRWG in 2019 fail to recover the Snapper and Pearl Perch stocks to the notional MEY (60%) by 2027. While a total closure of the fishery would go some way toward achieving this objective, there would be significant stakeholder concern. Given the state of the spawning biomass of both species, significant management intervention is required to recover these stocks to sustainable levels. Although excessive fishing mortality in the past is likely to have adversely affected stock levels, increasing sea surface temperature and, to a lesser extent, the impacts of depredation on catch and discards is likely to hinder the recovery of these stocks into the future.

The MSE indicates that increasing the length of the spawning closure for these species will have a positive effect on the spawning biomass of Snapper and Pearl Perch into the future. The current one-month spawning closure offers minor benefits to spawning biomass due to the pulse fishing that occurs prior to, and after, the spawning closures. Further, it is important to note that the current closure of 15 July to 15 August is inappropriate as a spawning closure for Pearl Perch, given the species spawns in autumn in southern Queensland, and in summer around the Swains Reef, however practically timing these closures together achieves management objectives.

An increase in minimum legal size has a positive effect on spawning biomass by protecting more spawning animals before recruiting to the fishery. Delaying the age at which these species recruit to the fishery allows larger animals to spawn, which are more productive than younger fish. Such a strategy will result in fewer fish being caught with a higher mean size than those caught prior to the imposition of the increased size limit.

Regardless of the management measures to recover Snapper and Pearl Perch stocks, there is likely to be an increase in the number of fish released by recreational and commercial fishers and these species exhibit high discard survival rates. Fishers are reporting an increase in the predation of released fish by sharks and dolphins. Similarly, depredation by sharks has also increased in recent years. The incidence of predation and depredation is currently unknown and there is an urgent need to quantify this component of fishing mortality, and to assess its impacts on fisher behaviour. Incorporating parameter values for post-release survival and depredation allows for the estimation of their effects on spawning biomass.

The projected increase in SST is a clear threat to the Snapper population in Queensland. Although annual variation will see SST in the optimal Snapper spawning range for some period each year, the length of this period is likely to become shorter assuming the current SST trajectories eventuate. It is likely to become increasingly difficult to implement management strategies for this species that achieve fishery objectives. The effects of SST on Pearl Perch remain unknown.

5. Implications

The primary implication of the development of the MSE tool is Fisheries Queensland's ability to provide evidence-based management decisions. Stakeholders are less likely to accept restrictive management measures without evidence that the changes are likely to achieve fishery objectives. The MSE can demonstrate the effects of proposed management on a virtual stock prior to their implementation. The efficacy of management changes is generally measured against fishery objectives via stock assessments, which are performed years after the changes. The MSE tool, therefore, facilitates the implementation of strategies that are more likely to achieve fishery objectives within prescribed timeframes. As such, management measures can be implemented to achieve fishery objectives rather than implementing restrictions that may not achieve management objectives.

The MSE has been developed with the flexibility to include other species. A significant implication of this research is that potential management changes to a range of species can be evaluated provided stock assessment outputs are available. At present, at least 14 line-caught species are the focus of stock assessments[7] and it is possible to assess the effects of management changes on the spawning biomass of these species.

The MSE indicates that significant management intervention is required to increase the spawning biomass of Snapper and Pearl Perch in Queensland. Any management changes imposed to increase spawning biomass will necessarily result in the release of captured individuals. Given the number of fish released, significant efforts will be required to educate fishers on methods that maximise the survival of released fish.

Although the post-release survival of Snapper and pearl is quantified, the effects of depredation and post-release predation remain unknown. Fishery stakeholders have reported significant increases in the depredation of hooked fish by sharks and increasing predation of released fish by sharks and dolphins. The inclusion of parameters for these metrics in the MSE facilitates the testing of the effects of these components of fishing mortality. Ideally, empirically derived estimates of depredation and predation are required to increase the accuracy of MSE (and stock assessment) outputs. As such, an implication from this research is the need for research to quantify these metrics.

This study implies that significant management intervention is required to recover Snapper and Pearl Perch in Queensland. However, the study conducted by Filar *et al.* (2021) indicates the current SST trajectory is likely to adversely affect the future recruitment of Snapper and a southward shift of the Snapper population is likely. Achieving the management objective of reaching a SBR of 60% by 2027 for Snapper is unlikely to be achieved without a full closure of the fishery. The MSE results suggest that is a more realistic to aim for a SBR of 40%. This target is achievable given the levers available to Queensland fishery managers without the need for complete closure of the fishery. The effects of SST on Pearl Perch remain unknown.

[7] https://www.daf.qld.gov.au/business-priorities/fisheries/monitoring-research/data/stock-assessment-program

6. Recommendations

1. DAF (both Fisheries Queensland and Animal Science) should provide the resources to update the required data inputs used in the MSE at the completion of future stock assessments for Snapper and Pearl Perch.

2. The MSE should be used to assess the potential management changes of other species, particularly those species where significant management interventions are necessary to rebuild spawning biomass. Fisheries Queensland and Animal Science should dedicate resources to this task where required, such as Spanish Mackerel.

3. The current iteration of the MSE achieves the objectives of this project. However, significant improvements are possible in the future. One improvement would be the inclusion of harvest rules for future SBRs following the hockey stick approach consistent with the harvest control rules and preferred harvest strategy approach for other fisheries in Queensland (e.g., the Reef line harvest strategy[8]). A SBR of 60% could trigger a predetermined harvest rule that allows for an increase in the TAC and/or the recreational bag limit to maintain SBR at that level. Similarly, an SBR of 20% would trigger a harvest strategy that restricts fishing mortality in order to increase SBR from that point forward. This would allow future decision making under the harvest strategy transparent, and accessible by fishery managers, the working group and broader stakeholders

4. Resources should be dedicated to educating fishers about maximising the survival of released fish. The RRWG should be engaged to discuss the most efficient methods of extending information to fishers.

5. Following from 4, above, the mandatory use of tools that mitigate the effects of barotrauma, such as release weights, venting tools or Coucum's Cages, should be considered by fishery managers and the working group.

6. The depredation of rocky reef fish should be quantified to increase the accuracy of MSE (and stock assessment) outputs. Fishers are reporting increasing numbers of sharks depredating catches in the RRFF.

7. Following from 4 – 6, above, although the post-release survival of released Snapper and Pearl Perch is quantified, these estimates excluded predation after release. There is a need, therefore, to quantify predation of released fish by sharks and dolphins in time and space to improve post-release survival estimates. Further, there is an urgent need to research methods to best avoid depredation and the predation of released fish.

8. Fishing power has been quantified for the RRFF. However, fishing power change was based on subjective estimates of the effects of a range of technological changes on catches between 1982 and 2012 provided by fishers. There is a need, therefore, to derive empirical estimates of fishing power, particularly with the advent of spot-lock electric motors and digital steering for outboard motors, both of which allows the fisher to maintain position without the need to deploy an anchor. Similarly, the effect of powerful sonar equipment that identify fishable locations when fishers are moving at steaming speed remains unquantified.

9. The larval dispersion model outputs would benefit from the incorporation of spatial layers of rocky reef habitat. Further, knowledge of true spawning aggregation areas is currently incomplete and could not be represented in the model. Efforts should be made to quantify these potential inputs to future larval dispersion models.

[8] https://www.daf.qld.gov.au/__data/assets/pdf_file/0007/1481920/Reef-line-harvest-strategy.pdf

7. Extension and Adoption

The primary method of extending the outputs of this project was through Fisheries Queensland's RRWG. The extension of results at the RRWG meeting, convened on 13-14 July 2021, enabled engagement with a variety of stakeholders. The RRWG was comprised of commercial fishers, recreational fishers, charter operators, a representative of the Great Barrier Reef Marine Park Authority, a representative of New South Fisheries and fishery managers. The Principal Investigator of the current project is also a member of the RRWG and co-investigator, Michael O'Neill, also attended the meeting. It is expected that the RRWG members engage with their networks to extend results broadly. The minutes from the appropriate MSE discussion are presented in Appendix 5 (page 37) and a communique of meeting outcomes can be found at https://www.daf.qld.gov.au/business-priorities/fisheries/sustainable/fishery-working-groups/rocky-reef-working-group/communiques/communique-13-14-july-2021.

A media release, along with Twitter and Facebook posts, were developed for this project (Appendix 6, page 39). However, the Executive Director of Fisheries Queensland declined to approve the release of any media items for this project at that time (email received 30/1/2020). This decision was made primarily due to concerns about stakeholder reaction to potential management strategies, timing associated with announcing broader fishery reform activities, Covid-19 impacts and the Queensland election cycle. As a result, it was proposed that communication and extension of results from this project would be restricted to the RRWG members and relevant fishery managers.

During project development, Facebook was seen as a method of extending results. However, a Facebook post developed for the FRDC-funded research project "Assessing the spawning characteristics and reproductive biology of Pearl Perch (*Glaucosoma scapulare*) in Queensland" (FRDC Project No. 2018/074) received an overwhelming negative response. This was likely due to the implementation of the fishery reforms mentioned above including the imposition of vessel monitoring system (VMS) tracking for line vessels. The proposed changes attracted significant criticism from fishers and resulted in disengagement of some stakeholders and the Department. As such, the use of Facebook as a method of extending project information and results was abandoned.

The MSE has been adopted by Fisheries Queensland and represents a significant benefit in the formulation of future harvest strategies. Harvest strategies are a cornerstone of the Sustainable Fisheries Strategy and define the objectives for each fishery that apply to all fishing sectors. At present, the MSE developed as part of this project is the only operational MSE available to Fisheries Queensland and represents a significant advance in managing the RRFF species.

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Appendices

Appendix 1 – Project staff

Matthew Campbell (Animal Science)	Nils Krueck (UTAS)
Michael O'Neill (Fisheries Queensland)	Syed Hussain (MathWorks)
Ken Taggart (Jundra.)	Peter Brady (MathWorks)
Ali Khorsandian (Jundra)	Branko Dijkstra (MathWorks)

Appendix 2 – Intellectual Property

No intellectual property has been generated from this project. The algorithms used in the MSE modelling remain the intellectual property of MathWorks. Similarly, UTAS retain the intellectual property of the larval dispersion modelling.

Appendix 3 – Equations for simulation and parameters used

Table 10: Equations for simulating the population dynamics per fish species (biological model), where *t* is time in months, in *k* regions and *a* fish age.

Monthly and regional dynamics	**Equation**
Number of fish: $N_{a,k,t} = \begin{cases} R_{a,k,t} & a = 1 \\ \sum_{k'} \mathbf{T}_{\boldsymbol{k,k',t-1}} N_{a-1,k',t-1} \exp\left(-Z_{a-1,k',t-1}\right) & a > 1 \end{cases}$	(1)
Recruitment number of fish – Beverton-Holt formulation: $R_{a=1,k,t} = S_{y-1}/\left(\alpha + \beta S_{y-1}\right) \exp\left(\eta_y\right) \rho_k \phi_{k,t}$	(2)
Spawning index, annual number of eggs: $S_y = 0.5 \sum_k \sum_t \sum_a N_{a,k,t} m_{a,k} f_{a,k}\, \theta_{k,t}$, for the months *t* within fishing year *y*.	(3)
Fish survival: $\exp\left(-Z_{a,k,t}\right) = \exp(-M) \prod_f \left(1 - v_{a,t,f} u_{k,t,f}\right)$	(4)
Recruitment parameters: $\alpha = \frac{S_0(1-h)}{(4hR_0)}$ $\beta = \frac{(5h-1)}{(4hR_0)}$ $R_0 = exp(\Upsilon) \times 10^6$ $h = \frac{r_{comp}}{\left(4 + r_{comp}\right)}$ $r_{comp} = 1 + exp(\xi)$	(5)

Table 11: MSE parameters for Snapper and Pearl Perch respectively.

Parameter	**Equations and values**	**Notes**

MSE inputs				
		Snapper	**Pearl Perch**	
max(a)		41 yr	30 yr	Maximum recorded age from New South Wales and Queensland.
$m_{a,k}$	Maturity-at-age			Estimated outside the model, Snapper and Pearl Perch were generally fully mature by four years of age. Same schedule was assumed in all regions.
	a			
	0	0.079928	0	
	12	0.279339	0.194901518	
	24	0.560638	0.512290227	
	36	0.792298	0.786592475	
	48	0.920448	0.924026849	
	60	0.97385	0.974784989	
	72	0.992213	0.991402344	
$f_{a,k}$	Fecundity-at-age			Calculated by integrating the length-to-fecundity relationship over the growth curve for mean length-at-age with standard deviation, i.e., $f_l = xl^y$.
	x	3.1×10^{-4}	8.9×10^{-5}	
	y	2.984	2.235	
Growth	L_∞	104.366	70.161	Von Bertalanffy growth. Estimated using age and length (in cm) data from New South Wales and Queensland. The estimated standard deviations for length at age are shown. Growth of female and male fish was the same.
	k	0.062	0.151	
	t_0	-2.875	-0.902	
	σ	6.05	5.93	
M	Natural mortality	0.163	0.22	The values were from Hoenig (1983), based on the maximum ages above.
d	Discard mortality	0.12	0.11	Published rates: McLennan *et al.* (2014), Campbell *et al.* (2014).
$\phi_{k,t}$	Monthly recruitment pattern			Aligned to $\theta_{k,t}$
r_{comp}	Recruitment compensation ratio			This parameter was the recruitment compensation ratio (Goodyear, 1977), based on the log scale coefficient $\xi, r_{comp} = 1 + \exp(\xi)$. Set from the stock assessment results. The r_{comp} and the R_0 parameters defined the α and β parameters in the Beveton-Holt function (O'Neill *et al.*, 2018).
$v_{a,t,f}$	Sector/fleet dependent vulnerability, for the logistic equation see Haddon (2001), for the domed equation see (Leigh and O'Neill, 2017).			Trap selectivity was dome shaped with a right asymptote, with four parameters, line selectivity was logistic with two parameters. Set from the stock assessment results. MLS and discard mortality settings were built into the vulnerability schedules.

Parameter	**Equations and values**			**Notes**
MSE inputs				
		Snapper	**Pearl Perch**	
$\theta_{k,t}$	Monthly spawning pattern			Snapper: see Ferrell and Sumpton (1997); Pearl Perch spawning pattern quantified as part of FRDC 2018/074.
	Month	Proportion	Proportion	

	1	0	0
	2	0	0
	3	0	0.33
	4	0	0.33
	5	0	0.33
	6	0.25	0
	7	0.25	0
	8	0.25	0
	9	0.25	0
	10	0	0
	11	0	0
	12	0	0

η_y	Annual log-recruitment deviations	Set from the stock assessment results.
$v_{a,t,f}$	Sector/fleet dependent vulnerability, for the logistic equation see Haddon (2001), for the domed equation see Leigh and O'Neill (2017)	Trap selectivity was dome shaped with a right asymptote, with four parameters, line selectivity was logistic with two parameters. Set from the stock assessment results. MLS and discard mortality settings were built into the vulnerability schedules.
$u_{k,t,f}$	Harvest rate per region-month-fleet	Calculated by converting whole-stock annual harvest rates (from stock assessment results) using historical region-month-fleet harvest data, scaled by u_{scalar}.
Estimated by the model		
R_0	Virgin recruitment (whole-stock)	Estimated on the log scale. R_0 is used to derive S_0 using equations 1 and 3 in Appendix 3 – Equations for simulation and parameters used Table 10.
ρ_k	Fraction of stock recruitment into New South Wales waters.	Estimated with logit link to enable the regional MSE dimensions. Queensland = $1 - \rho_k$
u_{adj}	Harvest rate adjustment	For adjusting harvest rates (fishing mortality fractions) from the annual-whole-stock values into region-month-fleet values. This allowed for scale changes relating to region-month-fleet aspects compared to total whole-stock area values that fish were assumed equally distributed in the stock assessment (Walters and Martell, 2004).

Table 12: Key elements for forecasting.

Features
Future harvest rates: $u_{ktf}^{forecast} = \bar{u}_{ktf}^{historical} \Omega_{inc}^{y} (1 - dp)^{-1} \exp(\epsilon)$

where $\bar{u}$ were the mean harvest rates from the last n years of the historical simulation period, Ω were the annual fishing power × effort growth rates compounded by the number of years y into the forecast, and dp was the adjustment rate for shark depredation (Rabearisoa *et al.*, 2018).

Adjust recreational harvest rates for the bag limit effect; calculation steps are per month:

1. Calculate the current month's exploitable numbers of fish.

$$N_e = \sum N_{a,k,t}\, v_{a,t,f}$$

2. Calculate the month's expected recreational catch rate per person with error.

$\hat{c}^1 = \frac{q_{rec}\Omega_{inc}^{y} N_e (1-dp)^{-1} \exp(\epsilon)}{2.2}$; where q_{rec} is the recreational catchability rate per boat for 2.2 fishers and a per person bag limit of 4 fish, as estimated using Queensland boat ramp survey data.

3. Estimate the un-truncated mean labelled $\hat{c}^2$ for no bag limit effect. This requires optimisation.

Setup initial values to estimate $\hat{c}^2$ for a negative binomial (NB) distribution, with parameters b=4 for a bag limit effect of 4 fish, g=2 for the initial un-truncated mean $\hat{c}^2$, 0.78 was user set for the NB success probability, and catch sequence x = 0:b-1. The optimisation function was:

untrunc = @(g) (b - sum((b-x).*(nbinpdf(x,g,0.78))) - $\hat{c}^1$).^2, and

$\hat{c}^2$=fminbnd(untrunc,0,50); function reference MathWorks (2021).

4. Sum the $\hat{c}^3$ un-truncated catch distribution:

$\hat{c}^3$=sum(nbinpdf(0:100, $\hat{c}^2$,0.78000).*(0:100)) ; function reference MathWorks (2021).

5. Sum the $\hat{c}^4$ catch distribution truncated for the bag limit applied:

$\hat{c}^4$=sum(nbinpdf(0:100, $\hat{c}^2$,0.78000).*min(0:100,bag-limit));

6. Calculate the month's recreational harvest rate u adjustment for the bag limit effect:

$AdjRecUforBagLimit = \hat{c}^4/\hat{c}^3$; estimated every month based on fish abundance N_e.

Commercial TAC:

For each month within the fishing year and region, the retained commercial harvests were tallied. If the TAC was reached before the end of year, then the simulated commercial harvest rates were set to zero to stop fishing for the year. If the TAC was filled mid-month, then the month's harvest rate was adjusted down accordingly. Commercial harvests were calculated for competing harvest rates between other fleets f', by the exploitable biomass adjustment: $\sqrt{\prod_{f'} 1 - v_{a,t,f} u_{k,t,f}}$.

Minimum legal fish total lengths (MLS cm):

Fish vulnerability schedules were adjusted according to the forecast MLS. This was done by calculating the fractions of legal sized fish per fish age-group, using the growth curve and its standard deviation.

Time closures:

Time closures were applied equally to all fleets within a region. A time closure was set by specifying a start and end date. The fraction of days open or closed in a month adjusted the future harvest rates $u_{ktf}^{forecast}$. Pulse fishing pre- and post-closure was considered by $\sqrt{1 + closureMonthFraction}$ effect. For example:

No closure U	ClosureFractionDays	Pulse	U adjusted	ClosureFractionApplied
0.03353957	1	1	0.03354	1
0.020801666	1	1	0.020802	1
0.001657288	1	1	0.001657	1

0.026099119	1	1	0.026099	1
0.043794858	1	1	0.043795	1
0.001471541	1	1	0.001472	1
0.00131473	0.5	1.224745	0.000805	0.612372
0.022404825	0.5	1.224745	0.01372	0.612372
0.042214308	1	1	0.042214	1
0.000296419	1	1	0.000296	1
0.003882318	1	1	0.003882	1
0.041861072	1	1	0.041861	1

Appendix 4 – Supplementary results

Snapper

Table 13: Forecasted Snapper spawning ratio (B_t/B_0, %) for the nine strategies developed by the Rocky Reef Working Group for Snapper. The starting point for each scenario is a spawning ratio of 24.7%, the 'mid' scenario from (Wortmann *et al.*, 2018b). All terms are defined in the caption for Table 1.

Strategy	Description	2027	2040
1	Current management strategy (Status quo)	24.5	24.0
2	Status quo with increase in the MLS to 45 cm	29.6	32.9
3	Status quo with increase in the MLS to 50 cm	33.2	37.7
4	Increase MLS to 45 cm and reduced bag limit to 2	29.4	33.1
5	Status quo with increased spawning closure duration to 2 months	26.5	27.2
6	Increase size limit to 45 cm, increased spawning closure duration to 2 months, reduced bag limit to 2, reduce TAC to 30 t	31.7	36.4
7	Increased spawning closure duration to 3 months, reduce TAC to 30 t	30.3	34.0
8	Increased MLS to 45 cm, reduce bag limit to 2, increase spawning closure duration to 3 months, reduce TAC to 20 t	35.9	41.2
9	Complete closure of the fishery to all sectors	61.9	86.6

Table 14: Forecasted Snapper spawning ratio (B_t/B_0, %) for the three strategies developed by recreational fishing groups to supplement those provided by the RRWG. The starting point for each scenario is a spawning ratio of 24.7%, the 'mid' scenario from (Wortmann *et al.*, 2018b). All terms are defined in the caption for Table 1.

Strategy	Description	2027	2040
1	Current management strategy (Status quo)	24.5	24.0
2	Status quo with increase in the MLS to 40 cm, increase bag limit to 5	27.0	28.9
3	Status quo with increase in the MLS to 40 cm	24.8	26.7
4	Increase MLS to 45 cm, reduce bag limit to 2, increase closure duration to six weeks	28.8	32.3

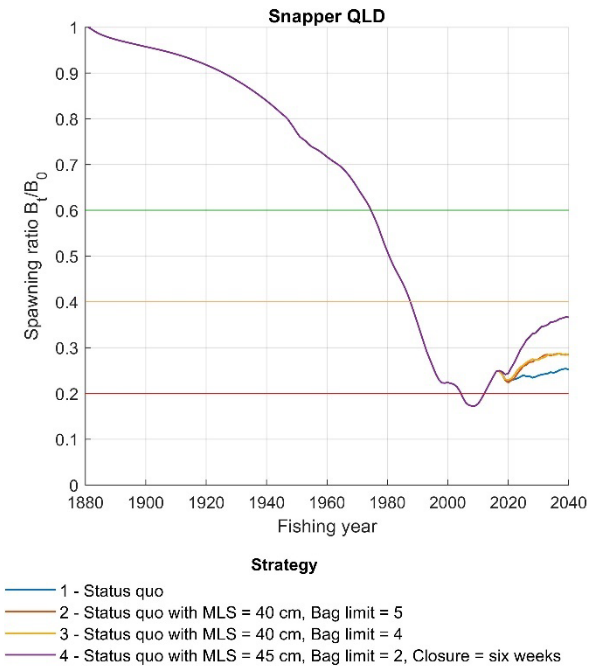

Figure 11: Snapper spawning biomass ratio estimates based on the three supplemental strategies developed by recreational fishers for 1880 – 2040. Descriptions of each strategy are shown in Table 4. Status quo values for depredation, discard mortality, fishing power and recruitment deviation are shown in Table 8.

Pearl Perch

Table 15: Forecasted Pearl Perch spawning ratio (B_t/B_0, %) for the nine strategies developed by the Rocky Reef Working Group for Pearl Perch. The starting point for each scenario is a spawning ratio of 27.5%, the higher scenario from (Sumpton *et al.*, 2017). All terms are defined in the caption for Table 1.

Strategy	Description	2027	2040
1	Current management strategy (Status quo)	37.1	38.0
2	Status quo with increase in the MLS to 45 cm	43.5	46.1
3	Status quo with increase in the MLS to 50 cm	48.6	52.7
4	Increase MLS to 45 cm and reduced bag limit to 2	43.4	45.9
5	Status quo with increased spawning closure duration to 2 months	39.3	40.4
6	Increase size limit to 45 cm, increased spawning closure duration to 2 months, reduced bag limit to 2, reduce TAC to 10 t	45.5	48.5
7	Increased spawning closure duration to 3 months, reduce TAC to 10 t	40.5	43.1
8	Increased MLS to 45 cm, reduce bag limit to 2, increase spawning closure duration to 3 months, reduce TAC to 5 t	47.0	50.6
9	Complete closure of the fishery to all sectors	69.5	85.9

Appendix 5 – Rocky Reef Working Group minutes

The minutes from the RRWG meeting convened on 13 – 14 July 2021 are reproduced below with permission from Fisheries Queensland. These minutes are for the MSE agenda item only.

Animal Science Queensland presented the new FRDC funded Management Strategy Evaluation (MSE) tool that was developed for Queensland's depleted Snapper and Pearl Perch stocks with UTAS, Jundra and MathWorks.

Efficacy of management strategies are generally measured against biomass targets in stock assessments, which generally occurs years after implementation. MSE tests the effects of management on a virtual stock prior to those measures being implemented and is a significantly advanced management tool. A range of outputs from the MSE for a number of different management scenarios were presented to the working group, with outputs representing the median spawning biomass of each species. Management scenarios tested include combinations or size limits, possession limits, closed season time frames, total allowable commercial catches and no change to the current arrangements (status quo).

The MSE indicated that the status quo for Snapper would result in no rebuilding and only minimal rebuilding of Pearl Perch under the most optimistic scenarios over the forecast period. The MSE indicated that only strong management action could result in rebuilding of both stocks over the forecast period. The MSE does not include discard mortality or potentially negative environmental impacts such as warming water temperature. This means the outputs are optimistic and may overestimate the rate of recovery of these stocks.

The MSE focused on the Queensland portion of the East coast stock and modelled predicted impacts of scenarios in monthly time steps. The MSE modelled biomass out to 24 years from the last stock assessment results, which was 2016 for Snapper and 2013 for Pearl Perch. The model can be updated with new stock assessment data once a stock assessment is published. The starting point for the MSE assumed the optimistic scenario from each stock assessment (i.e. where the Snapper biomass was estimated between 10-23% the MSE started assuming a biomass of 23%). The MSE assumes the same current level of fishing effort. The working group was also provided outputs from various cumulative considerations of fishing power, depredation and recruitment variation - modelled separately for the most optimistic MSE scenario. It was noted that at high discard mortality levels (50%) Snapper populations won't recover even if a minimum size limit of 50cm was employed.

The working group asked clarifying questions and discussed various aspects of fisheries management options. It was noted that through management arrangements, the main influence we can have to rebuild stocks is influencing fishing mortality on stocks - we can't control temperature or recruitment strength for example. Some members suggested that a reduced possession limit may shift fishing effort away from the stock (shift fisher behaviour), potentially increasing recovery time (see comment about shifting effort in SWRFS agenda item).

The was also concern raised that large size limits may result in high discard mortality. While the species have high survival rates after release the concern was specifically around post release mortality from dolphins and sharks. The working group considered other ways to help stock rebuild such as reducing post release mortality (from sharks and dolphins) by using a release weight, venting tool and educating fishers in the techniques. It was noted the following video is available online and has been shared via social media last year and this year around the Snapper spawning closure https://www.youtube.com/watch?v=p1wpfXEIZfo and https://www.facebook.com/FisheriesQueensland/videos/327833401719854/?sfnsn=mo&d=n&vh=e.

Some members suggested high catch rates experienced recently are contraindicative of a depleted stock status, however, Snapper is known to be a schooling species and fishers target schools and shoals where fish congregate, creating hyperstability of catch rates. A recreational fishing member suggested management changes were only made recently and they wouldn't expect more changes now to be supported by the sector. A commercial fishing representative suggested commercial fishers moved away from fishing for Snapper due to the stringent, exact numbers, reporting requirements under the TACC since November 2019. The comment was also made that some commercial fishers up to 300km to get away from recreational fishers and sharks (suggesting sharks were more strongly associated with recreational fishers). As such, commercial fishers cannot fish the same areas anymore but that they were seeing fish in deeper colder water offshore (270m of water).

The working group was encouraged to consider the rebuilding timeframes required under the Sustainable Fishing Strategy and consideration of the MSE outputs in developing a harvest strategy for the fishery. Members were asked to provide alternative scenarios for consideration prior to the next meeting.

The working group asked why the large size increase scenario for Snapper (50cm) appeared so successful being one of only two scenarios that reached over 40% biomass in the 24 year time frame. As the average age of Snapper reaching maturity is around 4 years, or approximately 45cm, a larger size limit close to that would provide a greater level of protection for fish to spawn at least once before being susceptible to harvest, and that larger fish can have significantly greater reproductive output than smaller individuals.

The working group sort clarification around consideration of the Queensland portion of the stock only rather than the whole east coast stock (including NSW). There is evidence that enough movement of genetic material occurs north and south for the east coast Snapper stock to be one genetic stock, however, published tagging results show localised populations, and that Snapper display a site fidelity around 2 km on average. While limited mixing occurs around the border, there is limited larval flow northward from NSW back into Queensland. As a result, management arrangements applied in Queensland would affect Queensland stocks, and while it may benefit NSW stocks also, the management of NSW stocks has a limited impact on Queensland Snapper stocks. New research using acoustic tags (IMOS) is expected to begin soon.

Concern was raised about the potential impact of climate change shifting species south and niche filling by other species and regarding trawl impacts on habitat and through bycatch. It was noted trawl bycatch reduction devices are in place, and there has been a significant drop in trawling (50%) recently, and trawlers cannot operate around Peel Island where juveniles are known to occur. Fishery observer work outside Moreton bay has shown little Snapper and few Pearl Perch in catches and none are known from inshore beam trawls either (note previous Action item to get a presentation on T4 trawl bycatch fishery observer results).

The potential for a web-based application of the MSE in future was identified. The working group was again requested to provide alternative scenarios to apply to the MSE.

Appendix 6 – Media release

FOR INTERNAL USE ONLY

Written by: Fidelis Rego

Authorised:

Facebook	**Queensland Pearl Perch and Snapper stocks are currently depleted. So, we're working with the University of Tasmania and software company MathWorks on a computer modelling tool to find out the best ways to manage this fishery. It's all about protecting our fish for the future**
Twitter (240 characters)	**Queensland Pearl Perch and Snapper stocks are currently depleted. So, we're working with the University of Tasmania and software company MathWorks on a computer modelling tool to find out the best ways to manage this fishery**

Queensland Government

Department of Agriculture and Fisheries

XXX January 2020

Computers the right tool to rebuild Queensland fish stocks

Key Points

- A new research project will develop a computer-based modelling tool to improve the management of Queensland's stocks of rocky reef fish like Snapper and Pearl Perch
- Stocks of these fish are currently classified as depleted, and the Queensland government is determined to rebuild this fishery for the future
- The project will be run by the Department of Agriculture and Fisheries, University of Tasmania and software developer MathWorks and is co-funded by the Commonwealth through the Fisheries Research and Development Corporation

Main Story

Researchers are developing a new tool to help improve the management of Queensland's rocky reef fish stocks.

Minister for Agricultural Industry Development and Fisheries Mark Furner said the project would involve his department, scientists from the University of Tasmania and software developer MathWorks.

"At the moment, stocks of rocky reef fish like Pearl Perch and Snapper are classified as depleted in Queensland and we want to rebuild this fishery for our children and their children," Mr Furner said.

"We've already introduced several measures to rebuild stocks including a change to the Pearl Perch size limit, commercial catch limits and a new seasonal closure that runs from 15 July to 15 August.

"But fishery managers need to know how any future reforms could impact fish stocks.

"Through this project, we will develop an interactive computer-based tool that will allow fishery managers to assess how Pearl Perch and Snapper stocks respond to different management arrangements."

Mr Furner said this tool would help ensure Queenslanders will continue to enjoy Snapper and Pearl Perch into the future. "This tool will be based on stock assessment models developed by DAF and MathWorks will enhance these models with an interface to allow the user to vary the management strategy for a particular species to determine the response of the stock to those arrangements," he said.

"The tool will have the capacity to determine the time required for fish stocks to reach sustainable levels depending on the management strategy employed.

"This research will provide fishery managers with a powerful tool with which to make evidence-based decisions to ensure fish stocks are sustainable into the future."

The project is co-funded by the Australian Government, through the Fisheries Research and Development Corporation (FRDC).

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