Developing tools to inform management risk and improve recreational fishery monitoring for a complex multi-sector, multi-jurisdiction fishery: the 'Western Victorian Snapper Stock'

Paul Hamer, Athol Whitten, Khageswor Giri

May 2019

FRDC Project No **2013/201**

ISBN 978-1-76090-121-9 (Print)

ISBN 978-1-76090-126-4 (pdf/online/MS word)

Developing tools to inform management risk and improve recreational fishery monitoring for a complex multi-sector, multi-jurisdiction fishery: the 'Western Victorian Snapper Stock'

2013/201

2019

This publication (and any information sourced from it) should be attributed to:
Hamer, P., Whitten, A., and Giri, K. (2019). ***Developing tools to inform management risk and improve recreational fishery monitoring for a complex multi-sector, multi-jurisdiction fishery: the 'Western Victorian Snapper Stock'.*** **Final Report, FRDC project 2013/201, Fisheries Research and Development Corporation, Canberra.**

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Researcher Contact Details

Name: Paul Hamer
Address: 2a Bellarine Hwy, Queenscliff, Victoria, 3225
Phone: 03 52580111
Fax: 03 52580270
Email: paul.hamer@vfa.vic.gov.au

FRDC Contact Details

Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6285 0400
Fax: 02 6285 0499
Email: frdc@frdc.com.au
Web: www.frdc.com.au

Contents

Tables

Figures

Acknowledgments

This project was supported by funding from the Fisheries Research and Development Corporation and the Victorian Recreational Licence Trust large grants program. We would like to thank all the contributors to the project listed in appendix 1. We are grateful for the cooperation of the Hobsons Bay City Council, City of Greater Geelong, Parks Victoria and Hastings Yacht Club in allowing the installation of boat ramp cameras, and Matt and Stewart from Aussie-Net Solutions Online for their advice on IP cameras and support with camera and image management. Dr Rick McGarvey (SARDI) and Dr Richard Little (CSIRO) provided valuable project advice and review, particularly in supporting development of the MSE modelling framework. We would also like to acknowledge the ongoing support of the creel survey program managed by Simon Conron and supported by funds from the Recreational Fishing Licence Trust and the Victorian Fisheries Authority, and all the survey staff who have contributed to this highly valued program over many years.

Abbreviations

AFMA	Australian Fisheries Management Authority
HCR	Harvest control rule
IP	Internet protocol
MSE	Management Strategy Evaluation
PIRSA	Primary Industries and Regions South Australia
PPB	Port Phillip Bay
PRM	Post release mortality
SARDI	South Australian Research and Development Institute
SnapAsses	Snapper stock assessment model
SnapMat	Snapper recreational size and bag limit management advice tool
SnapMSE	Snapper management strategy evaluation model
SA-MSF	South Australian Marine Scalefish Fishery
SS	Stock Synthesis
VFA	Victorian Fisheries Authority
WPB	Western Port Bay
WVSS	Western Victorian Snapper Stock

Executive Summary

What the report is about

This report involves the 'Western Victorian Snapper (*Chrysophrys auratus*) Stock' (WVSS) which supports arguably the most important marine fin-fish fishery for Victoria. While the majority of the harvest is by Victorian fisheries, this stock is a straddling stock shared with South Australia. This report describes a largely scientific project conducted by the Victorian Fisheries Authority (VFA) in collaboration with fisheries modelling scientists from MEZO Research. The project was initiated in 2013 to address concerns about uncertainty of management risks associated with increased fishing pressure across sectors and jurisdictions, and the inability to track recreational harvest trends and adequately incorporate recreational fishing pressure into stock assessment and management. The report firstly (chapters 1 and 2) describes development of new methods to monitor recreational boat fishing effort and relative harvest trends for the key Snapper fishing areas in Victoria (Port Phillip Bay and Western Port Bay). Secondly (chapter 3) the report describes the development and application of a new simulation tool (management strategy evaluation (MSE) model) for informing management risk, with scenario studies focussing on implications of alternative fishing mortality and recruitment dynamics. Thirdly (chapter 4) a management advice tool that estimates likely effects of size and bag limit changes on recreational Snapper catches is developed and tested on various regulation changes. Finally (chapter 5), the report outlines an MOU agreement between the Victorian (VFA) and South Australian (PIRSA, Primary Industries and Regions South Australia) management jurisdictions to guide cross-jurisdictional collaboration on stock assessment and management issues. This MOU is the first of its kind for a shared fish stock between Victoria and South Australia. The project work was mostly conducted from 2014 – 2018.

Background

Historically the WVSS has been considered a Victorian fishery, with the management risk being primarily due to fishing activities managed under Victoria's jurisdiction. Recent studies have confirmed earlier indications that the stock extends from Wilson Promontory in central Victoria to Kangaroo Is in South Australia, with the main spawning and nursery area being in Port Phillip Bay, Victoria. In the mid-late 2000s commercial harvests from the WVSS in South Australian waters increased dramatically, and at the same time there was a significant increase in harvest by commercial operators under Commonwealth management. Over the 10 years from 2004/05 to 2013/14 more than half the commercial harvest from the WVSS was taken by non-Victorian fisheries. At the same time the stock was recovering after low stock biomass during the 1990s, and the recreational Snapper fishery in Victoria was rapidly growing on the back of the stock recovery.

At the time when catches were peaking during the late 2000s to early 2010s, there had also been consecutive years of lower recruitment detected by fishery independent surveys, and a decline in biomass was expected. There was a perception that the recovered stock was at risk of being quickly depleted (boom-bust) due to growth in fishing pressure but there was no system to inform managers on the risk associated with different levels of fishing mortality and how to actively manage fishing mortality to meet sustainability or performance objectives over the longer term. The new risk posed by the harvests being taken by the Commonwealth and South Australian commercial sectors was concerning for Victorian managers and stakeholders. It was clear that timely management to control overall fishing mortality would be impeded without a defensible scientific framework for informing management risk across sectors and jurisdictions. This project was created to address these concerns by developing analytical tools to support an informed approach to assessing and managing fishing pressure risk, improving monitoring and informed regulation of recreational fishing, and promoting collaborative assessment and management of the WVSS across jurisdictions.

Aims/objectives

1. To provide managers and stakeholders with a robust and transparent approach to harvest management decisions that provides for both biological sustainability and certainty of access,

2. To provide managers with cost effective options for ongoing monitoring of recreational catch and a tool to assist in deciding among different regulatory approaches for managing catches by the recreational sector,
3. To establish a multi-jurisdictional MOU for assessment and collaborative management of the Western Victorian Snapper Stock.

Methodology

The project developed approaches using remote internet protocol (IP) cameras at boat ramps to monitor recreational boat fishing effort in the main Victorian fishing areas of Port Phillip Bay and Western Port Bay, and to integrate the fishing effort data with recreational survey (boat ramp creel survey) data on Snapper catch rates and length compositions to create a 'harvest index' to track Snapper harvest trends over time. The boat ramp camera trial explored two monitoring approaches; time lapse image capture, where an image of the ramp is recorded every two minutes and sub-sampling routines are applied to estimate total effort, and an 'activity sensor' approach, where images are recorded only when certain types of activity are detected (i.e. boat/vehicle movement) within a specified activity area.

A new 'Management Strategy Evaluation (MSE)' modelling tool, 'SnapMSE', utilising the free population modelling framework, 'Stock Synthesis', was created to evaluate management risks and trade-offs associated with different levels of fishing mortality in relation to specified objectives. The application of the SnapMSE in this project involved assessing management risk associated with alternative harvest control rules for managing fishing mortality under scenarios of different recruitment regimes. Recruitment regimes were simulated based on historic recruitment variation estimated for the stock since 1978, and so were realistic of potential future scenarios. Possible management objectives for spawning biomass levels were used to evaluate the performance of the different harvest control rules. A bag and size limit Snapper management advice tool, 'SnapMat', was designed to use recreational creel survey data to predict the impact of changes in bag and size limit regulations on recreational harvest levels for the main Snapper fisheries of Port Phillip Bay and Western Port Bay. Various realistic scenarios of regulation changes were evaluated.

The analytical tools developed utilised 'R', an open source software environment for statistical computing and graphics that is commonly used by scientist worldwide, and have been created so they are accessible to fisheries scientist with moderate experience using R. The MOU agreement between the VFA and PIRSA was developed via numerous phone meetings and a drafting workshop. An operational framework was developed for guiding implementation of the MOU.

Results/key findings

The project demonstrated that IP cameras can be a cost-effective approach for monitoring trends in recreational boat fishing effort, and when combined with creel survey data can be used to monitor trends in targeted Snapper fishing effort, harvest from individual access points (boat ramps) and to derive a recreational 'harvest index' for monitoring trends in recreational Snapper harvest across the fishery. If occasional total recreational Snapper harvest estimates are made using larger scale sampling methods (i.e. phone-diary), the 'harvest index' can be applied to interpolate total harvest estimates in the intervening years. An example of the 'harvest index' approach for the major Snapper fishing month of November and most heavily used Snapper fishing access point in Port Phillip Bay (Patterson River boat ramp) showed that harvest can change substantially at the interannual time-scale due to the combination of changes in effort and catch rates. An ongoing approach and associated costs for monitoring recreational boat fishing effort and Snapper harvest trends was provided. Using the preferred method involving 'activity sensing' software, we estimated that full annual effort coverage of a single ramp with up to three adjacent lanes would cost under $AUD 3,000 including operating costs and depreciation.

The first MSE model framework for a Victorian fin-fish fishery was successfully developed. The evaluation of alternative harvest control rules under high, average and low recruitment regimes, showed that maintaining the annual exploitation rate at around 10-15%, similar to the status quo, was likely acceptable for meeting the trial management objectives applied in this study over the long-term. Both a constant exploitation rate strategy of 10% and Tier 1 style harvest control rule, as applied in Commonwealth fisheries, with a target objective of maximum economic yield, performed similarly.

Further structured application of the MSE framework, in collaboration with stakeholders, is required to inform and develop management planning for the WVSS and test robustness to other uncertainties.

Application of the bag and size limit management advice tool, ‘SnapMAT’, showed that ‘realistic’ regulation changes would have clear potential to reduce recreational retained catches based on recent stock conditions. Choice of the size or bag limit changes, or combined approaches will depend on the objectives of catch reduction. Bag limit reductions had limited impact for the recent stock conditions as few surveyed anglers achieved the bag limits, but greater impacts for an earlier period when catch rates were higher. Increasing LML was predicted to be highly effective at reducing harvest of smaller Snapper, however severe reductions in the bag limit for mature Snapper ≥40 cm (i.e. from 3 to 1) were required, or a slot limit approach, to make significant reductions in recreational retained catch of larger fish.

The MOU between VFA and PIRSA regarding management of the WVSS was signed in October 2018. The first formal cross-jurisdictional MOU meeting is expected to occur in 2019.

Implications for relevant stakeholders

The monitoring, modelling and other analytical tools developed will improve the assessment of overfishing risk on the WVSS and the capacity of managers, policy makers and stakeholders to work together on a planned and informed approach for managing fishing mortality risks, including development of operational objectives. The MOU between and the VFA and PIRSA will ensure ongoing cross-jurisdictional collaboration on assessment and management of the WVSS and provides assurance to stakeholders in each State that the stock assessment is rigorously reviewed and that their interests are considered when each jurisdiction considers management changes.

Recommendations

Boat ramp cameras can produce robust information on fishing effort, however information on catch rates and catch composition is essential for effort to be converted to relative harvests (i.e. harvest index), and for the prediction of impacts of size and bag limit changes. Continuation of boat ramp creel surveys is essential to provide this information, but greater coverage and survey numbers are required to improve the certainty around recreational catch rates and catch compositions. Exploration of other approaches to augment the current weekend creel surveys is recommended, such as a phone app./electronic diary or other online reporting systems. Bias in such ‘opt in’ reporting systems should be assessed by comparison with the randomised creel survey data. Effort data itself can be used as a direct measure of relative fishing mortality for the recreational sector, and the use of an effort index for management could be explored.

For the MSE framework to be utilised for its intended purpose, operational management objectives need to be developed in collaboration with scientists, managers, policy makers and stakeholders. This project was primarily focussed on the development of the new tools to inform management planning, not management planning itself. While the trial objectives applied in this study provide a starting point, a forum for discussion and solidification of management objectives and a management procedure for the WVSS is important, which could be achieved via creation of a WVSS stakeholder reference group.

Expansion of a boat ramp camera system in Victoria will be more likely if they are used to achieve multiple objectives; including effort monitoring for fisheries management, provision of real time information to the public on ramp conditions/launch-retrieval wait times and other safety related information through a web or phone app. platform. VFA could work with other agencies or management bodies involved in boating safety and infrastructure to identify multiple objectives for these systems and explore cost-sharing options to expand coverage and ensure resources are sufficient to maintain systems. Finally, developing predictive models of Snapper angling effort and behavioural response to changes in stock abundance and regulations would be valuable to the better understand the scope for internal self-regulation of recreational fishing impacts on the WVSS.

Keywords

Snapper, *Chrysophrys auratus*, management strategy evaluation, boat ramp cameras, cross-jurisdictional management, western Victorian Snapper stock, recreational fishing effort

Introduction

This project involves the 'Western Victorian Snapper (*Chrysophrys auratus*) Stock' (WVSS) which supports arguably the most important marine fin-fish fishery for Victoria. Port Phillip Bay (PPB) is considered the major spawning and nursery area for the WVSS (Hamer *et al*. 2011) and is where most of the commercial and recreational catch and effort has historically occurred (Coutin *et al.* 2003). However, fishers managed under South Australian (SA) and Commonwealth jurisdiction also extract harvest from the WVSS. The multi-jurisdictional nature of the WVSS was emphasised by FRDC project 2012-020 (*The influence of fish movement on regional fishery production and stock structure for South Australia's Snapper (Chrysophrys auratus) fishery*) (Fowler 2016). This project confirmed the western boundary of the WVSS to be at the western edge of Kangaroo Is./Investigator Strait in South Australia. Snapper harvested from the WVSS in South Australian waters are considered to mostly originate from PPB in Victoria. The recent study supported previous information on the movement of Snapper between Victorian and South Australian waters from tagging and genetic studies (Sanders 1974; MacDonald 1980; Coutin *et al.* 2003). The WVSS is now reported in the 'Status of Australian Fish Stocks' as covering the region from Wilsons Promontory in Victoria, to Kangaroo Is. in South Australia (Fig. 1).

Between 2004 and 2009, commercial Snapper harvests by the South Australian Marine Scalefish Fishery (SA-MSF) from coastal waters off south-east SA increased from 5 tonnes to 225 tonnes per year (Fig. 2). At the same time harvests from the Victorian commercial and recreational sectors were on the increase, and significant harvests were also being taken by Commonwealth licensed operators in Victorian waters (Fig. 2). It was known that the increased harvests were being driven by several strong cohorts originating from spawning in Port Phillip Bay during the late 1990s and early/mid 2000s (Hamer *et al*. 2016). This period of increasing stock abundance represented a significant recovery of the WVSS biomass after an historically poor period during the 1990s (Fig. 2) (Coutin *et al*. 2003). Given the uncertainty of future recruitment, concerns were raised around the overall sustainability of the rapid growth of fishing pressure on the WVSS across sectors and jurisdictions, particularly given that the stock was in a recovering phase. Unconstrained growth in fishing pressure on the recovering stock presented a risk to maintaining higher biomass and satisfactory fishery performance over the longer-term, i.e. risk of 'boom-bust' scenario.

At the time when the catches were peaking during the late 2000s-early 2010s, there had also been consecutive years of lower recruitment detected by fishery independent surveys, and a decline in biomass was expected (Hamer *et al.* 2016). However, there was no system or suitable assessment methods to inform managers on risk associated with different levels of fishing mortality and how to actively manage fishing mortality to specified levels to meet sustainability or performance objectives. Over the period 2004/05-2013/14 over half the commercial harvest from the WVSS was by Commonwealth and South Australian fisheries. This additional new harvest risk was concerning for Victorian managers and stakeholders. It was clear that timely management to control overall fishing mortality would be impeded without a structured system for informing management risk across sectors and jurisdictions. Development of a defensible approach for identifying overfishing risks ideally utilises tools that can a priori inform on the levels of risk associated with allowing various levels of overall fishing mortality. This project was initially developed in 2013 to address these concerns by developing analytical tools to support an informed and defensible approach to managing fishing pressure on the WVSS across jurisdictions and sectors.

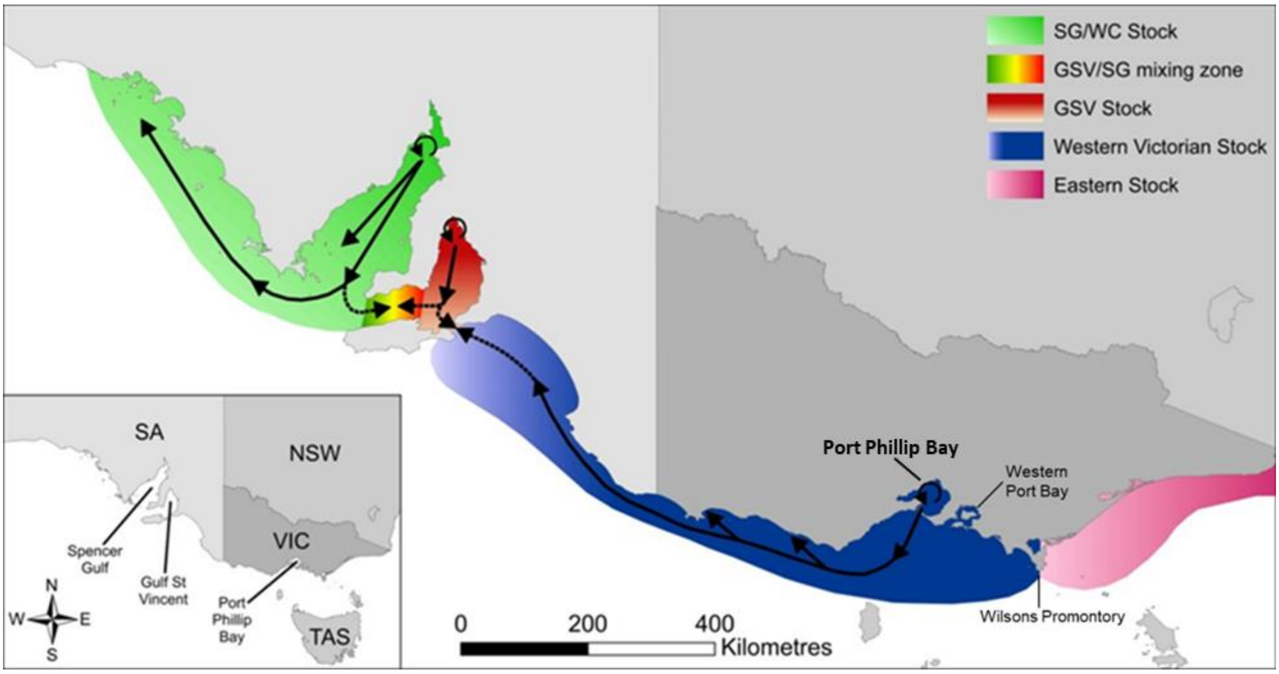


Figure 1 Map of the coast of south eastern Australia showing the stock structure for Snapper concluded from Fowler (2016). The arrows indicate the directions and extent of emigration of fish from the three primary nursery areas in NSG (north Spencer Gulf), NGSV (north Gulf St Vincent) and PPB. Inset shows the broader geographic region. SG- Spencer Gulf, GSV – Gulf St. Vincent, WC – west coast of Eyre Peninsula.

Changing landscape for the WVSS fisheries

Since this project was initiated in late 2013, there have been several changes that have altered the landscape of the WVSS fisheries with important implications for the scope and progress of the original project. In April 2016 the Victorian Labour Government implemented an election commitment to remove all commercial fishing by netting methods from Port Phillip Bay (PPB) by 2022, and to introduce a ‘catch cap’ of 88 tonnes/year for commercial Snapper harvest in PPB. The policy to remove netting and cap Snapper harvests in PPB was directed at improving opportunities for recreational fishing. Commercial fishery entitlements for PPB were reduced from 43 to 10 in April 2016, and by 2022, 8 commercial licences will be permitted to continue operating in PPB using non-net methods. It is expected that primarily hook (long-line) methods will be used in PPB post-2022, with the main target species being Snapper. Prior to 2016 there were no limits on annual commercial Snapper harvest in Victorian waters and no allocation of harvest between the commercial and recreational sectors. Further, prior to the PPB commercial Snapper harvest cap being introduced, a Snapper harvest cap of 35 tonnes (by Fisheries Notice) was imposed in 2012 for the Victorian Inshore Trawl fishery in coastal waters west of Wilson Promontory. This cap was created to limit the perceived potential for growth in the coastal water Snapper harvests by trawl method. These changes in effect established a quasi-allocation arrangement for the WVSS where commercial harvest is mostly capped, and recreational catch is managed primarily using size and bag limits. The capping of harvest by the main commercial Snapper fishery in Victoria negated the objective in the original project around developing a resource sharing framework between the recreational and commercial sectors.

The second change that occurred related to catches by fisheries outside of Victoria’s management jurisdiction. When this project was developed there was concern by Victorian fisheries managers that the Offshore Constitutional Settlement (OCS) was an ineffective instrument for limiting harvest or

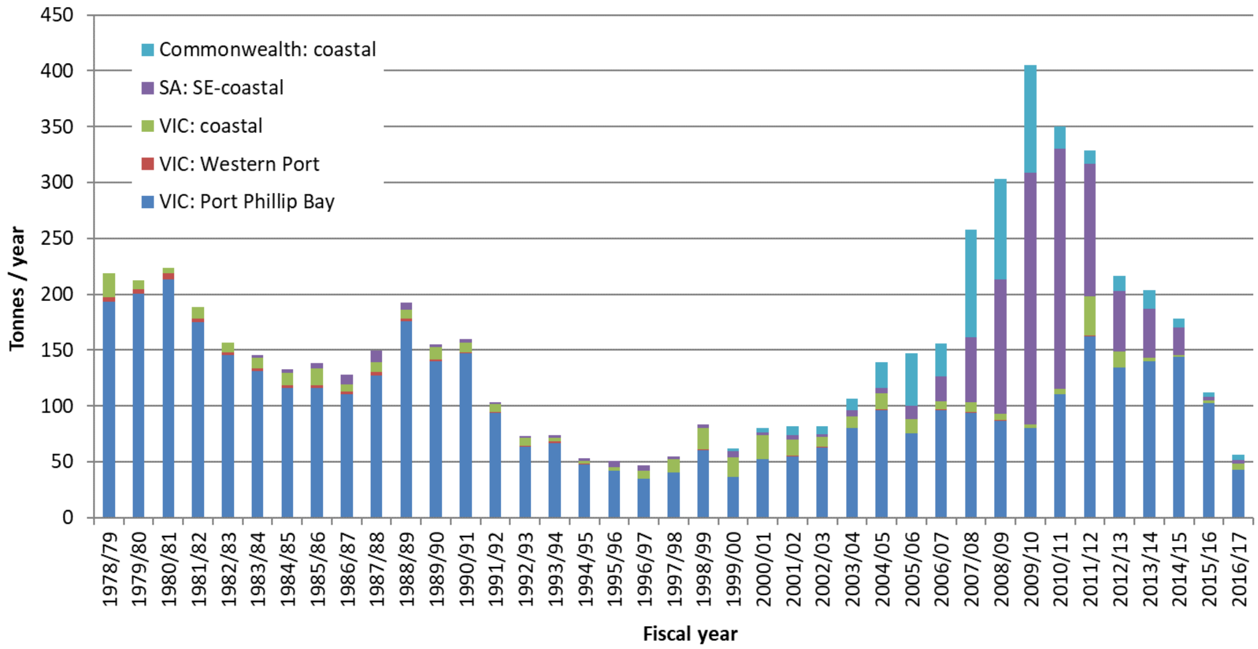


Figure 2 Commercial Snapper harvest across different areas and jurisdictions from the Western Victorian Stock (WVSS) from 1978/79 to 2016/17. **Note: Recreational harvest estimates in 2000/01 and 2006/07 for the Victorian region were estimated at approximately 400 and 660 t respectively** (Henry and Lyle 2003; Ryan et al. 2009). For the South Australian region of the WVSS, the recreational harvests were estimated at between 10-20 t for three recent surveys 2000/01, 2007/08, 2013/14 (Fowler *et al.* 2016).

bycatch mortalities of Snapper due to Commonwealth fisheries. Snapper is considered a State managed species under the OCS, but State fisheries management agencies have no power to directly influence management of Commonwealth licenced fisheries. During the early to late 2000s, Snapper harvest by Commonwealth licensed operators in the WVSS region (including VIC and SA) increased from less than 10 tonnes to approximately 100 tonnes. This level of catch by Commonwealth operators was unprecedented and considered unacceptable by State fisheries managers who began a dialogue with the Australian Fisheries Management Authority (AFMA) and the South East Trawl Fishing Industry Association (SETFIA) to develop approaches to reduce, and more effectively limit, Snapper fishing mortality associated with Commonwealth managed fishing operations. Ultimately, AFMA worked independently with SETFIA to develop and implement industry-imposed trip limits and move on rules to limit Snapper harvest and bycatch mortality. These limits/rules have so far been effective in reduction of the Snapper harvest from the WVSS by Commonwealth licensed operators.

Finally, the third change relates to the SA-MSF. The harvest from the WVSS by the SA-MSF has declined from an unprecedented peak harvest of 225 tonnes in 2009/10, to less than 5 tonnes in 2015/16. This decline was apparently related to reduced allocation of fishing effort to the south-east coastal region of SA by certain effective long-line fishers. The reduced effort is thought to have occurred for reasons mostly independent of fish availability. However, in December 2016 management changes were implemented by PIRSA to provide greater incentive for commercial long-line fishers to fish in the south-east coastal region. These changes were partly related to the finding that Snapper in the south-east coastal region of SA were not part of the Gulf St Vincent or Spencer Gulf stocks, and a desire to promote transfer of effort from the heavily fished Gulfs to lightly fished coastal regions. This was somewhat contrary to the Victorian direction of reduction and capping commercial Snapper harvests from the WVSS. It remains to be seen whether the catches by the SA-MSF in the south-east coastal region will increase again in response to these changes.

Implications of the changing landscape

Initially this project had a significant policy related objective around developing a recommended framework for guiding sharing and allocation decisions, and ongoing governance of harvest sharing across sectors, and the State and Commonwealth jurisdictions. The reductions in harvest pressure from both the SA-MSF and Commonwealth jurisdictions, combined with the Victorian policy to reduce and cap commercial Snapper harvest, particularly in the main fishery of PPB, have meant that the perceived need and desire across the State and Commonwealth management agencies for formal sharing and allocation frameworks has diminished. Therefore, while there is a clear recognition that multiple sectors/jurisdictions have entitlement to harvest Snapper from the WVSS, a less onerous approach than a formal resource allocation framework was preferred by the jurisdictional management agencies. This approach involves developing a memorandum of understanding (MOU) between the Victorian (VFA) and South Australian (PIRSA) management agencies to facilitate and formalise a collaborative approach to assessment and management of the WVSS. The Commonwealth fishery harvests would be continually monitored as part of the assessment process under the MOU, to track the ongoing success of the AFMA-SETFIA arrangements to limit Snapper harvests from the WVSS.

Irrespective of the recent changes to fishery sector allocation in Victoria, and the jurisdictional harvests by South Australian and Commonwealth licenced operators, informed management of overall fishing mortality or ‘harvest risk’ is still critical. What has not changed is the importance of the Victorian recreational fishery, both in socio-economic terms and harvest impacts. Fishing power is also likely increasing due to access to new technologies and fishing gears (technology creep, Marchal *et al*. 2006; Thurstan *et al*. 2018) and information (i.e. social media) to improve catch rates and reliably identify prime fishing times and ‘hot spots’. While reduction and capping of commercial Snapper harvests in Victoria has ameliorated pressure from the recreational sector to cut-back commercial fishing of Snapper, the recreational harvest impacts continue to present the highest risk to the biological sustainability and performance of the WVSS. Understanding management risk remains important, irrespective of which sector is responsible for the fishing mortality. Studies of the replenishment process and recruitment variability for the WVSS (Hamer *et al.* 2011; Black *et al.* 2016) indicate the high vulnerability of this stock to changes in replenishment rates or recruitment ‘regimes’. Ensuring that fishing pressure is managed to allow resilience of the WVSS to recruitment fluctuations is critical for biological sustainability and maintaining the high socio-economic value of the recreational fishery, while ensuring security of the resource for the remaining commercial operators. The original project ‘needs’ to develop approaches for better understanding risk and guiding harvest management decisions is therefore not impacted by the changes in relative sector or jurisdictional harvest pressures discussed above.

Scope

To effectively manage the exploitation of fish stocks to achieve biological, social and economic objectives, many fisheries management agencies have recognised the need to establish defined systems that inform or direct decisions on management of fishing mortality, referred to as ‘harvest strategies’ (Smith *et al*. 2008, 2014; Sloan *et al.* 2014). The use of harvest strategies to guide harvest management decisions is accepted as international best practice (Smith *et al*. 2014; Dowling *et al.* 2015). Development of robust harvest strategies that are likely to deliver on management objectives benefits greatly from being able to make predictions of how a fish stock will respond to various levels of fishing mortality and vulnerability (i.e. size/age composition of harvested fish) over the long-term, and importantly, an understanding of how such predictions may be influenced by various forms of harvest control rules, and uncertainties in biological parameters, data collection, stock assessment procedures and the estimated performance measures (Punt *et al.* 2016).

National guidelines have been developed to help facilitate development of harvest strategies in Australia (Sloan *et al.* 2014). These guidelines provide the important definitions and guiding principles for developing harvest strategies. However, the finer detail and technical aspects of harvest strategies, including decisions on reference points, will require development of analytical tools to compare performance of alternative harvest strategies in meeting objectives under different plausible scenarios of biological, assessment, and management implementation uncertainty. The latter is particularly important for open access marine recreational fisheries where harvest is often managed primarily using "blunt" instruments such as bag and size limits that do not directly control effort, and which are often set 'historically' based on information such as size at first maturity, yield-per-recruit and spawning biomass-per-recruit analysis (Buxton, 1992; Quinn and Szarzi, 1993; Kirchner 2001). Further, it is not common to regularly adjust recreational fishing regulations to manage overall harvests, such as would happen in a commercial fishery managed by quotas. Managing fishing mortality on the WVSS by the recreational fishery is challenging because, as with many recreational fisheries, harvest is not monitored on a regular basis. While empirical estimates of fishing morality can be made using, for example; tagging studies and catch curves, managers really need advice on the implications of different levels of fishing mortality for meeting objectives over the long-term.

A key part of this project is the development of a management strategy evaluation (MSE) modelling framework (Butterworth and Punt 1999; Little *et al.* 2007; Rademeyer *et al.* 2007; Punt *et al.* 2016) underpinned by the 'Stock Synthesis' population modelling framework (Methot and Wetzel 2013). The MSE model we develop in this project is applied to compare management risk under different levels of fishing mortality controlled by alternate harvest management strategies. Trial operational objectives are created to meet biological sustainability requirements, and performance targets for biomass that would be consistent with social and economic objectives. An important focus of the application of the MSE in this study was to evaluate the performance of candidate harvest strategies under different scenarios of recruitment variation, the most important biological uncertainty influencing the WVSS.

Successful application of a harvest strategy requires an informative stock assessment and associated performance indicators that measure management effectiveness in meeting objectives. For recreationally dominated fisheries, the most common information lacking from stock assessments is harvest history. Monitoring total recreational harvest (alternatively referred to as 'retained catch') can be difficult and expensive, and therefore if done at all, it is done sporadically with long periods between estimates (Hartill *et al.* 2016). This leads to uncertainty in assessments due to uncertainty in total harvests, and uncertainty in the effectiveness of management in maintaining harvests at recommended levels. While various approaches such as creel surveys, angler diary, phone apps. etc. can provide information on individual angler catches (i.e. catch rates and length compositions), monitoring "total" recreational harvest and effort is difficult without costly sampling programs (i.e. phone/diary, extensive creel surveys). Finally, effort is the main driver of fishing mortality, and therefore even if harvest is not estimated, effort monitoring can provide a useful index of changes in recreational fishing mortality.

Snapper fishing is largely boat based in Victoria, with the majority of catch and effort for the WVSS occurring in PPB and Western Port Bay (WPB). In this project we trial the use of boat ramp camera systems to cost-effectively measure boat fishing effort and develop a method for the integration of this information with creel survey data on harvest rates and composition to estimate relative change in recreational effort and harvest. The primary goal is to provide indices of variation in effort and harvest that can be used to estimate percent changes in effort and harvest from year to year that could be used to track variation in fishing pressure to inform management risk. If periodic total recreational catch estimates are also provided (i.e. anchor point total harvest estimates), a relative harvest index can allow for a representative interpolation of harvests in the intervening periods (i.e. Hartill *et al.* 2016) to inform stock assessment model predictions of biomass and fishing mortality rates.

Finally, while commercial harvests can be relatively easily influenced by management changes, adjusting open access recreational harvests to meet a desired management change (i.e. catch reduction target) is challenging. To address this, we developed a quantitative prediction tool that uses recent creel survey data to predict the impacts of size and bag limit changes on recreational Snapper harvests from the main fisheries in PPB and WPB. The tool could be applied to other species/fisheries/areas where recent creel survey data are available.

The project has the following objectives:

Objectives

1. To provide managers and stakeholders with a robust and transparent approach to harvest management decisions that provides for both biological sustainability and certainty of access,

2. To provide managers with cost effective options for ongoing monitoring of recreational catch and a tool to assist in deciding among different regulatory approaches for managing catches by the recreational sector,

3. To establish a multi-jurisdictional MOU for assessment and collaborative management of the Western Victorian Snapper Stock.

Note: revisions were made to original objective 3 and the project title.

Original objective 3: To develop a multi-sector, multi-jurisdiction sharing and governance framework, and an associated implementation plan for the western stock Snapper fishery.

The removal of the reference to sharing and governance framework from the original objectives, and formalising of the reference to the stock as the ‘Western Victorian Snapper Stock” in the Status of Australian Fish Stocks reporting, necessitated a change in the project title:

Original title: Development of a harvest management, governance and resource sharing framework for a complex multi-sector, multi-jurisdiction fishery: the south-east Australian ‘western’ Snapper stock

Revised title: Developing tools to inform management risk and improve recreational fishery monitoring for a complex multi-sector, multi-jurisdiction fishery: the ‘Western Victorian Snapper Stock’

The report is structured as stand-alone chapters that can be read independently. Overall outcomes are summarised in a general conclusion section.

Chapter 1: Trial of boat ramp cameras to monitor recreational boat fishing effort

Introduction

Recreational fishing is recognised as an important component of the overall harvests of coastal and estuarine fisheries in many regions of the world (Cook and Cowx 2004; Cooke and Cowx 2006; Ihde *et al*. 2011; Fenichel *et al.* 2013). There is increasing recognition of the need to monitor and include measures of recreational fishing pressure in stock assessment and management (McPhee *et al.* 2002; Post *et al.* 2002; Sutinen and Johnston 2003; Coleman *et al*. 2004; Arlinghaus and Cooke 2005; Lewin *et al*. 2007; Eero *et al*. 2015). The open access and dispersed nature of most recreational fisheries presents challenges for their monitoring (Pollock *et al*. 1994). Monitoring trends in effort and/or harvest, the main direct measures of fishing pressure on stocks, is difficult and expensive, and if done at all, is done on an irregular basis (Hartill *et al*. 2012; Bellanger and Levrel 2017). Occasional total recreational harvest and effort estimates are often used as 'anchor points' in stock assessments with various approaches used to interpolate values for these measures in intervening years (Zeller *et al*. 2008; Swartz and Ishimura 2014; Pauly and Zeller 2016). Interpolation approaches may involve proxies of effort such as population growth, vessel registrations or other general population indicators that might correlate with recreational fishing participation. However, recreational fishing effort in any year is difficult to predict due to the dynamic social and environmental influences on effort. Interpolation based on general population indicators can lead to poorly informed assessments, lack of stakeholder confidence in data, and potentially misleading management advice (Hartill *et al*. 2016). This is particularly the case when recreational effort is a significant or the majority component of the overall fishing pressure (Griffiths and Fay 2015).

While access point or roving creel surveys are commonly used to estimate fishery and stock performance proxies, such as catch rates and size composition, they often lack the sampling intensity and temporal coverage to accurately estimate effort. Advances in remote camera technology and hardware, such as internet protocol (IP) cameras, have made it possible to conduct continuous monitoring of activity at fishery access points such as boat ramps and docks, land-based access points, or even specific on-water locations such as artificial reefs and marine parks (Smallwood *et al.* 2012; Hartill *et al*. 2016; Keller *et al*. 2016; Power and Anson 2016; Askey *et al*. 2018; Harasti *et al.* 2019). IP cameras can upload images to offsite storage and be accessed remotely via mobile network to check operation, adjust settings and manage tasking routines etc. The IP cameras can be programmed to capture and upload images at specific time intervals and periods (time lapse) depending on the requirements/objectives of the monitoring program. In New Zealand, purpose-built (non-IP) boat ramp camera systems have been used to monitor boat fishing effort for more than a decade by capturing images of ramps in time lapse mode (i.e. every minute) and sub-sampling (60 days/year) the image sets to estimate total numbers of boat fishing trips (Hartill 2015; Hartill *et al.* 2016).

The main harvest component from the Western Victorian Snapper Stock (WVSS) is by the recreational boat fishing sector. The inclusion of recreational boat fishing effort and harvest information into stock assessment and management advice is therefore important. Since the mid-2000s there has been a resurgence in the WVSS recreational fishery, partly due to increased availability as the stock has recovered from historic low levels in 1990s, but also likely influenced by improvements in technology, promotion of the fishery and availability of information on how and when to target the species. Fortunately, since the late-1990s an access point boat ramp creel survey program has been conducted focussing on the main recreational Snapper fishing regions of Port Phillip Bay (PPB) and Western Port Bay (WPB). The creel surveys are primarily aimed at collecting catch rate and composition data as indicators of fishery and stock performance, along with various other auxiliary information including avidity, gear, targeting, technology use, demographics and more. These recreational data are invaluable for ongoing stock assessment as commercial sector information is reduced due to reductions in commercial effort from licence buy-backs, however, they do not adequately measure the dynamic impact of the recreational sector in relation to targeted fishing effort on Snapper, which is ultimately the main driver of trends in fishing mortality.

Over the last 20 years there have been two total recreational harvest estimates with suitable coverage for this fishery: 2000/2001 (Henry and Lyle 2003) and 2006/2007 (Ryan *et al.* 2009). These estimates when used as indicative of recreational harvests in intervening years are rightly questioned by stakeholders who argue that recreational effort can vary substantially from year to year due to local dynamics of fish availability, climatic and socio-economic factors. Further, most of the recreational Snapper fishing for the WVSS occurs over a three-month period (October-December) when Snapper aggregate to spawn in the main fishing areas of PPB and WPB. This short fishing season means that weather conditions from year to year can potentially have a strong influence on annual fishing effort and therefore harvest.

This chapter describes a trial study aimed at developing an approach using remote IP video cameras at boat ramps to cost-effectively monitor variation in recreational boat fishing effort. As the majority of the Snapper harvest from the WVSS is taken by boat-based anglers in PPB (Ryan *et al.* 2007), the study focusses on measuring boat fishing effort only, and primarily in PPB, with an additional trial location in WPB. The trial primarily focusses on using time-lapse image capture and sub-sampling approaches with manual (i.e. human based) image classification to estimate the number of boat fishing trips from individual ramps at a monthly scale. However, as new activity sensor functioning became available during the project, we also conduct a pilot study of the 'activity sensor' software as an alternative approach for measuring boat launch effort that can reduce costs related to data transmission and storage requirements, and the need for manual image classification.

In chapter 2 we develop an approach for integrating the boat fishing effort estimates from ramp cameras with creel survey information to create a relative harvest index, and to estimate total harvest amounts from individual ramps at a monthly scale.

Methods

Locations and camera details

Six boat ramp facilities were chosen for the ramp camera trial, five of these (Clifton Springs, Limeburners Point, St Helens, Altona, Patterson River) were in PPB and one was in WPB (Hastings) (Fig. 3). Launch facilities varied in the number of launching lanes, however, at all locations except Patterson River, a single camera head was sufficient to capture all launch lanes (Figs. 4-10). At Patterson River two camera heads were required to capture all lanes (Figs. 6, 7). After consultation with local site managers and camera installation contractors, camera and associated electronics were mounted on available infrastructure at each location rather than installing new poles and/or power supplies. All cameras were in elevated positions out of direct reach by the public and allowed assessment of vessel types (i.e. recreational fishing vessels or otherwise).

Mobotix M24 or M25 IP web cameras were used with lens and modem specifications tailored to each site. Details of camera configurations for each site are included in Table 1. All cameras except the Patterson River camera had 24-hour power from mains supply. At Patterson River, mains power was only available from sunset to sunrise, and power during daylight hours was provided by a 100AH rechargeable battery.

Monthly, daily and hourly patterns of launch activity

For the main study the cameras were programmed to operate in time lapse mode taking and sending an image via 3G/4G mobile network to an offsite FTP server every 2 mins (720 images per camera per day). The 2 min time lapse was chosen after observations by creel clerks of average times taken to launch or retrieve vessels and was expected to capture most launch or retrieval events (later verified by the activity sensor study results). While full field of view images in high resolution were captured every half hour for public web viewing (http://depirampcams.com/), the 2 min images were cropped and transmitted in lower resolution to reduce bandwidth costs. Cropped images were between 80 - 150 KB, while full images were over 500 KB. Image files were named with the following format: camera number_year-month-day_hour_min_second.decimal second, e.g. c02_2015-06-16_08_44_01.643.jpg. Image time stamps were automatically adjusted for daylight savings time by the camera software. The image files were backed up regularly and transferred to external hard drives for analysis and long-term storage.

The objectives of the time lapse study were to:

1. Test camera and image transfer/management systems over a prolonged period (minimum of 2 years),
2. Test and cost manual image processing and vessel activity classification,
3. Describe diel and seasonal patterns of fishing vessel launch/retrieval activity,
4. Develop sub-sampling approaches to estimate total monthly boat fishing trips from individual ramps,
5. Determine costs associated with ongoing operation of ramp cameras to monitor boat fishing effort,
6. Conduct a pilot study of activity sensor software as a more cost-effective method to measure boat fishing effort.

Objective 1 was achieved by observing the operation of the multiple camera systems over more than two years to identify problems that might limit or require improvements for their effective ongoing application for this purpose (e.g. hardware/electronic failures, data transmission reliability, vandalism, ongoing maintenance needs etc.)

Objective 2 involved comparisons of launch and retrieval data from manual classification of vessel activities from all 2 min images at various ramps over selected high and low fishing activity months. One person did over 95% of the image classifications. The images were classified by the observer as launches or retrievals, and vessel classes (i.e. recreational fishing boat, jet ski, kayaks, other vessels). To assist in costing estimations the observer also recorded information on time required to process and classify images and enter data into a spreadsheet.

Objective 3 used the classified 2 min image data to determine patterns of launches/retrievals across 24-hour periods in high and low activity months, weekends and weekdays, and across multiple ramps. This provided baseline data on boat fishing activity that could be used to inform the design of sub-sampling approaches.

Objective 4 utilised the full 2 min classified (i.e. ‘true’) datasets to develop and test the accuracy of different sub-sampling approaches for expanding up to estimate total effort (number of boat fishing trips) at individual ramps at the monthly scale.

Objective 5 was achieved by summarizing indicative fixed annual and variable monthly costs associated with the operation of ramp cameras in this study, and by using the data on time taken to manually process images to estimates image processing costs for different sub-sampling routines. These costings could then be considered along with the error associated with each sub-sampling routine to inform decisions on sub-sampling approach(es) to employ ongoing (i.e. achieve a desired trade-off between accuracy and cost).

Objective 6 Pilot study of activity sensor functioning is discussed separately below.

Exploration of fishing effort patterns

In the first stage of this study a full year (October 2014 - September 2015) of images were manually classified at one launch ramp adjacent to the main Snapper fishing area; camera 4R, Patterson River (Fig. 7). These data indicated the annual dynamic of Snapper fishing effort, confirming that the peak Snapper fishing effort occurred from October-December and the lowest effort occurred from June-August (see results, Fig.11). We then selected a subset of low and high effort months from various ramps to measure total monthly effort by viewing and classifying all recorded 2 min images for the selected months and ramps. This produced monthly data sets to further assess daily (i.e. weekend v weekday) and diel patterns of fishing effort, and how these varied among high and low effort months and locations (see Table 2). High effort months were specified as ‘October-December’ and low were ‘July-August’ (see results, Fig. 11). For these months, launches and retrievals were classified to assess any biases between measuring launches and retrievals with the 2 min time lapse image capture.

Sub-sampling study

Due to the time and cost of manual image classifications, it is desirable to develop sub-sampling approaches that produce acceptable accuracy in estimating the total effort for a specified time period/boat ramp, while requiring far fewer images to be manually classified. Exploration of complete monthly data sets of vessel launch/retrieval activity clearly indicated variation in the amount of fishing effort between weekends and weekdays, and that strong diel variation in fishing effort occurred, particularly during high effort Snapper fishing months. Therefore, inclusion of weekend (WE) and weekday (WD) “i.e. day type” strata into the sub-sampling study, along with variable weighting of the allocation of sub-sampling effort for periods of the day characterised by different levels of fishing effort was considered important.

Several sub-sampling algorithms were developed in R (R Core Team 2017) and applied to the full datasets of fishing vessel launch counts, referred to as the ‘true’ launches data. We used launches as the measure of number of fishing trips as there was a very slight bias towards higher counts of launches than retrievals, although either launches or retrieval could be used (see results, Table 3). We also considered that the application of different sub-sampling routines to estimate boat fishing effort was most useful at the monthly scale for ongoing application due to the strong seasonality of fishing effort and the objective of developing cost-effective indices over absolute annual effort estimation.

The ‘hourly-block’ was used as the unit of sub-sampling to avoid uncertainty around whether an isolated 2 min image shows a launch or retrieval, and to minimise the issue of double-counting from multiple randomly-selected images of the same boat. Thus an “hourly-block” is a set of 30 consecutive images taken every 2 min. There were 2 day-type strata: WD (Mon-Fri) and WE (Sat-Sun), and three x 8-hour diel activity periods: “high effort”: 4 am – 8 am; 4 pm – 8 pm, “low effort”: 8 pm - 4 am, and “medium effort”: 8 am – 4 pm.

Three sub-sampling algorithms/methods were compared:

Method 1:

> *Random Whole Days*: this method randomly selects a specified number of WE and WD days within a month and samples all the “hourly-blocks” within each of the selected days.

Method 2:

> *Random Hours*: this method specifies a number of WE and WD to sample, but the equivalent “hourly-blocks” are randomly selected across all available WE and WD for the month. For example; if 2 x WE and 3 x WD are specified, 48 hourly-blocks are randomly selected across all available WE for the month, and 72 hourly-blocks are randomly selected across all available WD for the month. There is no weighting of the sampling effort for the “hourly-blocks” according to the high, medium or low diel activity periods.

Method 3:

> *Targeted Random Hours*: this method is the same as Method 2 but weights the allocation of the “hourly-blocks” within each day type according to high, low and medium diel activity periods (above). This method effectively allows specification of proportionally higher or lower sampling effort for “hourly-blocks” in the higher, medium or lower effort diel activity periods within each of the day type strata.

Numbers of launches counted in the “hourly-block” sub-samples were then expanded to estimate the total launches for the month. Briefly, the numbers of launches for each hourly-block within each day type stratum was estimated using direct expansion to account for the unsampled fractions of the “hourly-blocks” (Pollock *et al*. 1994; Cochran 1977; Steffe and Chapman 2003). The “hourly-block” totals were then added for the day type strata to estimate the total number of launches for the month.

Precision and bias of the expanded total effort estimates were assessed using 1000 bootstrap simulations of the sub-sampling routines. Bias was calculated as the difference between the mean of the bootstrapped simulation estimates of total effort and the “true” value, and precision was expressed as the standard error of the simulations. The “estimation error” was calculated as the 95% confidence interval around the mean of the bootstrap simulations as a percentage of the mean value. For example: an ‘estimation error’ of 15% indicates that a single point estimate of the total launches using the particular sub-sampling routine would be expected to be within 15% of the true value 95% of the time.

Estimation error = $Y_{SE} \times 1.96 / \bar{Y}$

Y_{SE} = standard error of the bootstrap estimates of total launches

$\bar{Y}$= mean of bootstrapped estimates of total launches

Initial sub-sampling trials compared relative performance of the three sub-sampling methods for two ramps in high and low effort months (i.e. Fig. 9): Camera 4, right ramp– Patterson River, Camera 2 - Limeburners Pt, Figs. 3, 5, 7). This comparison informed the choice of a preferred method for a more focussed study across more ramps and months.

Expanded evaluation of sub-sampling with Method 3: ‘target random hours’

It was shown that *Random Hours* (Method 2) and *Targeted Random Hours* (Method 3) methods performed better than *Random Whole Days* (Method 1). There was a small reduction in estimation error using the *Targeted Random Hours* over the simpler *Random Hours*. For the expanded sub-sampling study the *Targeted Random Hours* approach was used as the preferred sub-sampling approach and two variants of this were compared.

For the *Targeted Random Hours* approach there are 8 hrs of high activity (4 am – 8 am and 4 pm – 8 pm), 8 hrs of low activity (8 pm – 4 am) and 8 hrs of medium activity (8 am – 4 pm) in each 24 hour daily period. Therefore, a ‘high’ (H), ‘low’ (L) or ‘medium’ (M) effort WE or WD ‘equivalent’ = 8 x “hourly-blocks” per day. Weighting of the sampling allocations of “hourly-blocks” to the diel effort groups was compared between two approaches.

SS1: The first *Targeted Random Hours* approach (referred to as SS1) weighted sampling effort for each diel activity period as below:

$nHWD_{effort}$ = (nWD +1) x 8 $nHWE_{effort}$ = (nWE +1) x 8

$nMWD_{effort}$ = (nWD) x 8 $nMWE_{effort}$ = (nWE) x 8

$nLWD_{effort}$ = (nWD-1) x 8 $nLWE_{effort}$ = (nWE-1) x 8

SS2: The second target random hour approach weighted sampling effort for each diel activity period as below:

$nHWD_{effort}$ = (nWD x 2) x 8 $nHWE_{effort}$ = (nWE x 2) x 8

$nMWD_{effort}$ = (nWD) x 8 $nMWE_{effort}$ = (nWE) x 8

$nLWD_{effort}$ = (nWD/2) x 8 $nLWE_{effort}$ = (nWE/2) x 8

$nHWD/WE_{effort}$ = number of hourly-blocks to be randomly sampled for weekdays/weekend days high effort diel period

$nMWD/WE_{effort}$ = number of hourly-blocks to be randomly sampled for weekdays/weekend days medium effort diel period

$nLWD/WE_{effort}$ = number of hourly-blocks to be randomly sampled for weekdays/weekend days low effort diel period

Thus, SS2 allocates proportionally more hours of sampling effort to the high activity diel periods than SS1.

We conducted bootstrap simulations for the SS1 and SS2 approaches for scenarios involving combinations of WE = 2, 3, 4 and WD = 3 - 10. For each scenario 1000 simulations were conducted, and the estimation errors and bias were calculated as the performance metrics to inform cost – accuracy trade-offs for future choice of a sub-sampling method. These simulations were conducted for launch data across 6 ramps and 10 months for low activity months, and 5 ramps and 7 months for high effort months.

Operating costs

Indicative costs for operation of the ramp camera monitoring systems were estimated. In these costings a ramp camera refers to a single camera covering a set of between 1-4 immediately adjacent lanes. The fixed annual costs required to operate the camera systems are indicative and would vary among suppliers and hardware, but cover depreciation, maintenance, web hosting (if required) and image storage/management by an external provider. Variable costs cover the manual image processing and data transmission (bandwith) cost, which will depend on the service provider/mobile data plans, image size and resolution (file size) and sub-sampling regimes. Costings are provided for the approach using 2 min time lapse image captures and manual processing/classification of 30% of images captured per month, which we determined achieved a satisfactory level of accuracy (see results).

Manual image processing times recorded by the image analyst were used to estimate image processing and manual classification costs. The processing time data were recorded as: minutes hourly-block^{-1} and provided a data set of times taken to process hourly-blocks of images across various ramps and high and low fishing effort months. For the individual ramps we determined the maximum, mean and minimum times required to process hourly-blocks of images for high and low fishing effort months. The averages of these values (i.e. average max, average mean, average min) were used to calculate the image processing times required per month for the various intensities of sub-sampling under the SS1 and SS2 *Target Random Hours* methods.

In the calculation of image processing times for SS1 and SS2 sub-sampling methods, it was also important to account for the number of high, low and medium effort hourly-blocks that would be sampled. This was important in determining image processing costs as high effort hours require more processing time (and cost) than low and medium effort hours. For the high effort hours, we applied the average of the maximum processing times observed across ramps, for the medium effort hours we applied the average processing times observed across ramps, and for the low effort hours we applied the average of the minimum processing times observed across ramps. For the high effort months, we also used the 90th percentile values of the maximum, mean and minimum values across the different ramps to provide a likely maximum estimate of processing time and cost requirements. Image processing times for each method were then converted to a cost estimate using an indicative hourly rate of $30/hour for manual image processing

Activity sensor pilot

A pilot study involving the recently developed Mobotix activity sensor software (MxActivitySensor, https://www.mobotix.com/other/Products/Motion-Analysis) was conducted to assess the potential of this technology to monitor boat launch/retrieval activity. The study was conducted at three ramps: camera 1 - St Helens (3 lanes), camera 6 - central and north ramps Altona (2 lanes each), and camera 7 – Hastings (4 lanes) (Figs. 4, 8, 10). These ramps were chosen as they had activity motion paths (i.e. left - right, up – down) of vehicles, and proximity of cameras to ramps that were considered suited to the activity sensor application after advice from the IP camera technicians.

MxActivitySensor is a movement-controlled, software-based image analysis function for detecting movement of objects in a monitored area or "activity zone". Activity zones can be a full image field of view or a user specified region within the field of view. There are adjustable software settings to specify the direction of movement through the activity zone that will trigger an image capture (i.e. left-right, up-down) and sensitivity (threshold). Lower sensitivity is applied for small movements and a higher sensitivity for more obvious movements across longer distances. Delay between recording of new events can also be varied. Activity sensor software works by triggering the camera to record and upload images only when particular movement activities are detected in the defined activity zone. The software works best when the movement is across the activity zone (left – right) or toward/away from the camera (up –down).

For use as a counting tool for specific events, such as boat launches, activity sensing cannot discriminate between movements that are similar, but due to different activities (i.e. a car without a trailer, car with a trailer, person walking across the activity zone etc.). Also, where the time that individual movements take to traverse the activity zone is variable, setting an appropriate delay time can be problematic. This presents a challenge for application of the activity sensor approach to boat launch/retrieval counting where there are lots of vehicle and human movement at the ramp zones, multiple adjacent ramps, and variable durations of individual movement events through the activity zones. A full study would involve experimentally trialling various settings and activity zones, while conducting and measuring controlled movement activities to optimise settings and reduce false triggering. Ideally these studies would be done on a per ramp basis to optimise settings for each camera. Furthermore, getting the best performance from the activity sensor functions depends to a large extent on the optimal position of the camera. In this study we used available poles with suitable camera positions close to ramps with clear and consistent motion paths through the activity zones.

This pilot study took advantage of the 'ground truthed' data on launches from the 2 min time lapse study to compare to activity sensor data. The pilot study specifically aimed to:

1. Assess whether image captures using activity sensor detected all the launch events that were recorded by the 2 min time lapse method,
2. Assess the level of additional events that are triggered/recorded above those of the individual vessel launches/retrievals and categorise these to various activities,
3. Assess the relationships between the total numbers of activity sensor triggers (i.e. image files uploaded) per day and the 'true' data on number of launches per day.

The result of the pilot will inform the potential of activity sensor technology for measuring boat launch activity, and the need for additional studies/infrastructure/approaches to optimise its application. For the selected cameras and months (Table 1b) we compared the numbers of launches classified by the human observer each day for the image sets derived from the 2 min time lapse and activity sensor methods. This indicated whether the activity sensor was recording all the launches that were recorded by 2 min time lapse.

The activity sensor images were classified according to the following categories:

1. Fishing boat launches = individual count of a unique vessel launch (this equates to launches data recorded for analysis of 2 min time lapse images)
2. Fishing boat retrievals = individual count of a unique vessel retrieval (this equates to retrievals data recorded for analysis of 2 min time lapse images)
3. Repeat image of the same boat (additional images of the same vessels being launched or retrieved)
4. Bird
5. Person
6. Car (i.e. vehicle not involved in a boat launch/retrieval)
7. Dog
8. Other (flag, car light, yacht/other vessel, rain, shadow etc.)

These classifications indicated what activities created false triggering and the degree of repeat triggering of the same launch/retrieval events. If false triggers due to events not associated with vessel launches/retrievals were only minor random 'noise' compared to the numbers of vessel launches/retrievals, then the number of events triggered on a particular day (i.e. the total number of activity image files uploaded for a particular day) would be expected to be strongly correlated with the number of launches/retrievals recorded for that day. Linear regression was used to assess the relationships between the total daily image triggers by activity sensor and the true numbers of launches counted from the 2 min time lapse images. Generalised linear regression was used to statistically compare relationships between true launches (dependent) and activity image triggers (predictor) for high and low effort months at three ramps: St Helens, Altona and Hastings. For these comparisons data were Log_{10} transformed to meet assumptions of normality and homogeneity of variances.

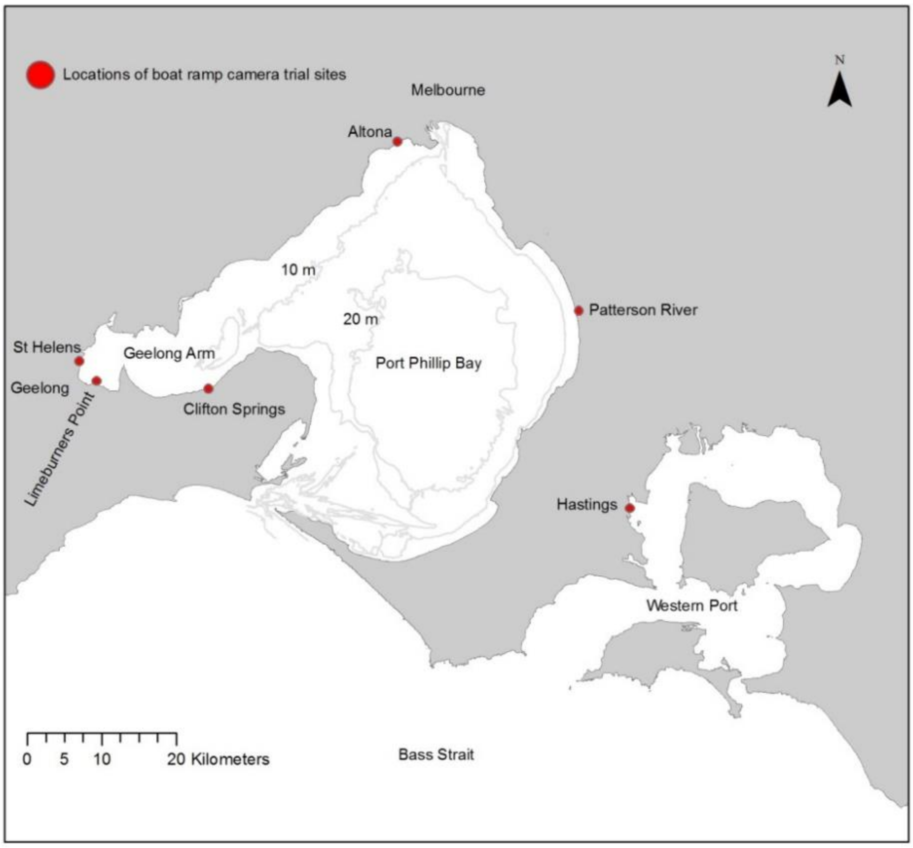


Figure 3 Map of Port Phillip Bay and Western Port Bay showing locations of boat launch facilities where ramp cameras were situated.

Table 1 a) Details of ramp camera set-up and specifications, b) activity sensor study camera locations and specifications.

a)

Location: camera number	**Operational start date**	**Camera model**	**Maximum resolution**	**Lens**	**Field of view**	**Modem**	**Power**
St Helens: Camera 1	1/8/2014	Mobotix M24	3.1MP; 2048 x 1536px	L32 6.0 mm	60^0 H x 45^0 V	3G	24 h mains
Limeburners Pt: Camera 2	14/8/2014	Mobotix M24	3.1MP; 2048x1536px	L43 8.0 mm	45^0 H x 34^0 V	3G	24 h mains
Clifton Springs – Camera 3	14/8/2014	Mobotix M24	3.1MP; 2048x1536px	L22 4.0 mm	90^0 H x 67^0 V	3G	24 h mains
Patterson River: Camera 4	11/9/2014	Mobotix M24	3.1MP; 2048x1536px	L22 4.0 mm	90^0 H x 67^0 V	4G/3G/WiFi	Mains: sunset-sunrise 104 AH Battery: sunrise-sunset
Patterson River: Camera 5	11/9/2014	Mobotix M24	3.1MP; 2048x1536px	L135 25.0 mm	15^0 H X 11^0 V	4G/3G/WiFi	Mains: sunset-sunrise 104 AH Battery: sunrise-sunset
Altona: Camera 6	9/1/2015	Mobotix M25	5MP; 2592x1944px	L25 4.1 mm	90^0 H x 67^0 V	3G/WiFi	24 h mains
Hastings: Camera 7	7/6/2015	Mobotix M25	5MP; 2592x1944px	L23 3.6 mm	103^0 H x 77^0 V	4G/3G/WiFi	24 h mains

b)

Location: camera number	**Activity sensor trial months**	**Activity sensor images classified for activity types**	**Event dead time (s) (delay)**	**Threshold**	**Trigger (motion direction though activity zone)**
St Helens: Camera 1	April-May – June, November 2015	Yes (April-May) No (June, November)	30	30	Left to right
Altona: Camera 6, central ramp	November 2016	No	20	15	Up/down
Altona: Camera 6, north ramp	November 2016	No	20	15	Up/down
Hastings: Camera 7	July, November 2015	Yes (July) No (November)	15	33	Right to left

Figure 4 Images of St Helens boat ramp camera (camera 1) showing; a, b) full camera field of view and c) zoomed view used for time lapse image captures. White box indicates activity zone used for the trial of the activity sensor software.

Figure 5 Images of Limburners Point boat ramp camera (camera 2) showing; a, b) full camera field of view and c) zoomed view used for time lapse image captures.

Figure 6 Images of Clifton Springs boat ramp camera (camera 3) showing; a, b) full camera field of view and c) zoomed view used for time lapse image captures.

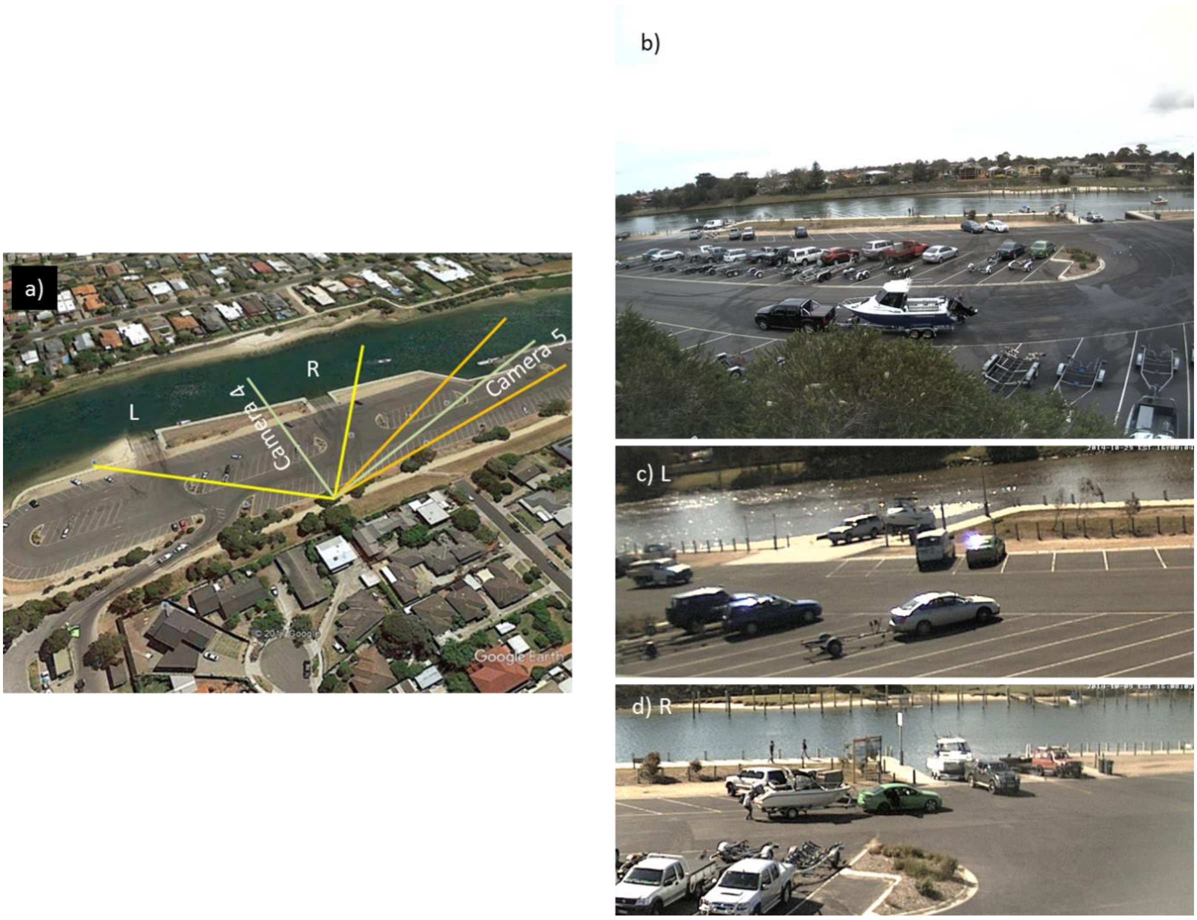


Figure 7 Images of Patterson River boat ramp camera (camera 4) showing; a, b) full camera field of view and c, d) zoomed views used for time lapse image captures.

Figure 8 Images of Patterson River boat ramp camera (camera 5) showing; a, b) full camera field of view and c) zoomed view used for time lapse image captures.

Figure 9 Images of Altona boat ramp camera (camera 6) showing; a, b) full camera field of view (N = north ramp, C = Central ramp, S = south ramp, and c) zoomed view used for time lapse image captures. White box indicates activity zones used for the pilot of the activity sensor software.

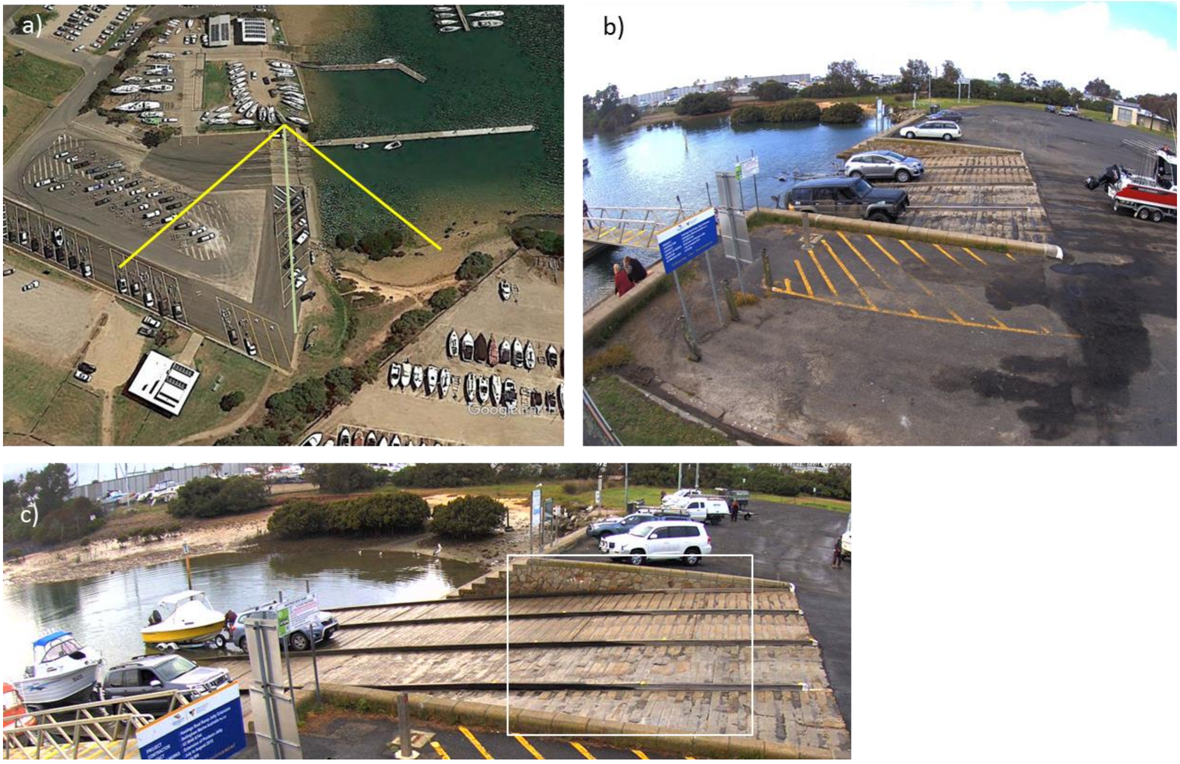


Figure 10 Images of Hastings boat ramp camera (camera 7) showing; a, b) full camera field of view and c) zoomed view used for time lapse image captures. White box indicates activity zone used for the trial of the activity sensor software.

Results

Data summary

A total of 29 months of 2 minute time lapse images across the 6 ramp facilities (28 launching lanes and 7 cameras) were viewed and classified to provide the base data sets for use in the study (Table 2). In addition to this, the 2 minute image sets for one launch ramp were classified for a full 12 month period (Fig. 11), and for two ramps, one month of the activity sensor recorded images were also classified (Table 4). Overall, approximately 1,000,000 images were manually classified for vessel launch and retrieval activity during this study.

Camera reliability

Operation of the Mobotix IP cameras was generally reliable. The main issues were related to occasional periods of image upload failures, which appeared related to bandwidth overloads/intermittent mobile coverage at some ramps. When images failed to upload to the offsite server via the mobile network they were stored in the camera's internal SD card and could be retrieved manually, although our experience was that this did not work perfectly. Hardware issues where minor, involving movement of camera heads, possibly due to roosting by large birds or storm events. For the Patterson River location where a battery was required for daylight power supply, battery replacement was required after approximately 2 years. A delay in replacing the battery resulted in down time for the Patterson River cameras during daylight hours in November 2016. No cameras were deliberately tampered or vandalised and no camera heads failed or required replacement during more than 3 years for any of the cameras, although a fitting failed on one camera head meaning its field of view moved and required manual repair and re-adjustment. Two internal power supplies failed, possibly due to a power surge or spike, and required replacement resulting in extended downtime of the Limeburners

Point and Altona ramp cameras. Installation of UPS units might be required at these locations and would be a worthwhile addition to each camera system (particularly those that require significant travel time for repair technicians) to limit downtime due to power supply issues.

Monthly, daily and hourly patterns of boat fishing activity

The monthly pattern of launch activity at the central ramp at Patterson River (Fig. 7d) for 2014-15 showed a clear peak from October to December, with a secondary smaller peak in February, and very low launches from May to August (Fig. 11). The total launches recorded across 'all' ramps at Patterson River across October, November and December 2014 was 11,485, with 5,485 launches recorded in November alone, compared to 292 in July 2015 (Fig. 11, Table 2). Across various launch facilities and months manual classifications of the number of launches and retrievals were very similar, with a very minor bias overall to counting more launches (Table 2).

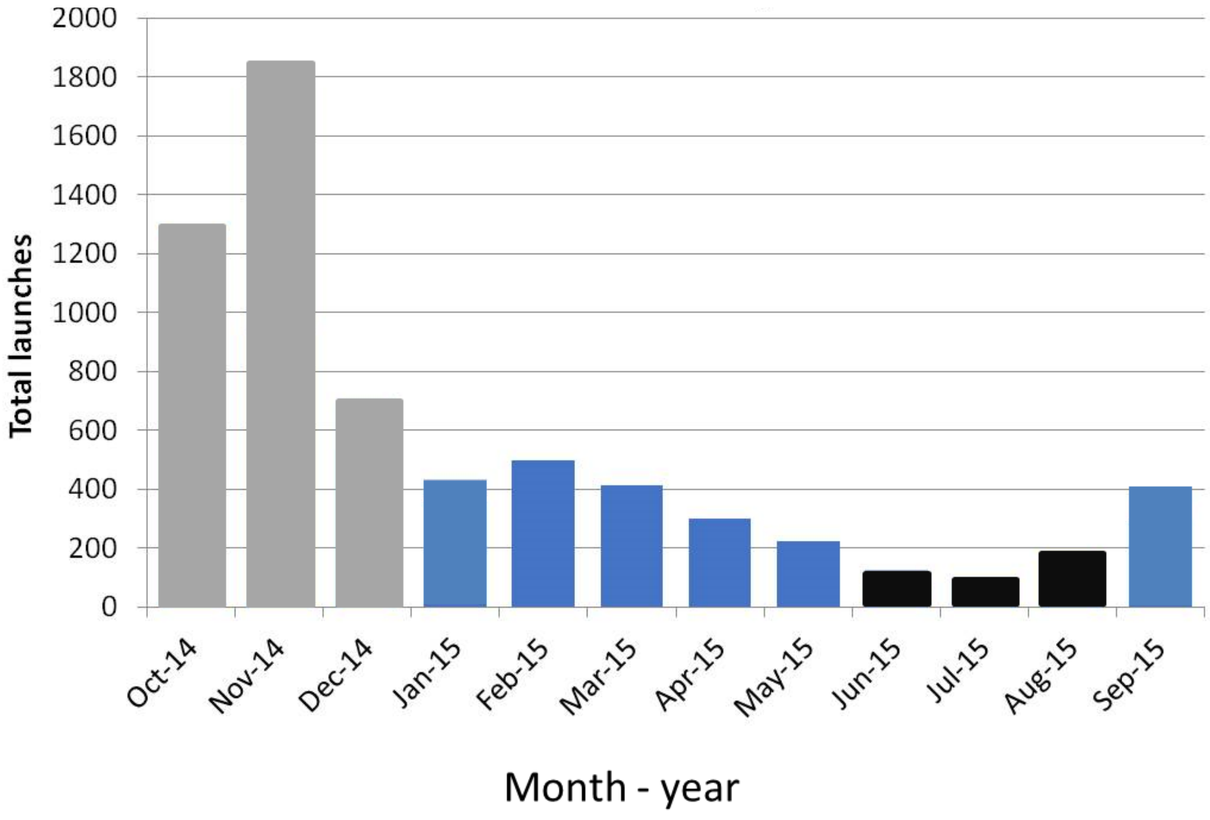


Figure 11 Monthly launches recorded over a 12-month period at the central launch ramp (camera 4R with 3 x launch lanes, see Fig. 7d) at Patterson River (October 2014-September 2015.) Grey bars indicate the high effort months representing the peak Snapper fishing period, black bars indicated the low effort months, blue bars indicate medium effort months.

Table 2 Comparison of monthly total estimates of recreational fishing vessel launches and retrievals from manually classified 2 min time lapse image captures at different boat launch facilities and months. Where multiple ramps occur at a facility the data are summed across all ramps.

Camera	Launch Facility (number lanes)	Month_year	Launches	Retrievals	Ratio of Launch: Retrievals
1	St Helens (3)	Nov_2014	885	886	0.999
1	St Helens (3)	Apr_2015	470	467	1.006
1	St Helens (3)	May_2015	365	352	1.037
1	St Helens (3)	Jun_2015	413	405	1.020
1	St Helens (3)	Aug_2015	244	247	0.988
1***	St Helens (3)	Nov_2015	757	760	0.996
2	Limeburners Pt (3)	Oct_2014	997	960	1.038
2	Limeburners Pt (3)	Nov_2014	933	893	1.045
2	Limeburners Pt (3)	Dec_2014	845	834	1.013
2	Limeburners Pt (3)	Jan_2015	816	838	0.974
2	Limeburners Pt (3)	Feb_2015	564	554	1.018
2	Limeburners Pt (3)	Mar_2015	864	880	0.982
2	Limeburners Pt (3)	Apr_2015	547	571	0.958
3	Clifton Springs (2)	Aug_2015	326	308	1.058
3	Clifton Springs (2)	Nov_2014	1897	1719	1.103
3*	Clifton Springs (2)	Nov_2015	1569	1480	1.060
3	Clifton Springs (2)	Nov_2016	1950	1774	1.099
4,5 (all ramps)	Patterson River (9)	Oct_2014	3938	3816	1.032
4,5 (all ramps)	Patterson River (9)	Nov_2014	5485	5553	0.987
4,5 (all ramps)	Patterson River (9)	Dec_2014	2062	1872	1.101
4,5 (all ramps)	Patterson River (9)	Jul_2015	292	304	0.961
4,5 (all ramps)**	Patterson River (9)	Nov_2015	3990	3964	1.006
6 (all ramps)	Altona (6)	Jan_2015	1141	1108	1.030
6 (all ramps)	Altona (6)	Feb_2015	1819	1842	0.988
6 (all ramps)	Altona (6)	Aug_2015	902	909	0.992
6 (all ramps)*	Altona (6)	Nov_2015	2566	2541	1.010
6 (all ramps)	Altona (6)	Nov_2016	5275	5542	0.952
7	Hastings (4)	Jul_2015	261	243	1.074
7*	Hastings (4)	Nov_2015	1853	1687	1.098
				Average ratio (±SD)	1.021 (0.044)

*missing data between 12-16th due to image uploading issues, ** missing data from 12-13, and 16th due to image uploading issues, *** four days missing due to image data transmission failure.

Diel patterns of launch and retrieval during the peak Snapper fishing month of November showed peaks in launch activity between 4 am and 8 am, and 4 pm and 8 pm at all the monitored ramps except for Limeburners Point where there were less pronounced morning and afternoon peaks, and a slightly later start to peak morning launch activity, and Hastings where there was no afternoon peak (Fig. 12). Peaks in retrievals typically occurred around 5 hours after the peaks in launches, except for Hastings where the peak retrievals were more dispersed across 5-10 hours after the peak morning launch period (Fig. 12 j).

Daily patterns of vessel launch activity showed peaks on weekends at most ramps in the low effort months, however, in the high effort months peaks were more haphazard and occurred both on weekdays and weekends depending on the launch facility (Figs. 13-20 ac). For example, for November at the Patterson River facility peaks in launches could occur on any day of the week (Fig. 16, 17), whereas at the Limeburners Point facility, weekend peaks were consistent in both the high and low effort months (Fig. 14).

Hourly (diel) patterns of launch activity showed clear early morning (4 am-8 am) and late afternoon (3 or 4 pm-8 pm) peaks at all ramps during the high effort months (Fig. 13-20 bd). During the low effort months diel patterns of launches were much flatter with peaks during late morning/midday. For both high and low effort months there were very low numbers of launches during the late night and early hours of the morning (i.e. 10 pm - 3 am). Daily variability in launches for individual hours of the day was notably lower for the low effort months than the high effort months (Figs. 13-20 ef).

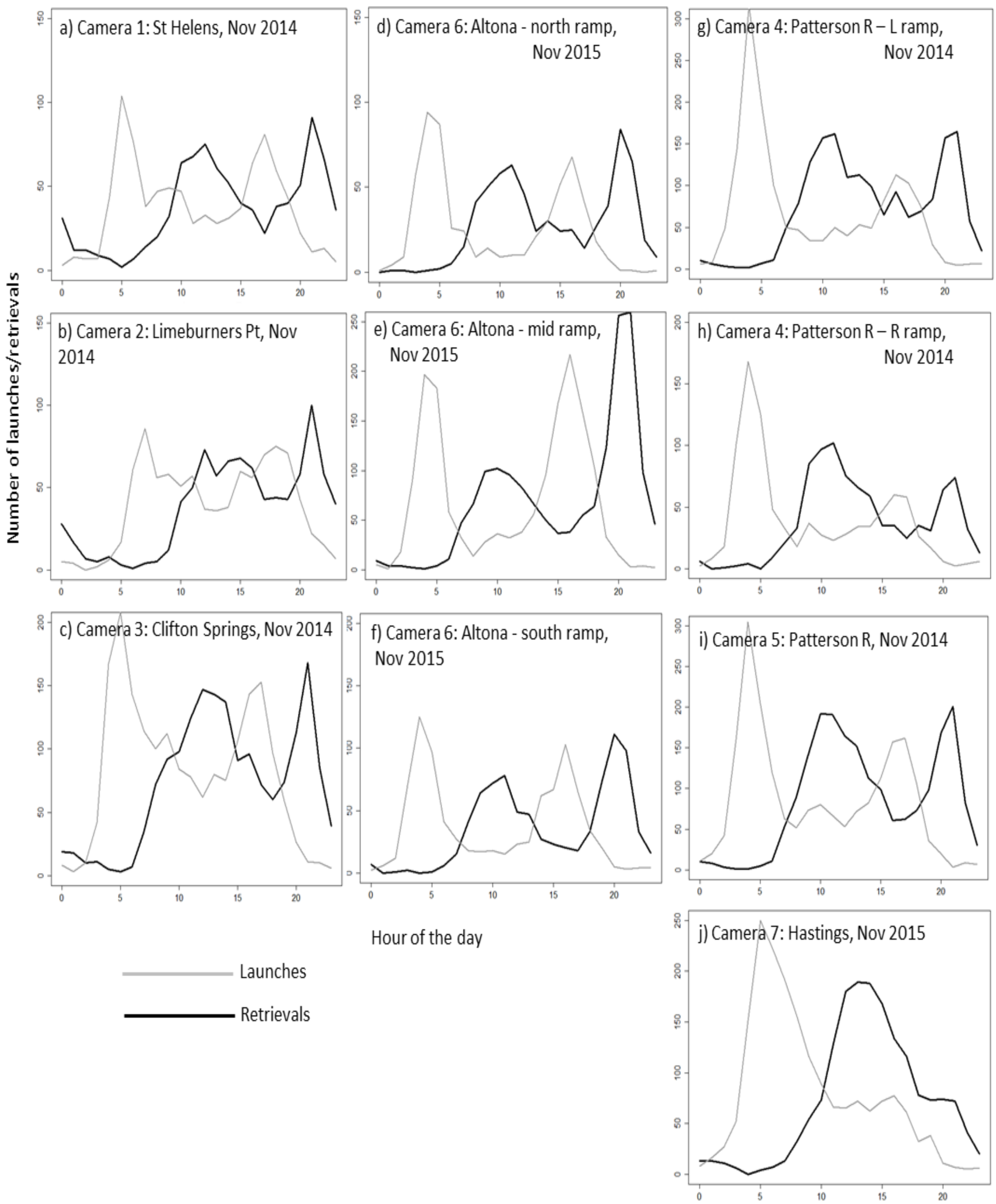


Figure 12 Diel patterns of launches and retrievals at boat ramps during the peak Snapper fishing month of November.

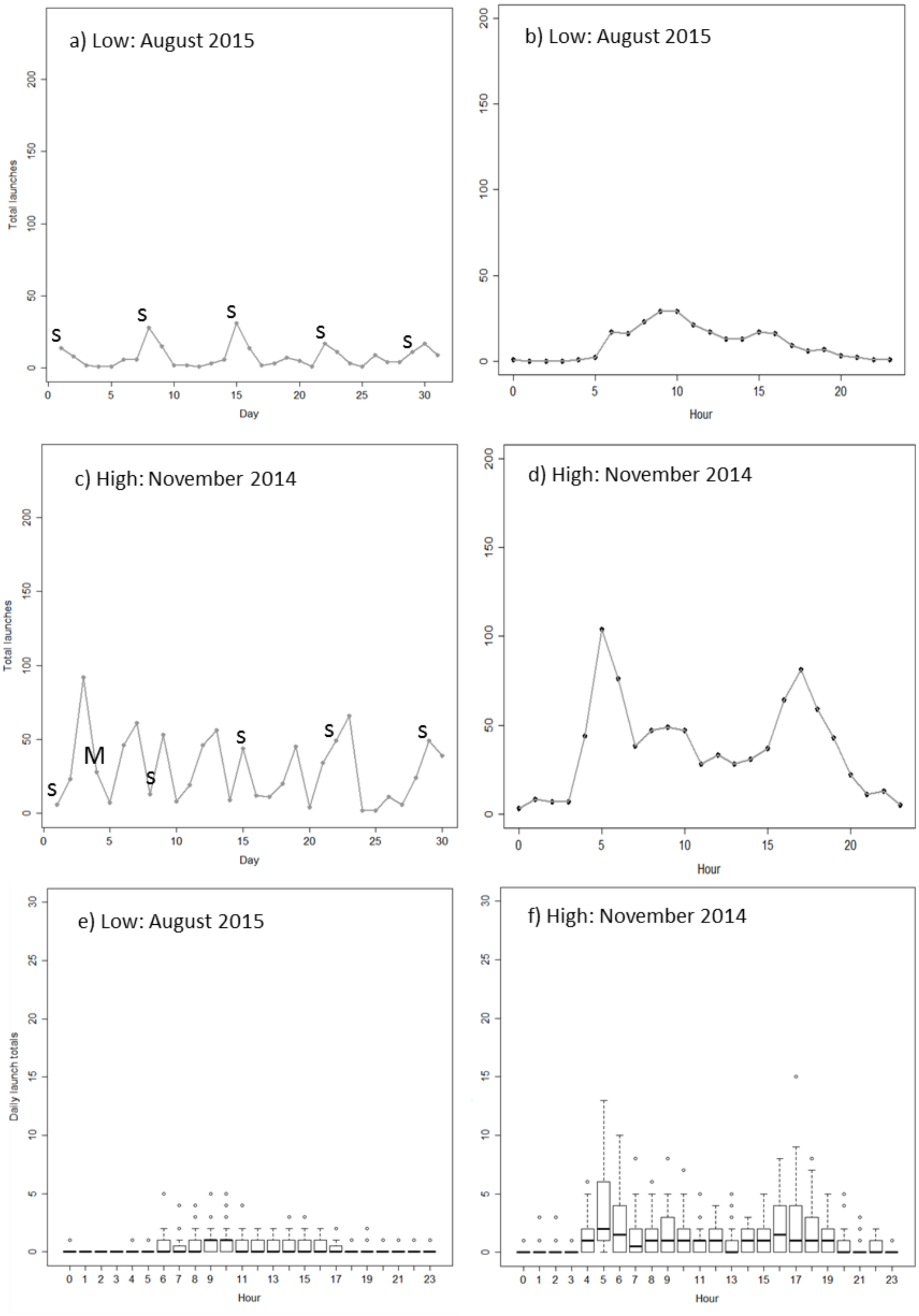


Figure 13 Recreational fishing vessel launches at St Helens boat ramp (camera 1) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday, M=Melbourne Cup public holiday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. November times are daylight savings times.

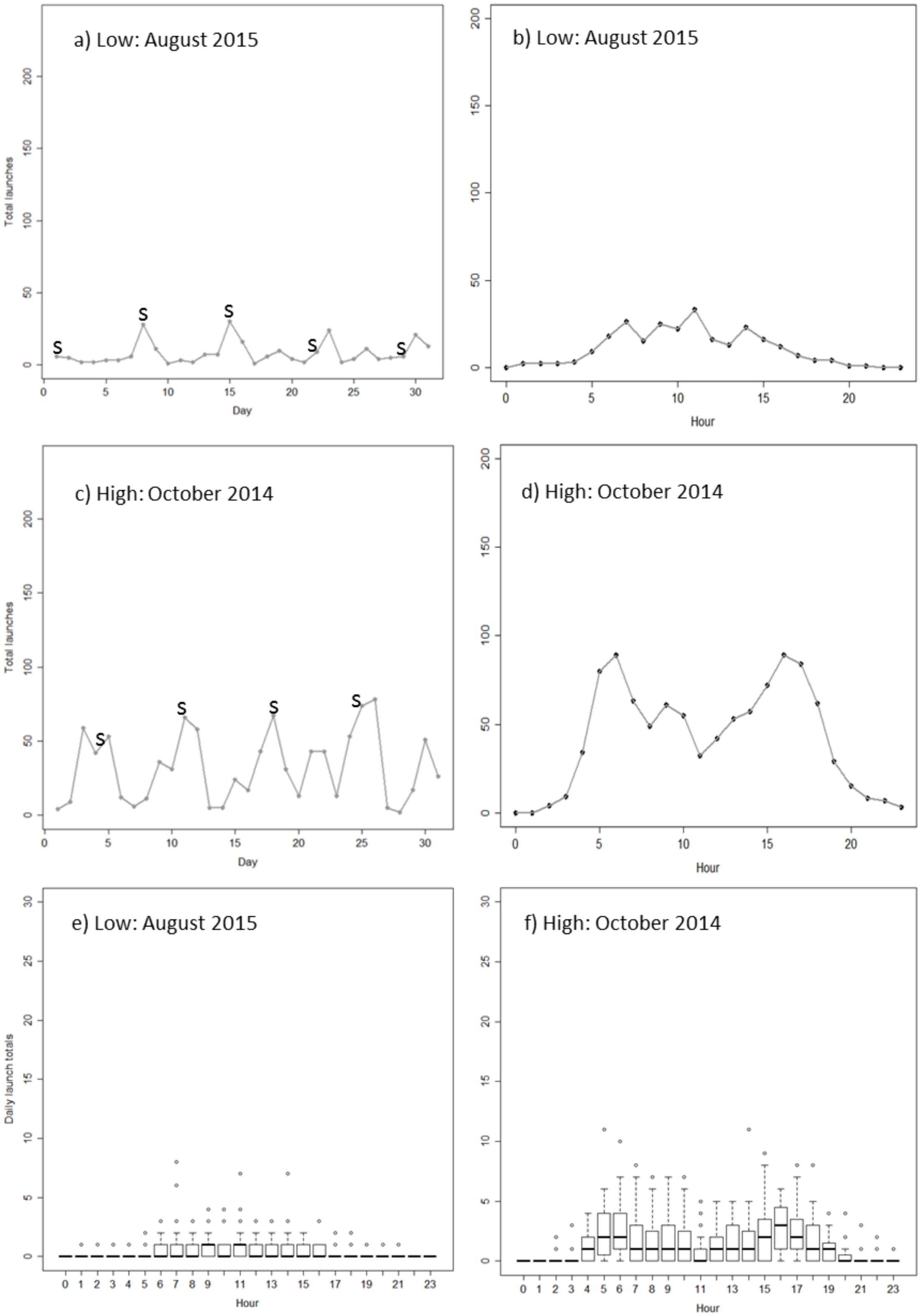


Figure 14 Recreational fishing vessel launches at Limeburners Point boat ramp (camera 2) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. October times are daylight savings times.

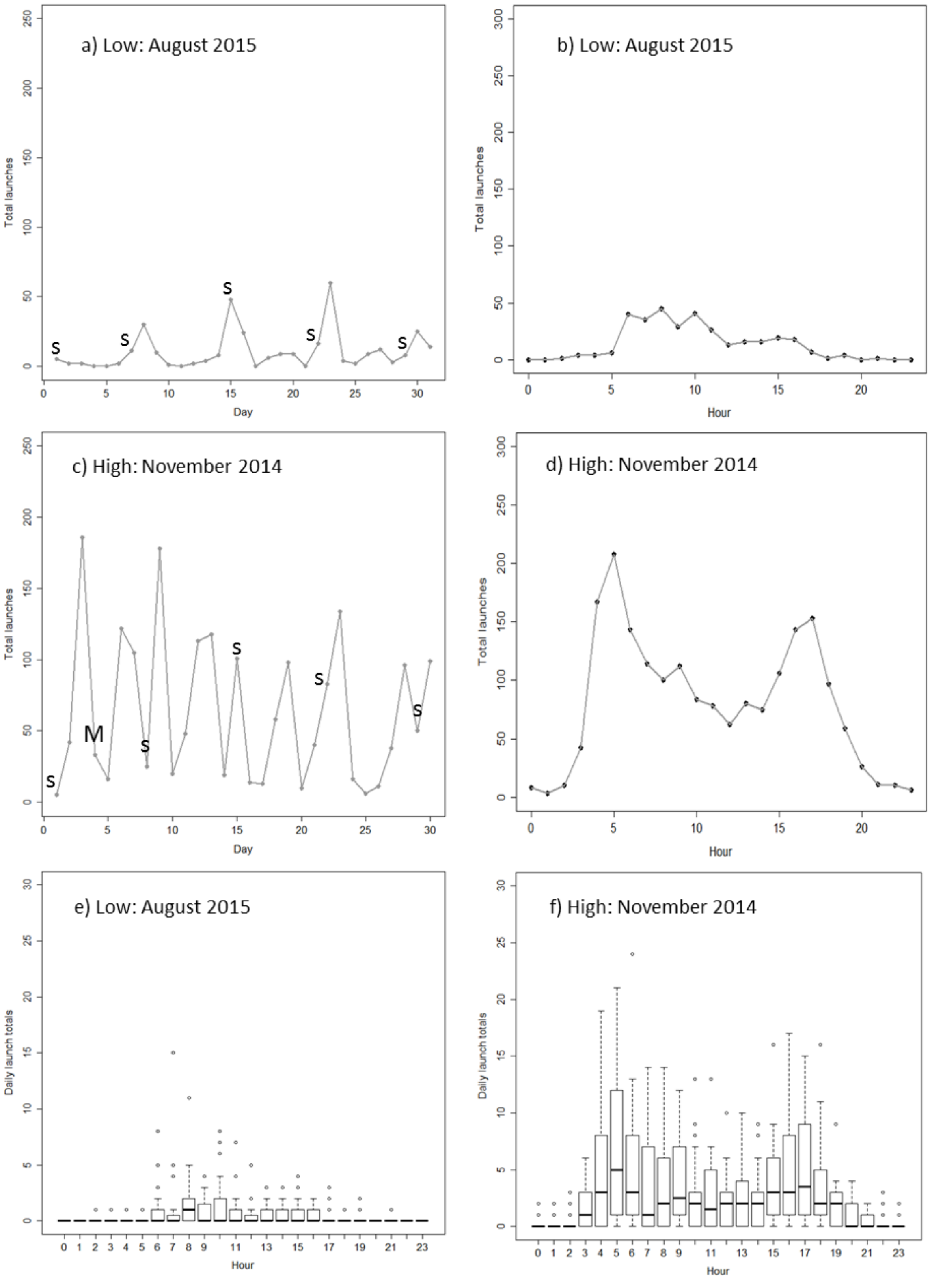


Figure 15 Recreational fishing vessel launches at Clifton Springs boat ramp (camera 3) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday, M=Melbourne Cup public holiday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. November times are daylight savings times.

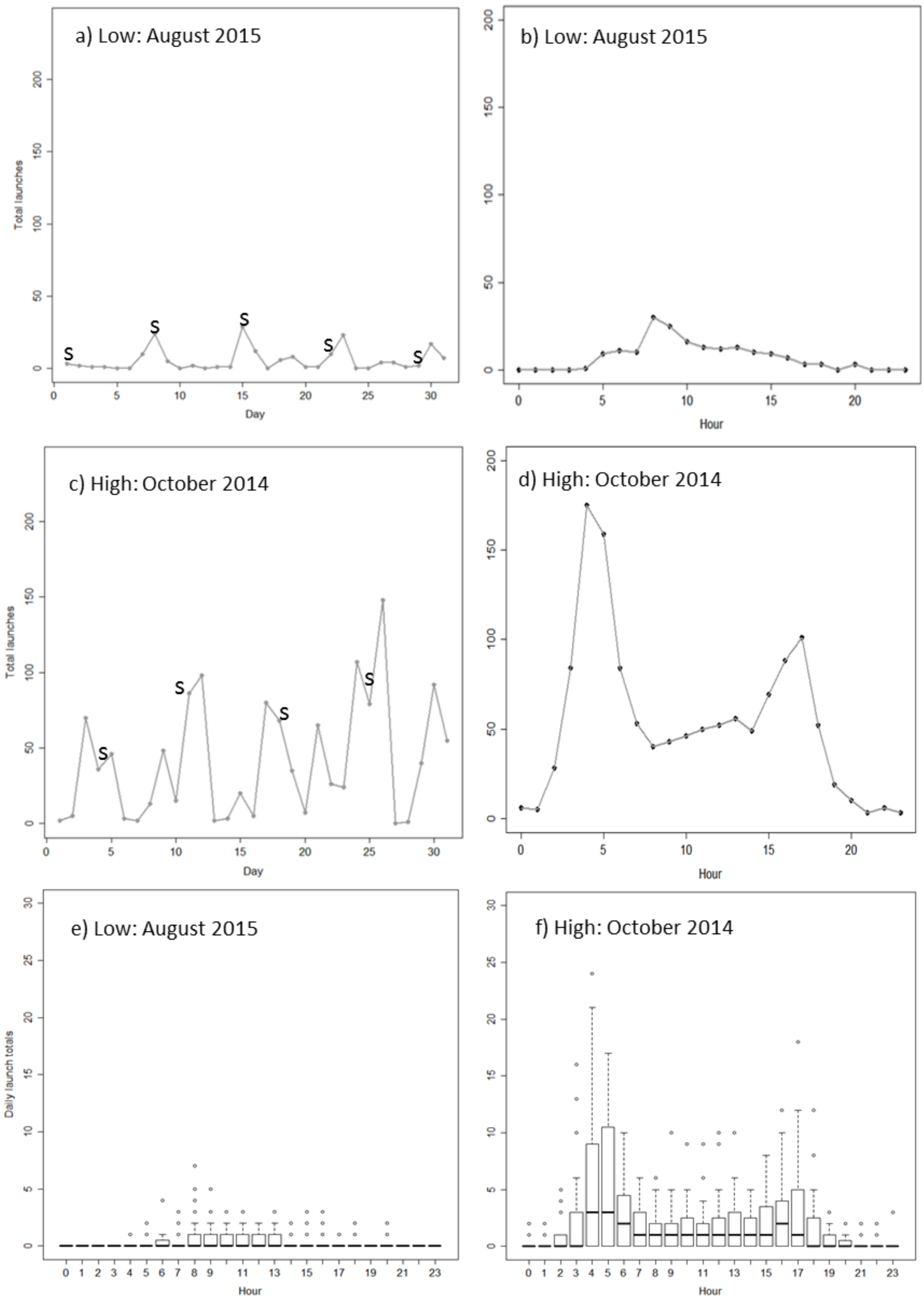


Figure 16 Recreational fishing vessel launches at the central ramp of Patterson River boat launch facility (camera 4R) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. October times are daylight savings times.

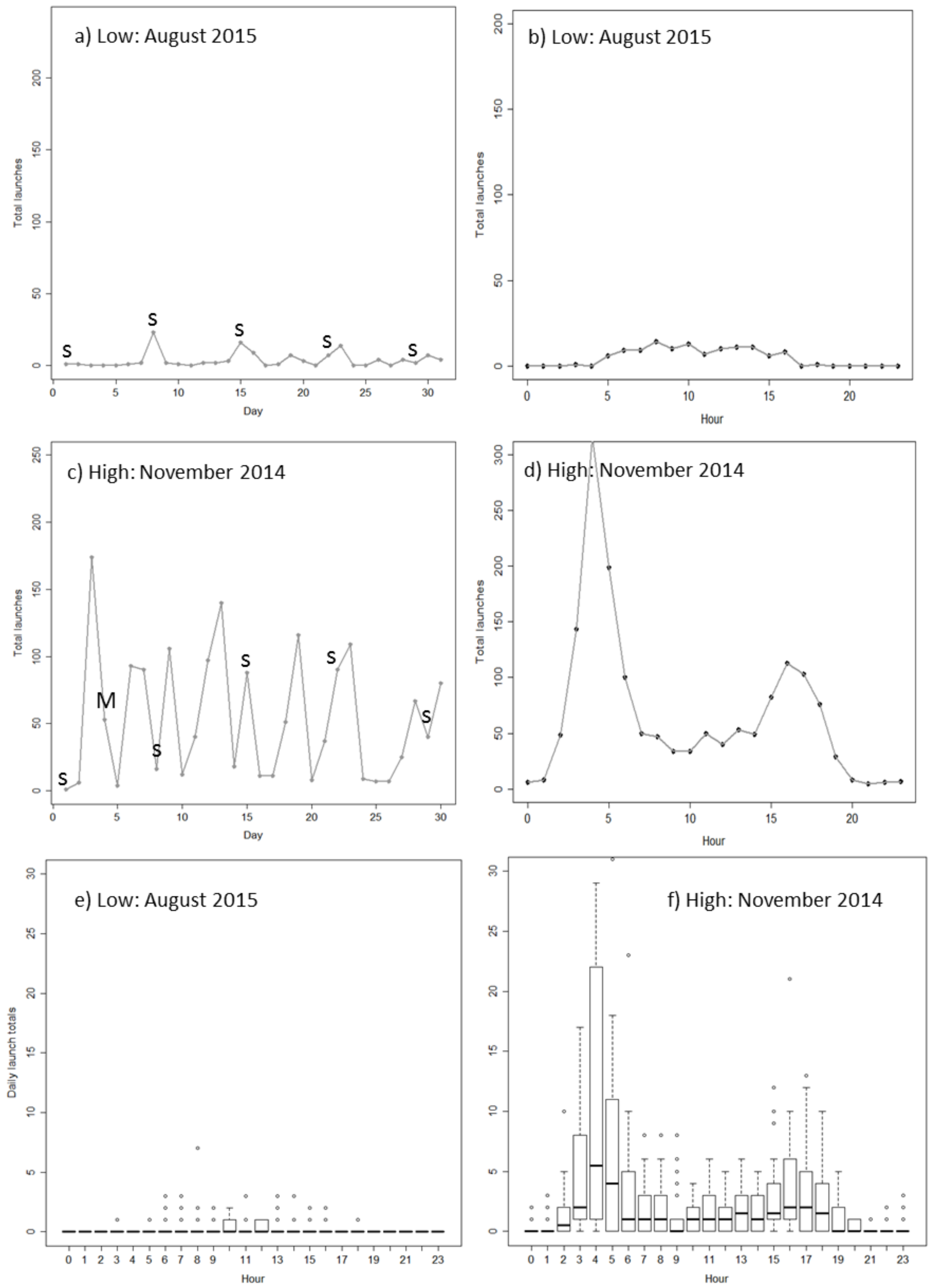


Figure 17 Recreational fishing vessel launches at the left ramp of Patterson River boat launch facility (camera 4L) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday; M=Melbourne Cup public holiday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. November times are daylight savings times.

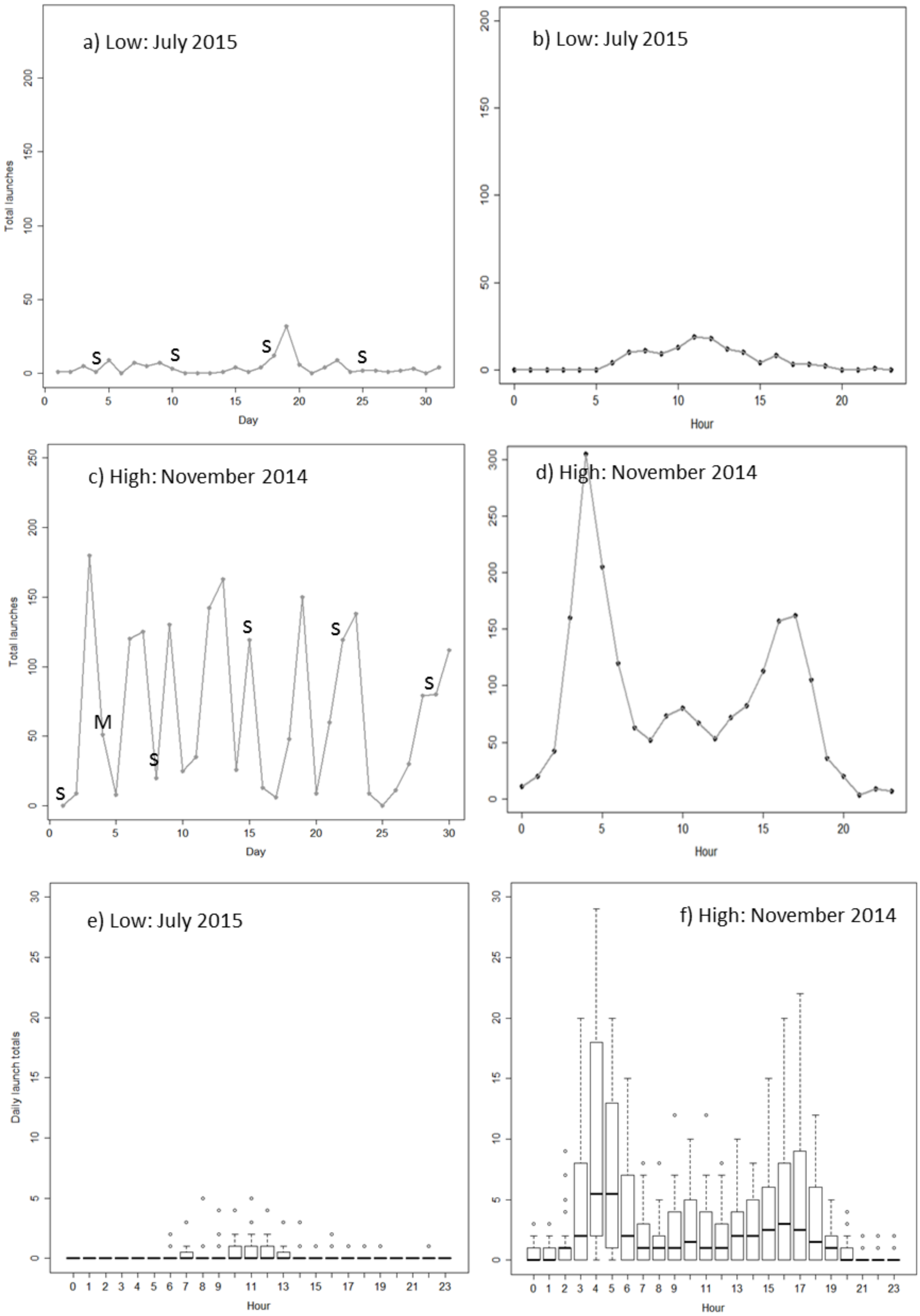


Figure 18 Recreational fishing vessel launches at the far right ramp of Patterson River boat launch facility (camera 5) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday, M=Melbourne Cup public holiday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. November times are daylight savings times.

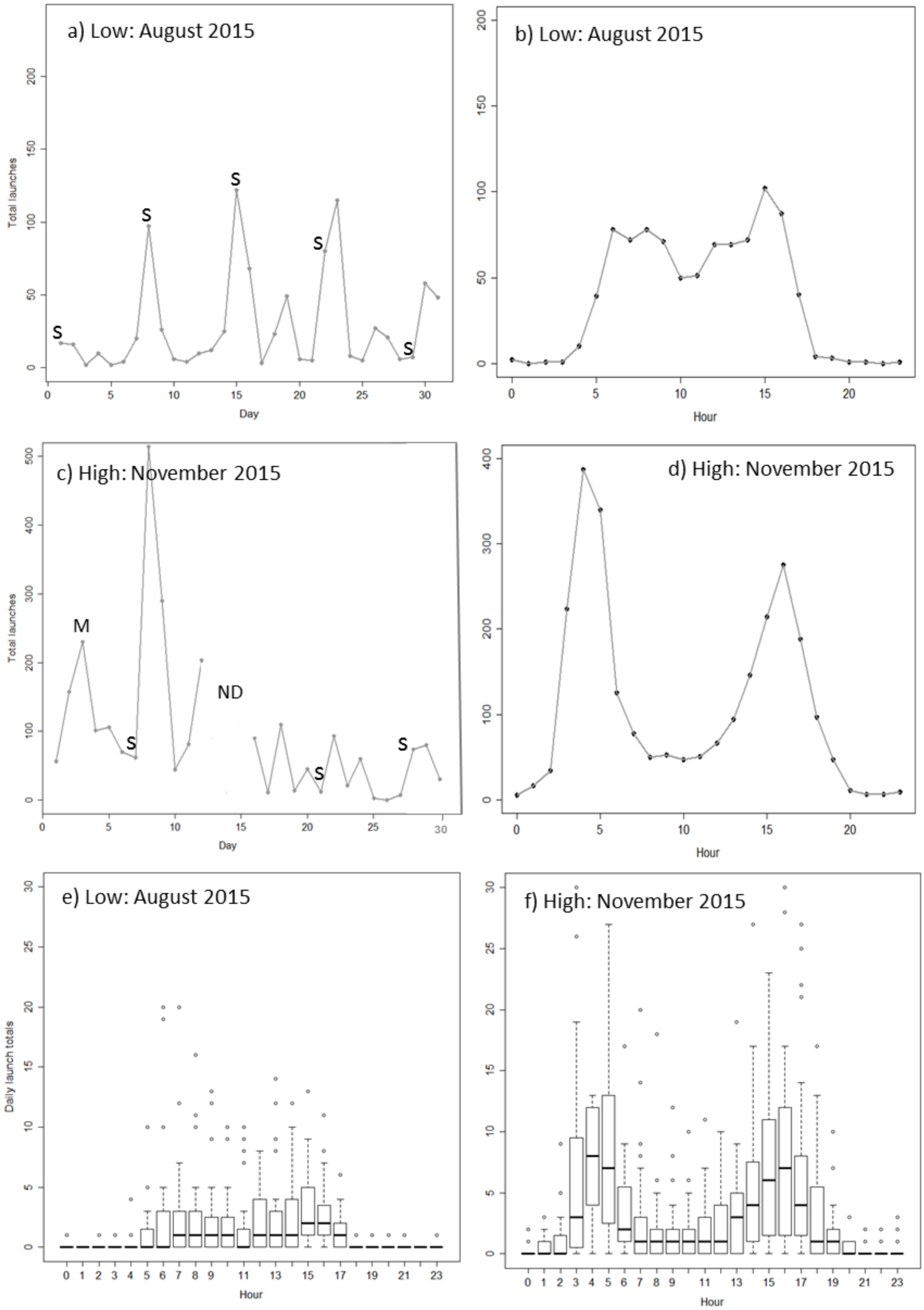


Figure 19 Recreational fishing vessel launches for all ramps of Altona boat launch facility (camera 6) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday, M=Melbourne Cup public holiday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. November times are daylight savings times.

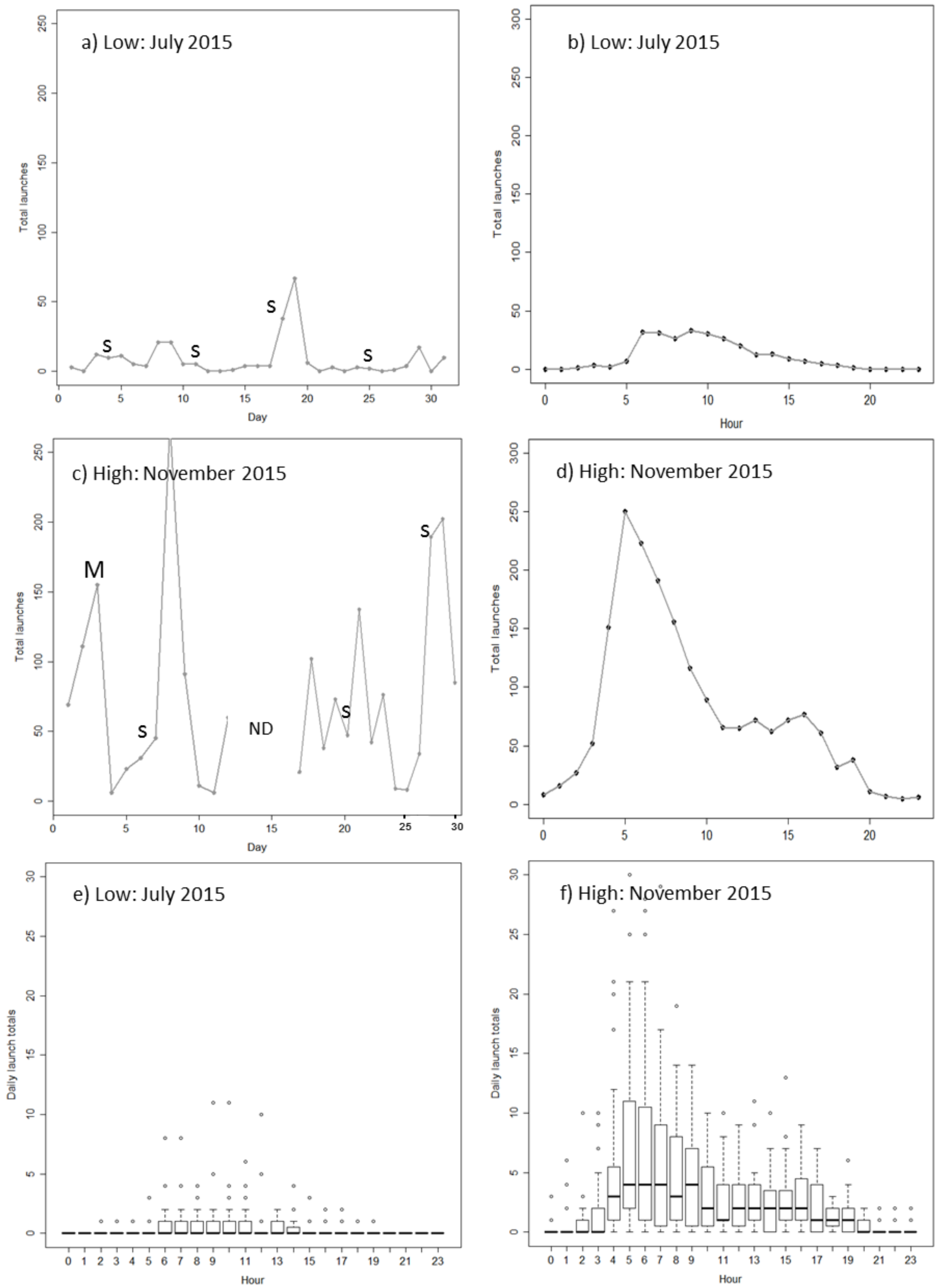


Figure 20 Recreational fishing vessel launches for Hastings boat launch facility (camera 7) for selected 'high' and 'low' effort months displayed as: a, c) total launches for each day of the month, S=Saturday, M = Melbourne Cup public holiday; b, d) total launches for each hour of the day summed across the month; e, f) box plot of distributions of hourly launches for the month. November times are daylight savings times.

Comparison of sub-sampling approaches

Comparisons of estimation errors among sub-sampling methods for camera 2 (Limeburners Pt) and camera 4R (Patterson River central ramp) showed that random sampling of whole days (Method 1) with WD and WE day type strata performed poorly compared to sampling of *Random Hours* (Method 2) and *Target Random Hours* (Method 3) with the same overall sampling effort (Fig. 21, 22). *Target Random Hours* performed marginally better than *Random Hours* (Fig. 21, 22). In low effort months, gains in estimation accuracy were best achieved by increasing the sampling effort allocated to WE hours compared to WD hours. This is consistent with the clearer peaks in WE effort in low effort months. In high effort months, there was only a minor increase in estimation accuracy with increased numbers of WE hours sampled, and gains in estimation accuracy were greater by increasing the amount of WD hours sampled (Figs. 21, 22). *Target Random Hours* was selected for further evaluation. Example plots (i.e. camera 2, Limeburners Pt) of the distributions of the estimates from 1000 bootstrap simulations using the *Target Random Hours* method showed normal distributions with means that converged on the true value, indicating unbiased estimation (Fig. 23).

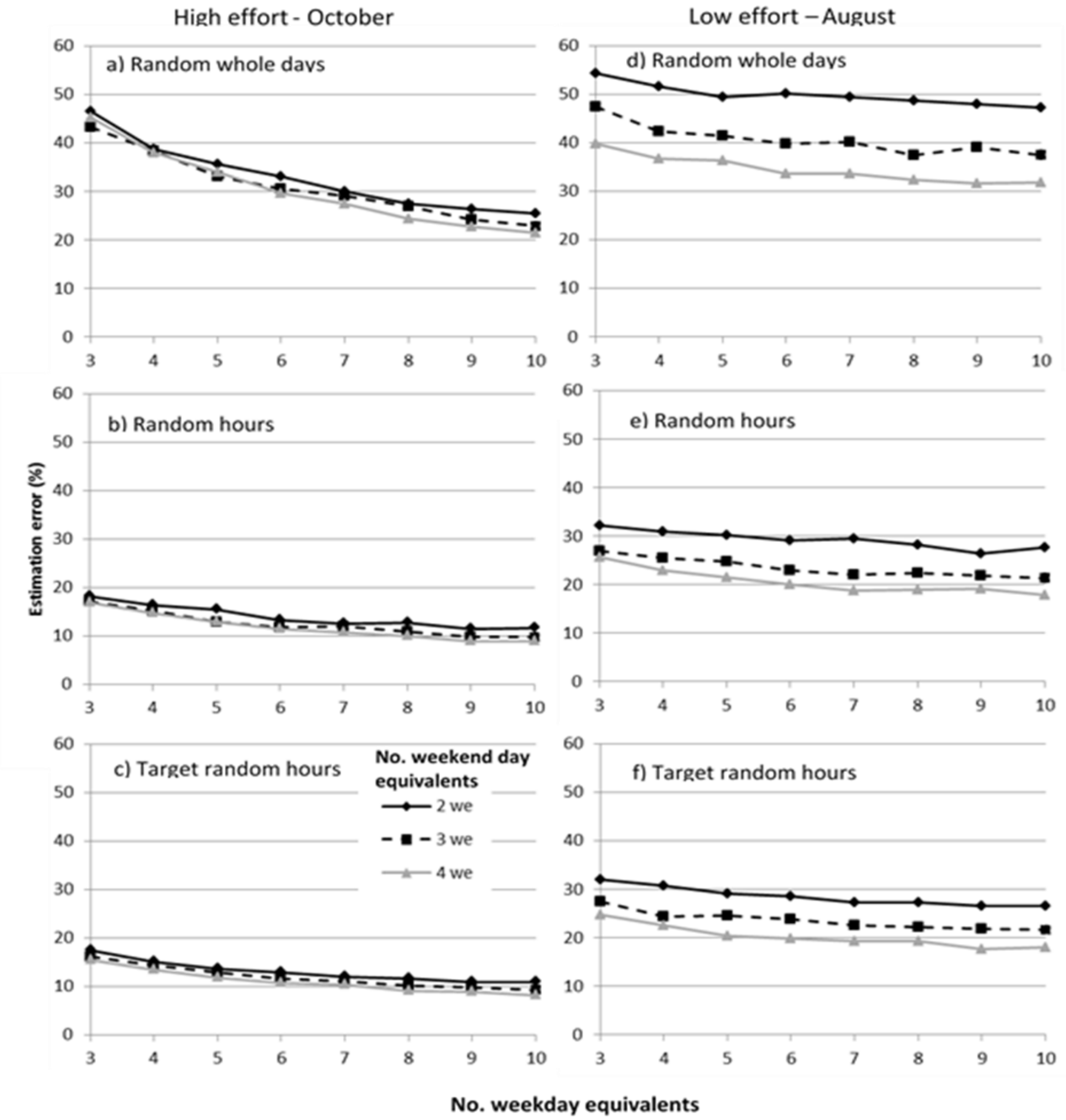


Figure 21 Comparisons of estimation errors among three sub-sampling approaches for 'low' and 'high' effort months at Limeburners Pt boat ramp (camera 2). For each sub-sampling approach estimation error is plotted for different combinations of sampling effort afforded to weekdays and weekend days.

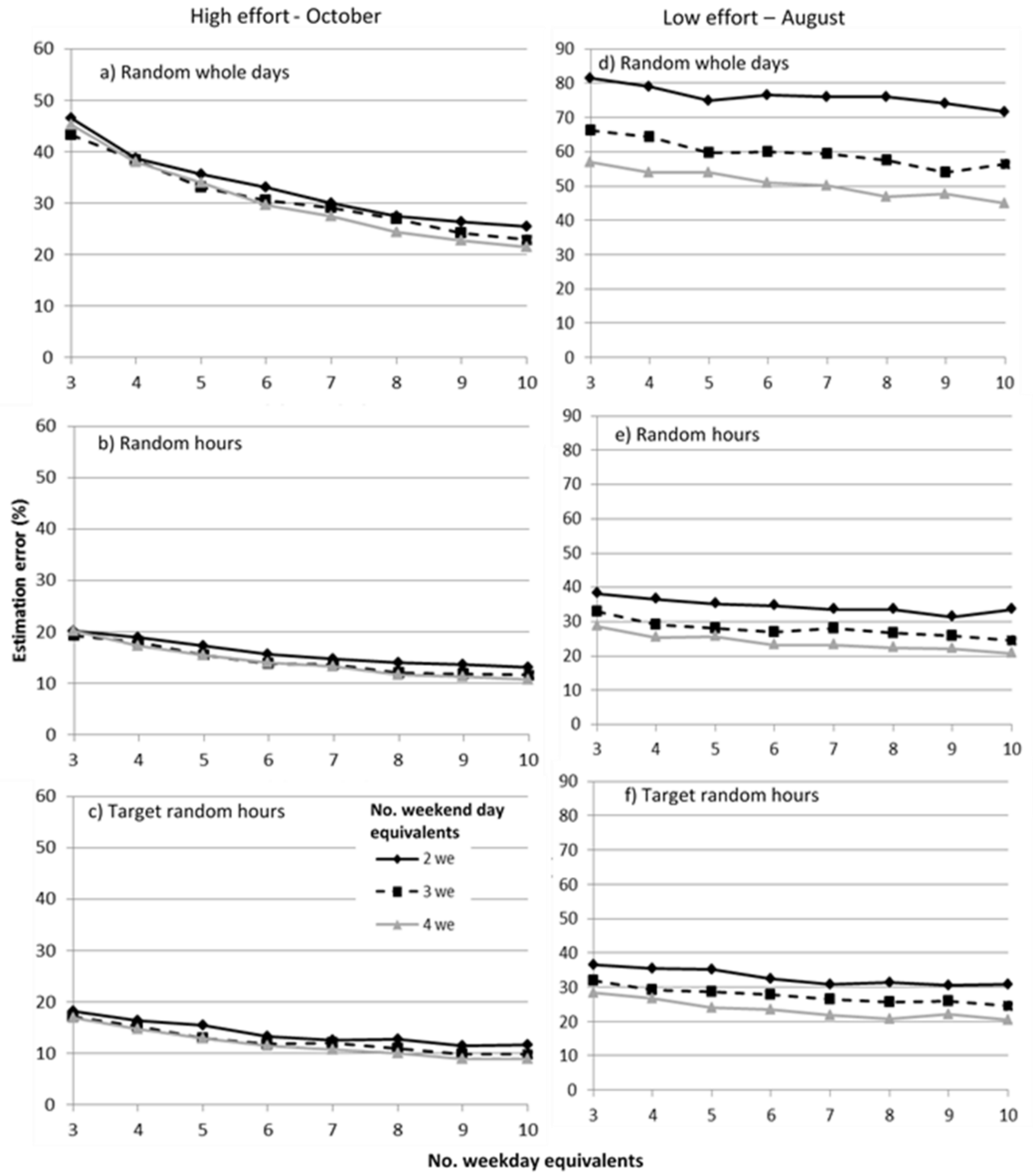


Figure 22 Comparisons of estimation errors among three sub-sampling approaches for 'low' and 'high' effort months at the central ramp of Patterson River boat launch facility (camera 4R). For each sub-sampling approach estimation error is plotted for different combinations of sampling effort afforded to week (Monday-Friday) and weekend (Saturday and Sunday) days.

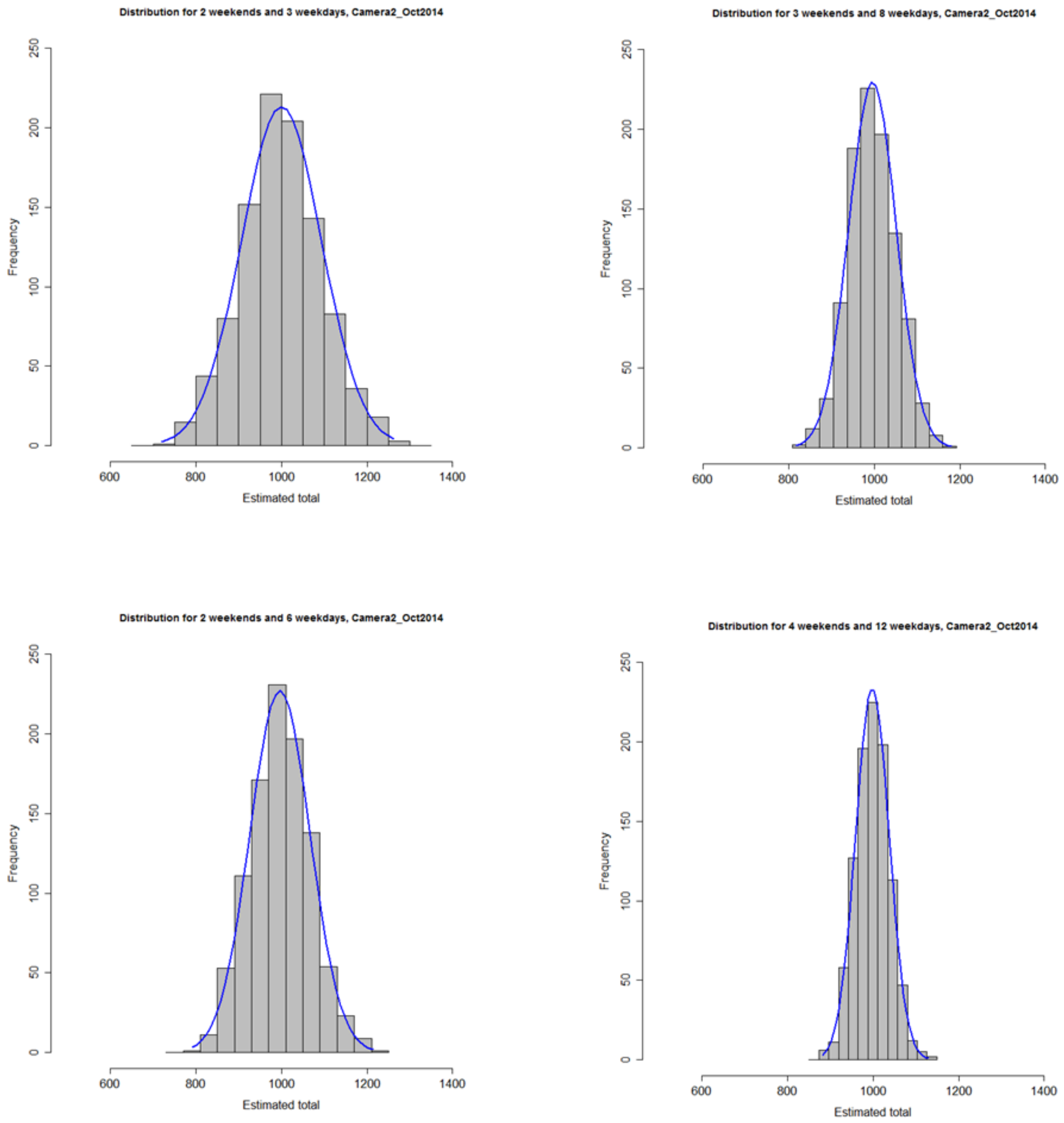


Figure 23 Frequency distributions for 1000 bootstrap estimates of total effort using the targeted random hours algorithm for Camera 2 during Oct 2014. Plots show (a) 5, (b) 8, (c) 11, (d) 16, equivalent days of sampling. The "true" total number of launches for this month was 997.

Expanded evaluation of sub-sampling with 'target random hours'

Estimation bias was minor for both the SS1 and SS2 *Target Random Hours* variants, and high and low effort months (Fig. 24). Even the worst biases observed across all the sub-sampling intensities tested were low relative to the total numbers of launches, i.e. less than 20 launches in high effort months and less than 5 launches in low effort months (Fig. 24). Targets for estimation errors of around 15% and 25% were considered acceptable for high and low effort months respectively. Higher estimation error in low effort months is acceptable because the errors translate to much lower numbers of launches compared to the high effort months.

For high effort months the SS1 approach could achieve a 15% mean estimation error with a 5 WD and 4 WE equivalent sampling intensity, which required sub-sampling of approximately 220 "hourly-blocks" per month, and between 5-7 hours of image processing time (Figs. 25, 26). For the low effort months, the SS1 approach could achieve a 25% mean estimation error with a 4 WD and 4 WE equivalent sampling intensity, which required sub-sampling of approximately 200 hourly-image blocks per month, and between 2-3 hours of image processing time (Figs. 25, 26).

For high effort months the SS2 approach could achieve a 15% mean estimation error with a 4 WD and 3 WE equivalent sampling intensity, which required sub-sampling of approximately 200 hourly-image blocks per month, and between 5-7 hours of image processing time (Fig. 25, 26). For the low effort months, the SS2 approach could achieve a 25% mean estimation error with a 4 WD and 4 WE or a 5 WD and 3 WE equivalent sampling intensity, which both required sub-sampling of approximately 225 hourly-image blocks per month, and between 3-4 hours of image processing time (Fig. 25, 26).

The SS2 methods samples proportionally more high effort diel hours than the SS1 approach, so although it can require less hourly-blocks to be sampled overall, the processing time is generally longer due to the greater time required to process the high effort hours.

Overall, the simulation studies demonstrated that unbiased and acceptable estimation error (<25% for low effort months, <15% for high effort months) could be obtained by sampling 30% of the available hourly-blocks in each month. The targets for estimation error we used may be more conservative than required for application to routine monitoring, particularly where the effort data is combined with other sources of data with higher uncertainty such as catch rate and size composition to estimate harvests. The level of sub-sampling should be decided based on the levels of accuracy and precision required for the objectives of the monitoring program. Both the SS1 and SS2 methods performed adequately and either could be applied for ongoing monitoring, however, the marginally better cost-effectiveness of the SS1 approach might favour it for longer-term use (Fig. 26).

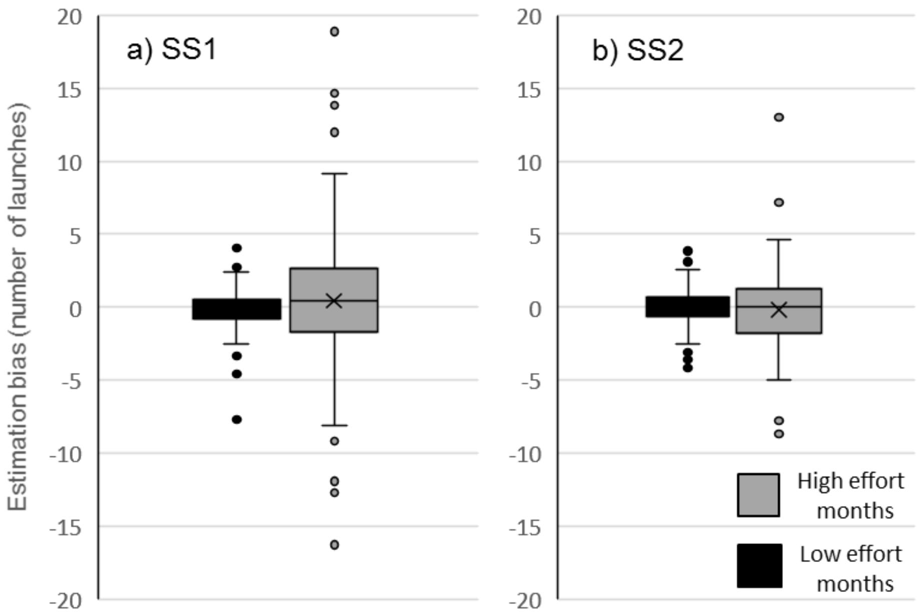


Figure 24 Box plots showing the distributions of estimation errors (i.e. differences between estimation means from bootstrapping of sub-sampling routines and the true number of launches) compared between high and low fishing effort months, and the two versions of the 'target random hours'. Data include error estimates from all the sub-sampling intensities trialled.

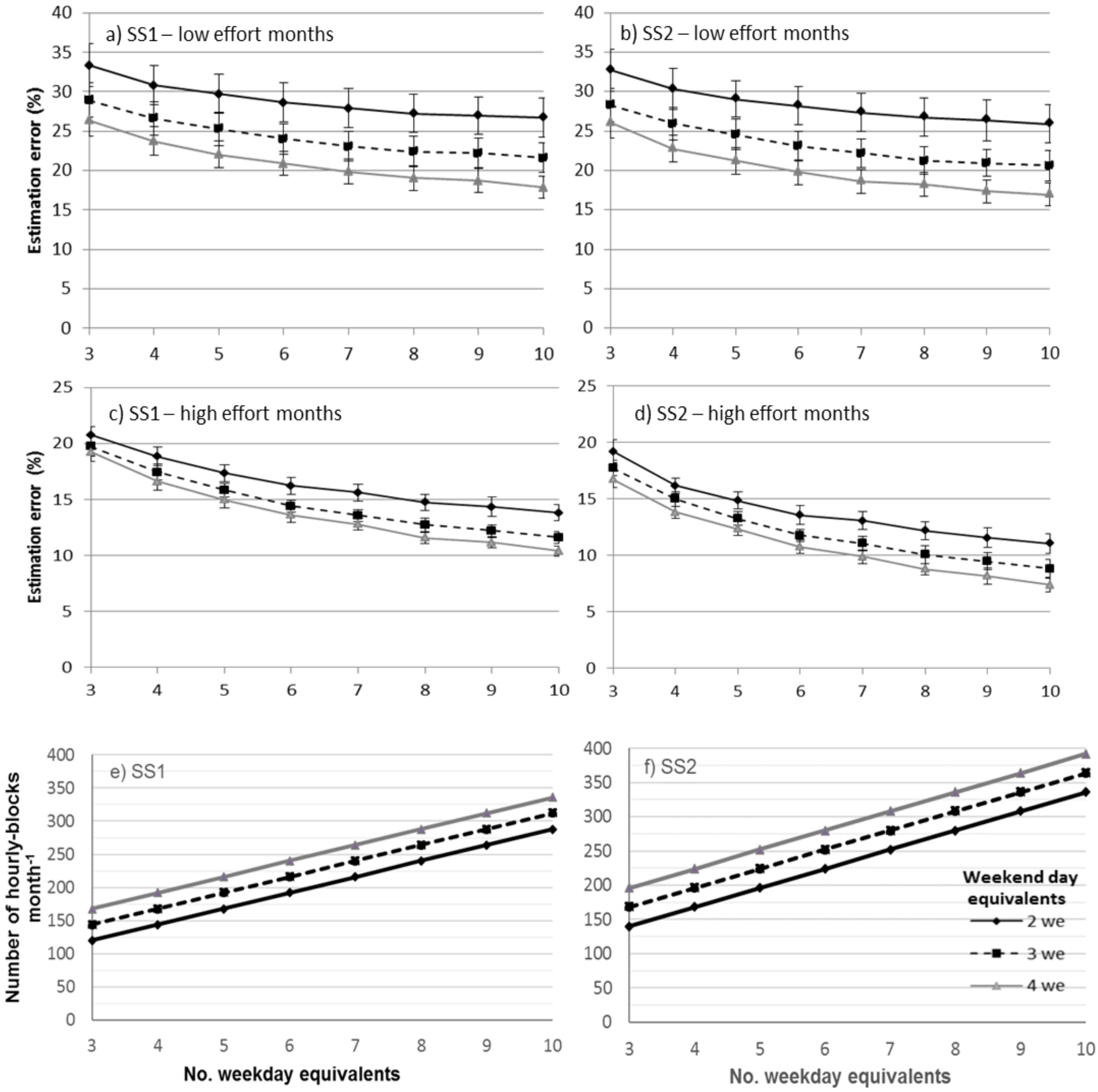


Figure 25 Comparisons of mean (±SE) estimation errors among two targeted random hours sub-sampling approaches (SS1 and SS2) for different boat ramps and 'low' (n = 6 ramps, 10 months) and 'high' effort months (n = 5 ramps, 7 months). For each sub-sampling approach estimation error is plotted for the different combinations of sampling intensity afforded to weekdays and weekend day strata. The required numbers of hourly-image blocks to be sampled per month for each sub-sampling routine are indicated in e) and f).

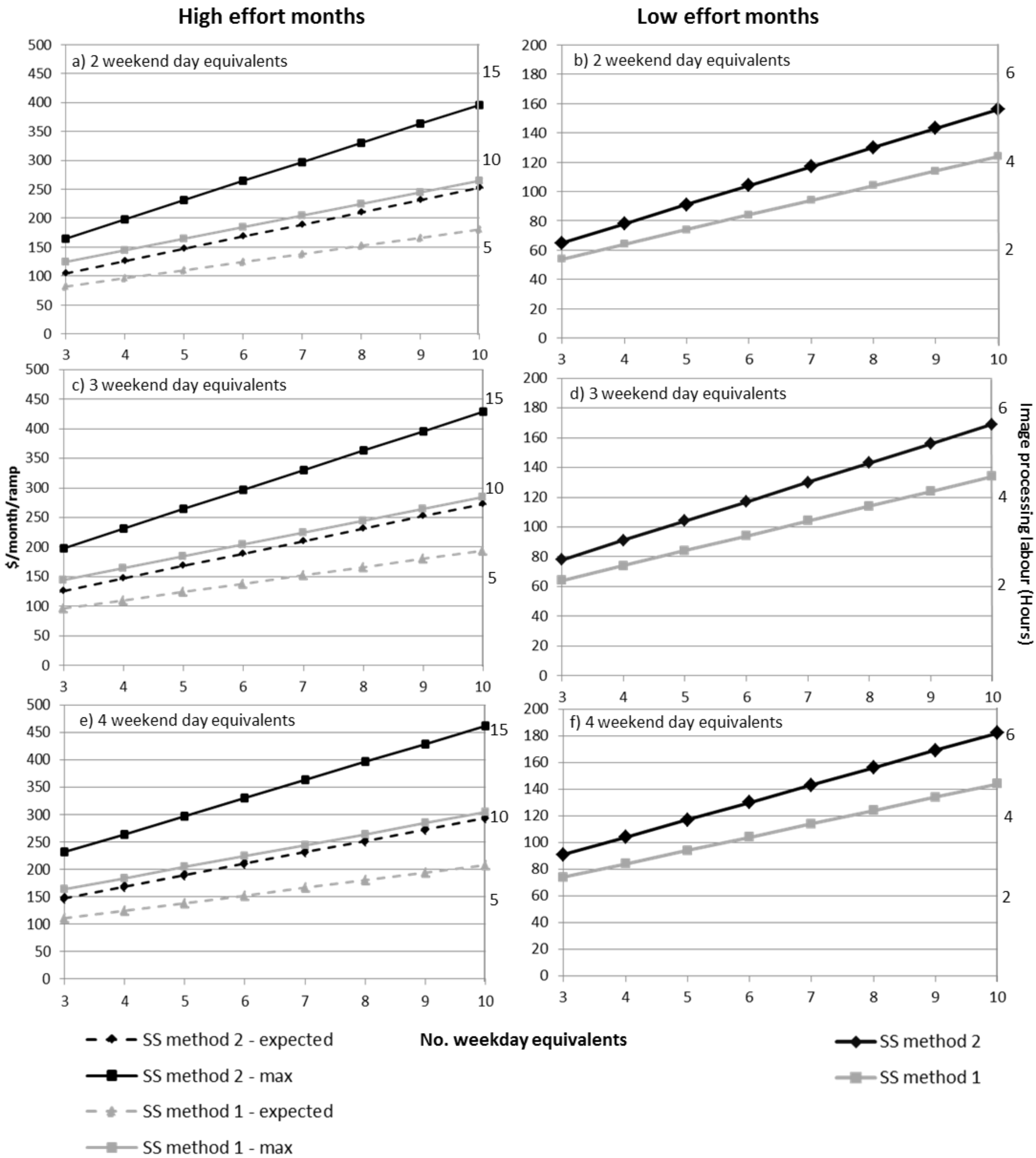


Figure 26 Comparisons of estimated image processing costs and labour times for different levels of sub-sampling under two target random hours subsampling approaches. Estimates are based on a single ramp with up to 3 lanes and a nominal pay rate of $30/hour. Image processing includes activity classification (launch or retrieve and vessel type) and entry into a spreadsheet. The maximum estimates for the high effort months provide an upper estimate that might be applied to exceptionally busy ramps in the high effort months.

Operating Cost

For costings, a ramp refers to a single camera monitoring up to 3 immediately adjacent launch lanes. The costing estimates summarised in figure 26 are based on a $30/hour rate for manual image processing labour and can be adjusted proportionally for alternative labour rates. Table 3 summarises indicative operating costs based on the experience of this project and the targeted estimation errors of 15% and 25% for the high and low effort months. The fixed annual cost, including depreciation of the camera head and associated hardware with an 8-year life-span, are likely to be around $2,100 per system/year. The monthly cost associated with data collection, bandwidth and image analysis would be between $175-225 per month for high fishing effort months, and $80-100 per month, for low fishing effort months. For ongoing operation of a ramp camera image sub-sampling approach, the cameras could be pre-programmed to only upload 2 min images for specific time periods of interest (i.e. fishing seasons, periods of the day etc.) which could reduce data (bandwidth and storage) related costs. For the activity sensor approach it would be recommended to re-validate the activity-launch prediction models for a high and low effort month each year, this would therefore require 2 min time lapse and manual classification to be done for 1-2 months each year per ramp. This would also allow the periodic checking of the proportion of recreational fishing versus other use vessels. An activity sensor camera full annual coverage would cost < $3,000 including the fixed annual cost and depreciation, and annual validation of the activity versus true launches relationships. This is approximately $1000-1500 per year cheaper than image sub-sampling and manual classification with 30% image sub-sampling rate (Table 3).

Table 3 Summary of indicative ramp camera operating cost summary ($AUD), note one camera is assumed to be monitoring one ramp with up to 3 adjacent lanes.

Source	Estimate
Camera hardware and installation	$7000 - $9000 per camera system, allow for system replacement after 8 years = approximately $1,000/year depreciation.
Maintenance	$300/year/camera system
Image/web hosting and management by external provider	$800/year/camera system
Total fixed annual costs, with depreciation	**Annual = $2,100/camera system**
Variable cost per ramp camera: *image sub-sampling and manual classification approach*	*Bandwidth:* Low resolution (150 KB/image), 2 min time lapse: mobile data charges $25/month/camera (4GB/month plan). *Manual image processing:* • $30/hr nominal rate, 30% of images/month • ca. $175-225/camera/month – high effort (6 months/year) • ca. $105-125/camera/month – low effort (6 months/year) **Annual = $1,680 - $2,100**
Variable cost per ramp camera: *activity sensor approach with annual validation*	*Bandwidth:* $25/month/camera (4GB/month plan) (could be a cheaper plan). *Manual image processing:* Annual validation costs (manual image classifications): $350 **Annual = $650**

Image file subsampling for ongoing application

For ongoing operation of the ramp camera effort sub-sampling approach, sub-samples of hourly-blocks would be routinely selected from the available full archived image sets for each month according to the chosen method. To facilitate this an R script was written for the target random hours approach that allowed specification of the sub-sampling intensities to apply, and then selected and compiled the sub-sampled image file sets accordingly. In the chapter 3, this 'one-off' sub-sampling with expansion is used to replicate what would happen in ongoing application and is combined with catch rate and composition data to estimate harvest. The error associated with the expanded total monthly effort estimate for a one-off sub-sample is described in chapter 3.

Activity sensor trial

Comparisons of daily launch totals determined from classification of complete 2 min time lapse and activity sensor image sets at two ramps showed highly consistent results. Differences in daily launch totals were typically less than 5 launches between the two image capture approaches (Fig. 27). This indicates that the activity sensor software picked up all the vessel launch activity measured by 2 min time lapse. It also indicates that the 2 min time lapse period was appropriate and did not miss notable numbers of launches.

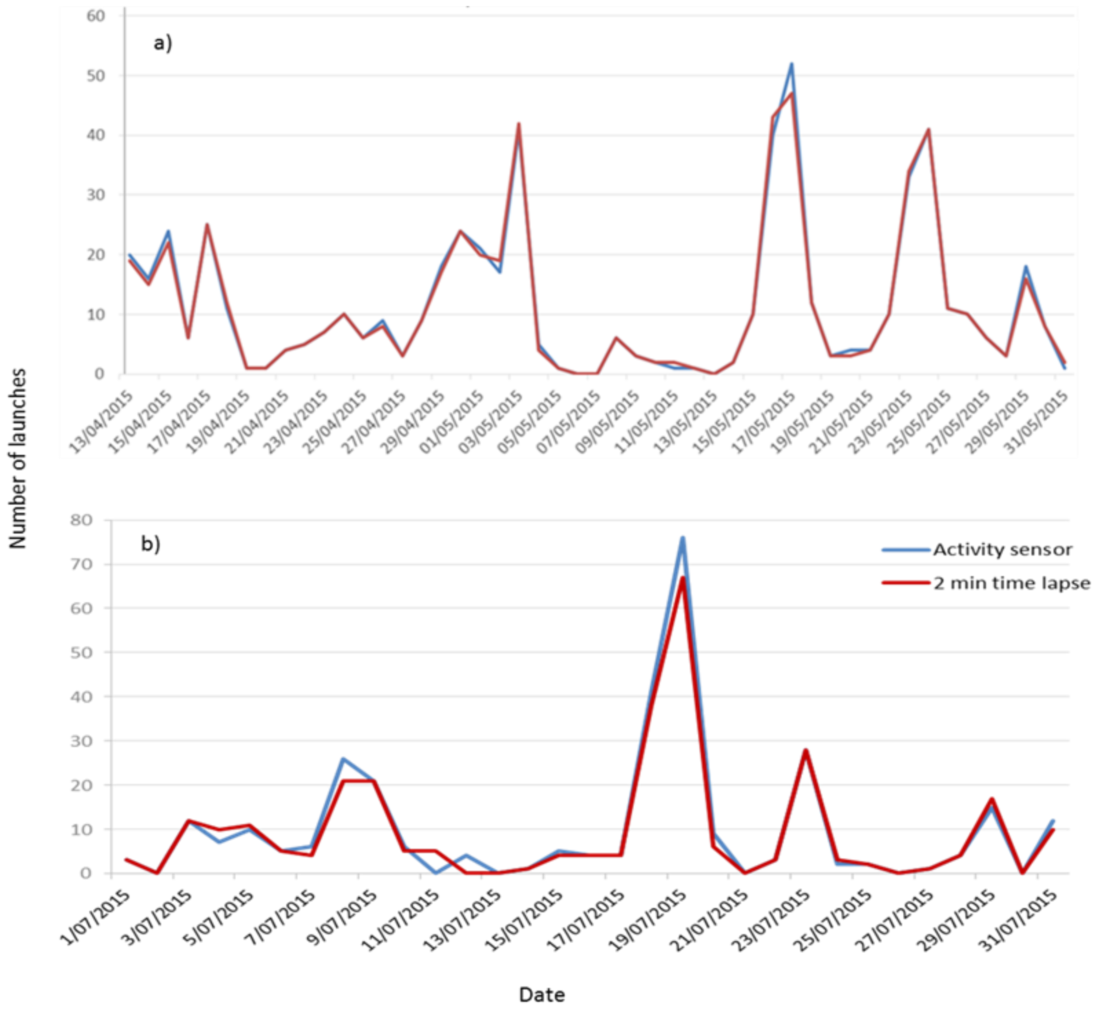


Figure 27 Comparisons of numbers of daily launches determined from classifying complete image data sets from 2 min time lapse and activity sensor image capture at two boat ramps; a) St Helens – camera 1, b) Hastings – camera 7

The numbers of images captured by activity sensor was however significantly higher than the sum of the individual launches and retrievals across all vessel types, although the total images uploaded by activity sensor were only 10-20% of the total images recorded by 2 min time lapse (Table 4). Most of the additional activity sensor images were repeat images of the same vessel being launched or retrieved (Table 4). This indicated that more tuning of the event dead time settings and activity zones were required to reduce repeat counting of the same launch and retrieval events. Approximately 70% of the activity sensor image captures were related to fishing vessel launch and retrieval activities. Birds, people and cars not involved with vessels, accounted for most of the other images captured by activity sensor (Table 4).

Table 4 Summary of activity types recorded by activity sensor at two boat launch facilities.

Image classification type	**Camera 7 – Hastings** 1-31/7/2015		**Camera 1 – St Helens** 13/4 – 30/5/2015	
	Freq.	Prop.	Freq.	Prop.
Fishing boat (single launch or retrieval events)	619	0.218	1180	0.154
Repeat images of the same boat	1310	0.462	4465	0.582
Bird	155	0.055	1045	0.136
Person	510	0.180	774	0.101
Car not with vessel	218	0.077	138	0.018
Dog	2	0.001	2	0.000
Other (flag, car light, yacht, rain, etc.)	23	0.008	67	0.009
Total activity sensor images	**2837**	**1.000**	**7671**	**1.000**
Total 2 min time lapse images	**22088**		**34268**	

The number of activity image captures per day was highly correlated with the true (actual) launch numbers, with most intercepts less than 5 and $r^2 \geq 0.8$ (Figs. 28, 30, 32). Also, the relationships were strong for ramps with different camera angles and numbers of lanes, suggesting the activity sensor, with appropriate camera positioning, can work effectively across different ramp layouts with different amounts of overlapping activity.

The number of activity image captures that are repeat detections of the same vessel launch or retrieval would be a function of the ramp layout, which influences the length of time vessels and associated vehicles are moving within the activity zones. In most cases it would be inappropriate to use a regression model of activity sensor v actual launches developed from one ramp to estimate launches or retrievals for other ramps. However, for individual ramps we were interested if the activity sensor v actual launches relationships were similar between high and low fishing effort months, suggesting that only occasional revalidation of the relationship might be required, and a single relationship could be applied to predict launches across different months/seasons. Launch/retrieval behaviour may differ across months due to aspects such as overall congestion of the launch facility and urgency to complete launch/retrieval, and this could influence the amount of repeat activity triggering of the same launch/retrieval events in different months.

For the St Helens ramp, comparisons of the linear regression models for log transformed data between May-June (low effort) and November (high effort) showed a non-significant interaction term (activity *month) ($p = 0.737$) indicating that the coefficients (slopes) were not statistically different between months. The month term was also non-significant ($p = 0.641$). However, despite the non-significant month term, plots of residuals for the back transformed predictions indicated that for the St Helens ramp, the model based on the May-June period tended to over predict the actual launches for November (% prediction error, mean ±SE = 35 ±11%), but for most days by less than 10 launches (Fig. 29 a). The model based on November data had a spread of over and underprediction of the actual launches for May-June (% prediction error, mean ±SE = 28 ±15%), but most residuals were between +5 and -5 launches (Fig. 29 b). These results indicate that the amount of activity sensor triggering per launch/retrieval event did not vary greatly between the high and low effort months at St Helens. At this ramp it may be possible to develop a generic activity sensor – vessel launch regression model.

For the Hastings ramp, comparison of the regression models for log transformed data between July (low effort) and November (high effort) showed a non-significant interaction term (activity sensor *month) ($p = 0.422$) indicating that the coefficients (slopes) were not statistically different between months. However, the month term was significant ($p = 0.019$). Therefore, while the regression models for each month could predict the relative variation in the launch activity for the other month, they could not accurately predict the absolute launches. Plots of residuals indicated that for the Hastings ramp, the model based on the July data underpredicted the actual launches for November (% prediction error, mean ±SE = -62 ±3%) (Fig. 31 a), and the model based on November data over predicted the actual launches for July (% prediction error, mean ±SE = 220 ±24%) (Fig. 31 b), although the large % error for the July predictions equates to lower numbers of launches due to much lower fishing effort in July (Fig. 31 b). These results indicate that greater numbers of repeat activity triggers per launch/retrieval event occurred in the lower effort month, perhaps due to people taking more time to launch and retrieve their vessel when the ramp was not busy, possibly pausing at the top of launch lane within the activity window to attach/remove tiedowns, allow water to drain etc..

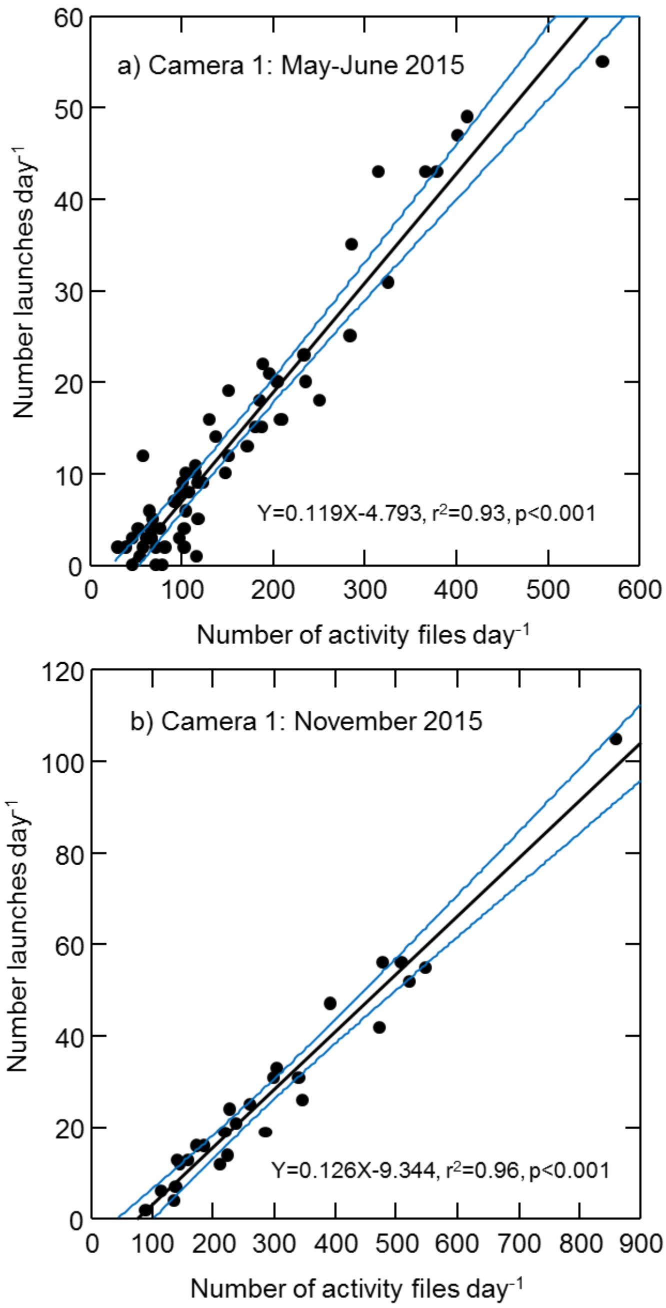


Figure 28 Camera 1, St Helens: Plots numbers of launches counted per day determined from 2 min time lapse images versus the number of activity files uploaded by the activity sensor software for a low (a) and high (b) effort month. Linear trend lines with 95% confidence intervals fitted.

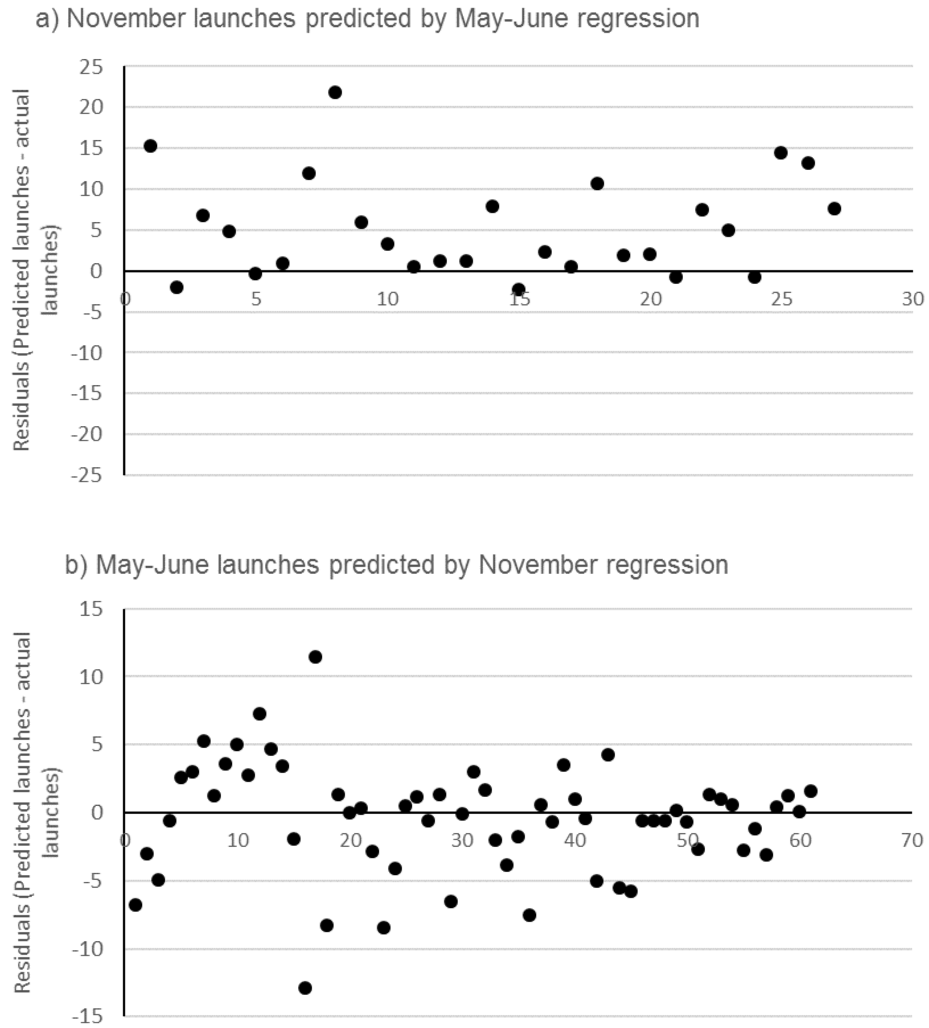


Figure 29 Plots of residuals for Camera 1, St Helens; a) when using the May-June activity sensor/actual launches regression model to predict numbers of launches in November from November activity sensor triggers, and b) when using the November regression model to predict numbers of launches in May-June from May-June activity sensor triggers. Residuals are calculated from the back transformed predictions from the models for $\log_{10}$ transformed data. Each point represents a full individual day.

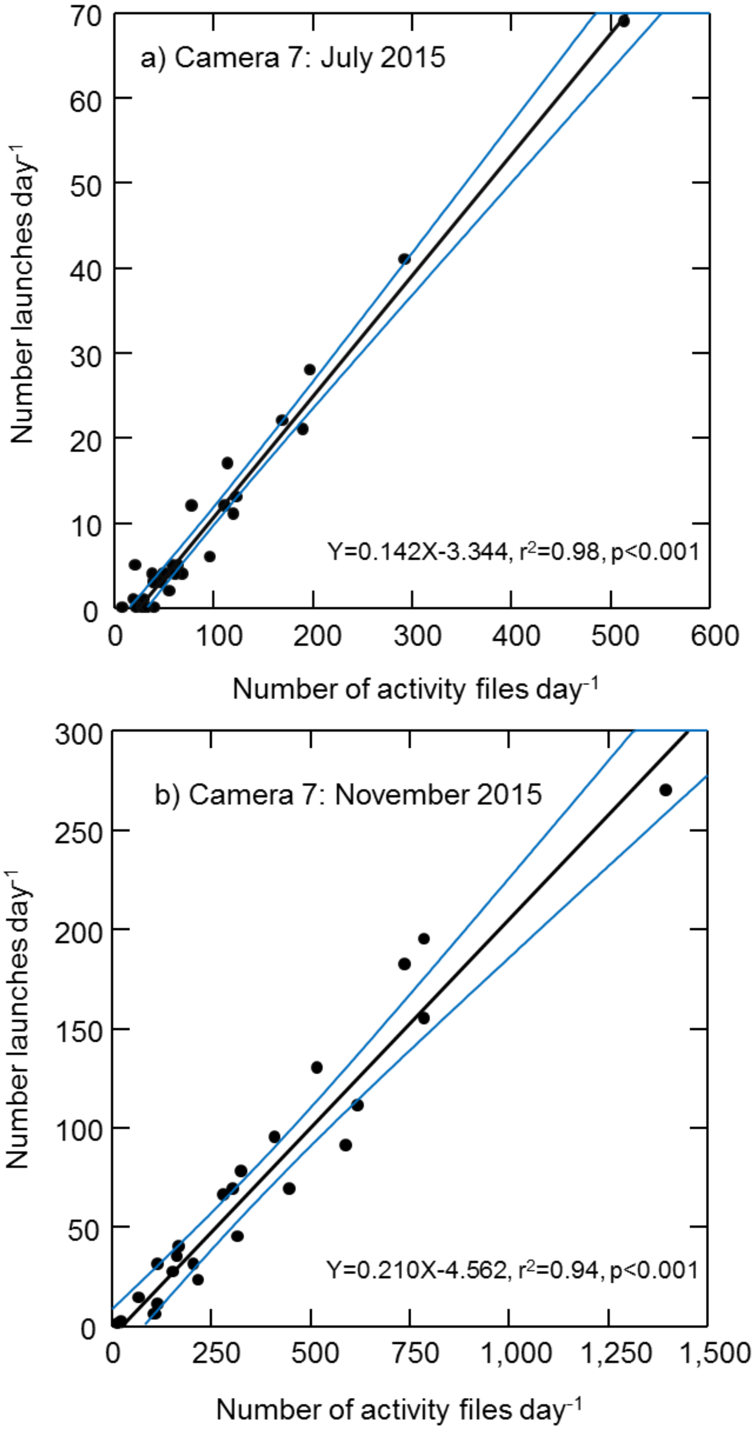
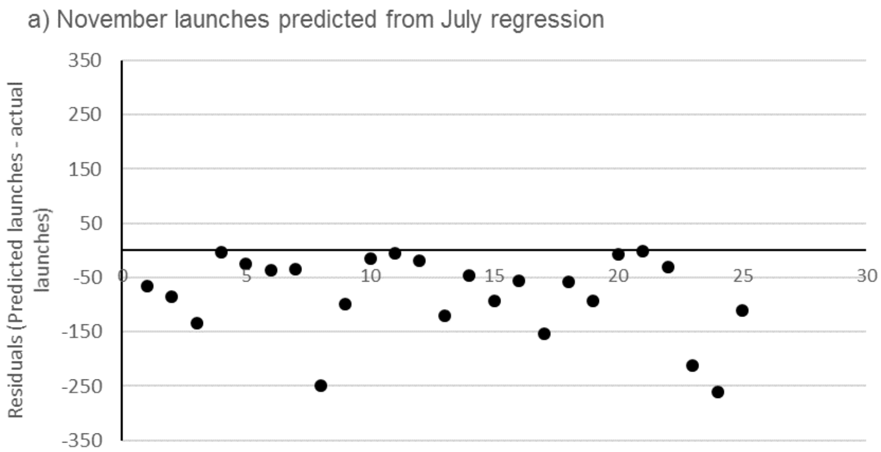


Figure 30 Camera 7, Hastings: Plots of numbers of launches counted per day determined from 2 min time lapse images versus the number of activity files uploaded by the activity sensor software for a low (a) and high (b) effort month. Linear trend lines with 95% confidence intervals fitted.



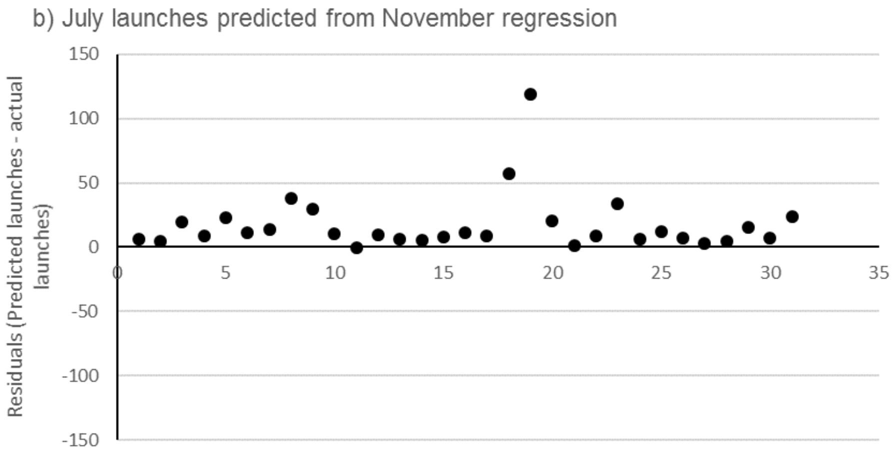


Figure 31 Plots of residuals for Camera 7, Hastings; a) when using the July activity sensor/actual launches regression model to predict numbers of launches in November from November activity sensor triggers, and b) when using the November regression model to predict numbers of launches in July from July activity sensor triggers. Residuals are calculated from the back transformed predictions from the models for log_{10} transformed data. Each point represents a full individual day.

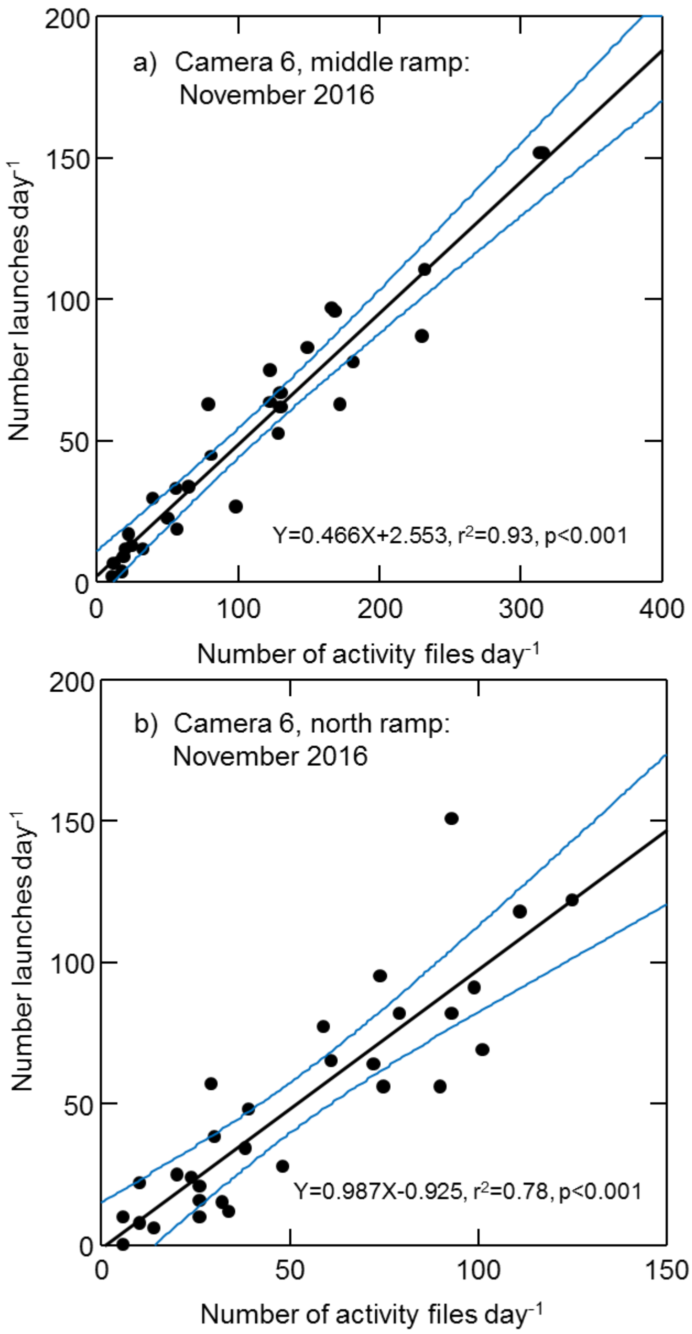


Figure 32 Camera 6, Altona: Plots of numbers of launches counted per day determined from 2 min time lapse images versus the number of activity files uploaded by activity sensor software for a high activity month and two launch lanes a) and b) (see Fig. 7) with different camera angles. Linear trend lines with 95% confidence intervals fitted.

Discussion

This trial demonstrated that boat fishing effort can be measured accurately by boat ramp cameras using 2 min time lapse image captures. Image sub-sampling of approximately one third of the total 2 min images captured per month can achieve unbiased expanded estimates of total boat fishing trips per month with accuracies of less than 25% difference from true values for low effort months, and less than 15% difference from true values for high effort months. While there was higher estimation error for low effort months, the low number of trips in these months means that this error equates to low numbers of actual fishing trips. Randomly sampling of whole days with weekday and weekend day strata achieved much lower accuracy than random hour sampling approaches with weekday and weekend day strata and is not recommended. Sampling of random hours stratified by weekdays and weekends, performed only marginally worse than a random hour approach that included the addition of higher sampling intensity (weighting) to higher effort diel periods compared to medium and lower effort periods. Target random hours approach is recommended due to the strong diel stratification of effort at most of the ramps during the high effort periods.

Ramp camera effort data has multiple values and can inform design of other sampling programs that involve intercepting fishing parties, such as access point creel surveys (Steffe *et al.* 2017). The data set of boat launch and retrieval activity across various regions will be useful for planning and reviewing the current creel survey program in Victoria as it provides a contemporary snap-shot of diel, daily and monthly patterns of fishing effort. It can also be used for conducting further simulation and modelling studies to inform the design of surveys to estimate total harvests from PPB and WPB, i.e. bus-route, aerial survey designs (Askey *et al*. 2018). It could also be used to look at weather and lunar effects on effort, and potentially develop predictive models incorporating such factors as wind strength and direction, barometric pressure, and moon phase. Such models might prove useful in hindcasting effort variation in earlier years. The creel survey program has historically estimated effort trends by counting boat tailers, the reliability of this technique can be tested against the ramp camera data set to determine whether historic occasional trailer counts can be used as proxies for effort variation at ramps not monitored with cameras and in previous years.

In the long-term it is desirable to limit the need to classify images as done in this trial. However, applying sub-sampling routines can still be cost-effective for targeted monitoring programs. For example, a monthly sub-sampling approach for one ramp with three lanes may incur data associated costs of <$AUD 350 per month for higher effort months and <$AUD 150 per month for lower effort months. If less accuracy was acceptable these costs are reduced. A targeted program for monitoring trends in recreational Snapper fishing effort for the WVSS could involve three months (October-November-December) and four camera systems at the highest usage launch facilities (Clifton Springs, Altona, Patterson River, Hastings, Fig. 3). The annual cost associated with data management and manual image classification for this program is estimated to be between $AUD 4,200 - 5,400. With the addition of annual fixed costs of around $2,100 for maintaining and replacing each system every 8 years, the total cost of the data collection program per year would be between $AUD 12,600-13,800.

This financial cost should be considered in relation to the costs, logistics (including occupational health a safety of creel clerks), and accuracies associated with other effort estimation approaches such as phone/mail/diary, roving and access point creel surveys. In the case of Victoria's access point creel survey program, it targets higher effort periods, weekends and fine weather days to achieve higher numbers of interviews per unit of survey time, with the main objectives to estimate catch rate and composition trends. The survey is not designed around the objective of effort estimation. Adapting the current access point creel survey to adequately estimate effort, as well as catch rates and composition would be costly, requiring more survey days to capture weekday strata, sampling after dark, and application of a truly randomised approach to capture the effort variation, including the poor weather days.

Combination of camera-based effort monitoring with access point creel surveys or other methods such as phone apps. and angler diaries for obtaining catch rate and compositional data will be an important step forward for monitoring of recreational harvest trends, given the high cost of total harvest estimates. Steffe *et al.* (2008) demonstrate the benefits of such supplemented access point sampling designs using traffic counters as a continuous effort monitoring system. Our experience with traffic counters has been mixed, with the main issues related to vandalism and calibration. Traffic counters could be a useful compliment to IP cameras for smaller ramps and targeted periods, but IP cameras have the great advantage that they can be easily checked for operational status, data are uploaded automatically, and calibration of activity is simpler because the activity can be directly observed.

While time lapse image capture and image sub-sampling may be suitable for targeted monitoring programs, the requirement for manual image classification will need to be reduced or mostly eliminated if ramp cameras are to be used on a larger-scale and for continuous monitoring. The pilot study of activity sensor software indicated this approach could provide suitably accurate estimation of boat launch effort, with limited requirement for manual image classifications. The results of the activity sensor trial would have also underestimated the potential of the activity sensor software because we did not experiment with different positioning of the cameras and/or fine tuning of software settings by structured activity experiments. The use of activity sensor image capture and targeted camera positioning has clear potential to significantly reduce costs of estimating boat fishing effort and is recommended for long-term application of the ramp cameras. We estimated that for full annual coverage of a single ramp with up to 3 or 4 immediately adjacent lanes using activity sensor would cost under $AUD 3,000 including all costs, with less than $AUD 1,000 of this cost-associated with the actual data generation. Given the high value of the recreational Snapper fishery this would be a minor cost given the benefits of having accurate data on fishing effort.

The activity sensor approach will require some time-lapse image capture and manual image classification of activity types to develop the regression models and provide consistency checks on proportions of activity that are due to boat fishing versus other activities at each ramp. Although data on proportions of vessels engaging in fishing could also be obtained by creel clerks, creel clerks already have enough work to do during survey times. Fine tuning of activity sensor settings through controlled activity experiments would be expected to reduce the repeat counting of the same launch/retrieval events, but occasional calibrations of regression models between activity sensor file counts and true vessel launches or retrievals data would be important. These calibrations may only require several weeks or random days of manual image classification across a range of effort levels each year to generate the required regression models. Overtime, it may be possible to use a standard regression model for different months or groupings of months (i.e. high, low effort), and factor variability in the regression relationship into the uncertainty of the estimations. It could also be possible to automate the processes of converting the activity count data to recreational fishing vessel launches, so that fishing activity data could be updated routinely and displayed for public or management agency viewing.

Summary

Depending on the monitoring objective, the use of IP cameras and the way images are captured and processed can be varied. IP cameras can be remotely tasked to turn on and off at different times (i.e. to only capture images in specified months, times or days), or to run continuously. Image sets can then be sub-sampled in various ways to achieve desired levels of estimation accuracy and cost trade-off. Due to post-processing and ongoing image upload costs, ramp cameras operating in time lapse image capture mode are most effectively used to target key ramps and times for targeted studies. However, with the development of activity sensor software, appropriately positioned cameras and fine-tuning of activity sensor settings, it is expected this technology will supersede the requirement for time-lapse image capture for ongoing monitoring and greatly reduce the cost and feasibility of boat ramp cameras for measuring boat fishing effort.

Chapter 2: Integration of boat ramp camera effort and creel survey data to estimate local recreational Snapper harvests and demonstrate a relative harvest index

Introduction

Monitoring recreational fishing harvest is challenging because recreational fisheries are often spread over large areas with many access points and have a diverse range of participants and skill levels. Effort in recreational fisheries also responds to a range of socio-economic and environmental influences operating on different time and space scales that can be difficult to predict and model or track with proxy indicators (Carter *et al.* 2015; Beaudreau and Whitney 2016; Powers and Anson 2016). This means that harvest can vary notably from year to year independent of the availability of the target species. Estimating total recreational fishing harvests is resource intensive and expensive (i.e. off-site large-scale phone diary surveys, on-site/access point surveys, harvest tags or permits etc.) and generally is not regularly done. The lack of continuous monitoring or recreational harvest however, has implications for optimising the socio-economic value and long-term sustainability of fisheries (National Research Council 1998; Pereira and Hansen 2003; Wolf-Christian *et al.* 2007). For example, stock assessments that estimate biomass require information on total harvest. The implementation of active harvest management approaches, such as harvest strategies, require regular information on harvest or fishing mortality as this is a key parameter that operational management aims to influence. Finally, information on recreational harvest is often important for the operation of allocation policies between commercial and recreational sectors.

While regular estimation of total recreational harvests does occur for some Australian jurisdictions (i.e. 5-year intervals in South Australia), in others such as Victoria, recreational harvest estimates have no regular schedule and occur sporadically many years apart, if at all. Development of improved approaches to interpolate/extrapolate total recreational harvests between occasional "anchor point" estimates is important. One approach is to develop a representative index of harvest variation that can be used to track variation in the recreational harvest over time. Where occasional total harvest anchor point estimates occur, the harvest index can be used to interpolate total harvest estimates between the anchor points. Hartill *et al.* (2016) provide a great example of this approach, whereby indices of recreational fishing harvest are calculated annually using creel surveys to collect harvest rate and composition data and boat ramp cameras to count fishing trips. These harvest indices are calculated at three major boat ramps for New Zealand's largest Snapper, *Chrysophrys auratus,* stock and recreational Snapper fishery. The harvest indices from these major ramps are then scaled to the occasional "anchor point" total catch estimates for the entire fishery/stock region to create a continuous annual time series of total recreational harvest.

Snapper support a highly important inshore recreational fishery in Victoria. The fishery is mostly boat based and largely focussed on two sheltered bays in central Victoria; Port Phillip Bay (PPB) and Western Port Bay (WPB), where adult Snapper (> 40 cm total length) aggregate to spawn in the spring and early summer (October – December) (Coutin *et al.* 2003; Hamer *et al.* 2011; Hamer and Mills 2017). The fisheries in these two bays are part of the broader Western Victorian Snapper Stock (WVSS) that extends for over 800 km from central Victoria to south-east South Australia, with PPB being the major spawning and nursery area (Hamer *et al.* 2011; Fowler *et al*. 2017). While smaller sub-adult fish are targeted in the later summer/autumn, the bulk of the biomass is harvested during the spawning fishery from October to December (Coutin *et al*. 2003; Ryan *et al.* 2009). Moreover, while there is also a commercial fishery, the harvest by this fishery is reported through mandatory reporting of catch and effort, is thought to be less than a third of the recreational harvest and is now limited by harvest caps. The long-term management of the WVSS will require ongoing information on the recreational component of harvest and the implications of this harvest (i.e. fishing mortality) for achieving sustainability, socio-economic and angler satisfaction objectives.

The Victorian Fisheries Authority (VFA) conducts an annual access point creel survey program that targets peak fishing periods in PPB and WPB during spring-autumn (mid-October-April). This program targets all major boat launch facilities in these two water bodies and has been running since 2002. The data from the creel survey program is currently used to provide recreational catch rate and length frequency composition for various species, as well as various other information on anglers. Snapper is a key species targeted by these surveys. The catch rate and composition information are important for ongoing fishery performance and stock assessment, however, they do not adequately measure the dynamic harvest impact of the recreational sector. There have only been two total recreational harvest estimates with suitable coverage for this fishery/stock over the last 20 years; one in 2000/2001 (Henry and Lyle 2003) and the other in 2006/2007 (Ryan *et al.* 2009). These estimates, when used as indicative of harvests in other years are vigorously questioned by stakeholders as it is argued that recreational effort, and therefore harvest, can vary substantially from year to year due to variable climate and socio-economic factors. There is a clear need to develop an integrated approach involving annual estimations of fishing effort with creel survey data, to monitor trends in recreational harvest pressure so this can be factored into stock assessment and management of the WVSS.

Chapter 1 described a trial of IP cameras positioned at boat ramps to estimate recreational boat fishing effort using both time lapse and recently developed activity sensor image capture methods. The outcomes of the trial indicated that this approach can provide sufficiently accurate estimates of effort, and that the costs of application are not prohibitive in relation to the perceived value of this fishery. Estimation of harvest involves the product of at least three random variables: effort, retained catch rate (or 'harvest rate' pertaining to retained fish) and catch composition. Ongoing implementation of boat ramp cameras to accurately measure effort trends, and the continuation of the current access point creel surveys provides the opportunity to produce an ongoing harvest index for Snapper in the major fishing locations. Because such an index would adequately capture the effort dynamics it should be more accepted by stakeholders and managers as representative of changes in harvest overtime. However, each of the variables that contribute to the harvest estimation has its own associated error, and these errors are multiplied when it comes to the estimation of harvest. Thus, while each of the components of the harvest equation might be estimated by targeted monitoring programs with acceptable precision for that program, the error of the harvest estimate may be significantly greater. Obtaining acceptable uncertainty for a harvest index may therefore require reconsideration of how the individual monitoring programs that estimate the key parameters for estimating harvest are structured, including how resources are allocated across the different monitoring components.

The objective of this chapter is to estimate Snapper harvest in weight and numbers and its associated error, using the ramp camera effort monitoring approaches discussed in chapter 1 and data from the ongoing access point creel surveys. For one ramp complex we also use the ramp camera effort estimates to validate records of on-site tickets sales and use this additional effort data to create a 5-year time series of harvest estimates, and demonstrate a relative harvest index, for the highest effort month (November) at this ramp facility. The harvest estimation approach demonstrated in this chapter can be used to create a "harvest index" for other launch facilities (i.e. access points). Where several launch facilities within a stock or fishery region are monitored with this approach, it will be possible to create a stock or fishery region 'harvest index' that is representative of variation in recreational harvest pressure across the fishery (Hartill *et al.* 2016). Such an index can then be scaled to occasional total recreational harvest estimates to create continuous time series of total recreational harvest required for stock assessments and sustainable harvest management of the WVSS.

Methods

While the ramp cameras can operate 24 hours, all year if required, the current creel survey program is targeted to higher fishing effort months and weekends. The scope of this study is therefore restricted to key ramps and the peak Snapper fishing and survey month (November) to demonstrate the approach for monthly scale access point harvest estimations. Table 5 lists the ramps and years that were included, and the approaches applied to effort estimation (discussed in detail below). A script was written in R (R Core Team 2017) to conduct the harvest estimations and calculate associated errors according to the methods described below.

Table 5 Summary of spatial and temporal coverage of the harvest estimation study, and approaches used for estimation of boat fishing effort.

Launch facility	***Years***	***Effort estimation methods*** *1 = 2 min time lapse with sub-sampling* *2 = activity sensor regression model* *3 = ticket sales*
St Helens	2014, 2015, 2016	1, 1, 2
Limeburners Point	2014	1
Clifton Springs	2014, 2015, 2016	1, 1, 1
Altona	2015, 2016	1, 1
Patterson River	2012, 2013, 2014, 2015, 2016	3, 3, 3, 1, 1,3
Hastings	2015, 2016	1, 2

Fishing Effort Estimation

In chapter 1 we explored two main approaches to using IP cameras at boat ramps to measure recreational boat fishing effort: 2 minute time lapse image capture with image sub-sampling, and activity sensor (herein referred to as *Image Sub-sampling* and *Activity Sensor*). At one launch facility; Patterson River, a ticket sales system also operates. This provided another source of effort data that was explored to provide an extended time series of effort for this ramp complex, herein referred to as *Ticket Sales*. Each of the three effort measurement approaches is discussed below. Note that charter boats while included in the effort estimations if they are a trailored vessel, often conduct multiple trips each day and are not typically surveyed by creel survey clerks. Harvest and effort by charter boats would therefore not be adequately incorporated into the effort and harvest estimations using the ramp cameras and standard creel survey methods applied. The charter fishery is not monitored by mandatory reporting in Victoria, and trends in charter fishing harvest are assumed to reflect trends in the general recreational fishery. Charter fishing harvest would however be expected to be included in total harvest estimates using the phone diary/licence data base approaches used previously (Ryan *et al*. 2009).

Image Sub-sampling

For this study we used a sub-sampling approach that required 220 hourly-blocks to be sampled for each ramp in each month (chapter 1), with approximately 45% of sampling allocated to WE (weekend) and 55% to WD (weekday) day type strata, with higher sampling effort in higher and medium diel effort periods than low effort periods (see chapter 1, *Target Random Hourly* SS1 method, with 4WE and 5WD). Based on the bootstrap simulations of this approach it is expected to estimate launch numbers per month to within ±15 % of the true numbers at individual ramps (chapter 1).

In chapter 1, uncertainty of this approach was expressed as an “estimation error” from bootstrapping (i.e. 95% confidence interval of the bootstrap estimates/mean of the estimates). In this study where the effort estimates (number of fishing vessel launches = number of fishing boat trips) are combined with the harvest rates (harvest per fishing boat trip), and length composition data to estimate harvest, the sub-sampling routine is only conducted once-off for each harvest estimate. The variance associated with the expanded effort estimate from a single sub-sampling is required to be combined with the other sources of variation that contribute to the overall variation in the harvest estimates.

The *Target Random Hourly* sub-sampling approach involves estimation of mean numbers of launches for each hour of the day for WD and WE day type strata each month. These means are then expanded to the total available WE and WD hours for each hour of the day for the month to estimate the total launches. The population mean for the stratified population is therefore:

$$\bar{Y} = \sum_{h=1}^{L} W_h \bar{Y}_h$$

and this is estimated in stratified sampling as $\bar{y}_{st}$:

$$\bar{y}_{st} = \sum_{h=1}^{L} W_h \bar{y}_h$$

The variance of $\bar{y}_{st}$ with the finite population correction factors is:

$$Var(\bar{y}_{st}) = \sum_{h=1}^{L} W_h^2 \frac{s_h^2}{n_h} \left(\frac{N_h - n_h}{N_h}\right)$$

The population total (i.e. total launches for the month) is estimated as

$$\hat{Y}_{st} = N\bar{y}_{st}$$

It follows that $\hat{Y}_{st} = N\bar{y}_{st} = N(W_1\bar{y}_1 + W_2\bar{y}_2) = N\left(\frac{N_1}{N}\bar{y}_1 + \frac{N_2}{N}\bar{y}_2\right)$ is the sum of the estimated total launches in each day type stratum, and the variance of the estimate of total launches is therefore:

$$\boldsymbol{Var(\hat{Y}_{st}) = N^2 Var(\bar{y}_{st})}$$

Where

h denotes stratum being considered (weekend and weekday hours)

L = number of strata, (in this case L=2)

N_h = total number of units (i.e. hourly-blocks) in stratum *h* (i.e. total number of hourly-blocks in the stratum)

$N = \sum_{h=1}^{L} N_h$, total population size (i.e. total number of hourly-blocks across all stratum)

n_h = number of units in stratum (i.e. the number of hourly-blocks in the sub-sample from the stratum)

$W_h = \frac{N_h}{N}$ stratum weight

$\bar{Y}_h =$ the population mean for stratum *h*

$\bar{y}_h = \left[\sum_{i=1}^{n_h} y_{hi}\right]/n_h$ is the sample mean for stratum *h*

y_{hi} = the value obtained in i^{th} unit of for each stratum *h*

s_h^2 = variance of stratum h. (i.e. the sum of the variances from each hourly-block sub-sample for the stratum)

Activity Sensor

Estimation of effort using activity sensor data involves the application of regression models of activity sensor triggers (i.e. number of image captures per day, independent variable) and actual launches per day (dependent variable) developed for a high effort month in one year to estimate actual launches in the high effort months of other years using the activity sensor data for those years. This assumes that the regression models and associated errors are consistent between the years. While this assumption requires further testing, the analyses in chapter 1 provided confidence that this is likely for similar high effort months.

When launch numbers are estimated from activity sensor image triggers**,** let *X* be a random vector (in this case a vector of regression coefficient) with the covariance matrix $\sum X$ and let *A (activity sensor image triggers for a month)* be a matrix that can act on X. The covariance matrix of the vector *AX* is

$$\sum AX = A \sum X \ A^T$$

The variance of the total effort for a month from activity sensor regression model would therefore be

$$Var \sum_{i=1}^{n} y_i = sum(A \sum X \ A^T)$$

where *n* is the number of days in the month.

Ticket Sales

At Patterson River, the most heavily used ramp facility during Snapper fishing season, tickets are sold as individual daily launch tickets or season passes (season = September 1 – August 31). A season pass costs approximately 11 x the cost of a daily launch ticket. The tickets are sold from a manned ticketing station which does not operate 24 hours but modifies operating hours in relation to seasonal patterns of fishing effort. During the peak Snapper fishing months (October to December), the office opens for longer hours, starting earlier in the mornings and closing later in the evenings to capture the majority of fishing launches (i.e. 2-3 am until 8 pm). Data from ramp camera classification of activity types indicated that from October to December 90% (±5 SD) of launch activity at the Patterson River facility is due to fishing trips. The number of ticket sales provided an additional source of fishing effort data but required validation against data collected from the boat ramp cameras.

To compare ticket sales with ramp camera data on number of fishing vessel launches, the ticket sales data were adjusted to account for the expected non-fishing related launches based on the boat ramp camera classifications. While it is unknown how often the individual season passes are used on average each month, the cumulative number of season passes that were valid each month, multiplied by two for the peak Snapper fishing months, when added to the daily launch tickets and adjusted for non-fishing launches closely approximated the number of fishing vessel launches determined from the ramp cameras (Table 6). When ticket sales data were used in the harvest estimations it was treated as an accurate measure of effort with no error.

Targeted and non-targeted Snapper fishing effort

Because not all fishing trips target Snapper, even in peak Snapper fishing months, and non-targeted trips have different harvest rates than targeted trips, it is necessary to portion the total effort estimates into the numbers of targeted and non-targeted trips with an associated variance. The proportions of targeted and non-targeted Snapper trips were estimated from creel surveys, which included a question on targeting preferences.

To calculate the variance of the estimated proportions of targeted and non-targeted trips, let $\hat{p}$ be the proportion of trips that were targeting Snapper in the month and the variance of this is estimated as,

$$var(\hat{p}) = \frac{\hat{p}(1-\hat{p})}{n}$$

Then the effort targeting Snapper was calculated as

$$Effort_{snapper} = Total\ effort\ at\ that\ ramp\ for\ that\ month * \hat{p}$$

The variance of the targeted Snapper fishing effort is $Var(Effort_{snapper})$ is calculated as the product of two random variables

$$Var(X * Y) = var(X) * Var(Y) + Var(X)[E(Y)]^2 + Var(Y)[E(X)]^2$$

Where *X* represents estimated total effort either from image sub-sampling, activity sensor or ticket sales, and *Y* represents the proportion of trips that were targeting Snapper ($\hat{p}$).

The same approach is repeated for not-targeted effort to provide the estimated numbers of trips and associated variances for both targeted and non-targeted Snapper fishing.

Harvest rates

Boat ramp creel surveys are primarily focussed on collecting information on retained catch rates and length compositions (both in terms of species and lengths), however, the surveys also collect information on other factors that allow categorisation of the fishing trip, such as; avidity, age bracket, target species, gear/bait, fishing region, technology used, post-code, and satisfaction. Importantly, for the purposes of this study the creel surveys provide data on the number of Snapper harvested for individual boat trips (i.e. the unit of effort) and the length composition of harvested fish. These data can be combined with estimates of the number of boat trips to estimate the harvests from individual boat ramps.

The surveys occur on weekend days to maximise the numbers of interviews per hour of survey time. They also do not occur on days when weather conditions are not conducive for boat fishing. The surveys follow a stratified randomised design, with AM and PM as day time strata and ramps and days as random. Each AM or PM survey day consists of surveys at 3 or 4 ramps with individual survey wait times of half or one hour. For this study we compiled the creel survey data for all interviews conducted in the adult Snapper season (October – December). Survey ramps were grouped into three regions for harvest rate estimation: North-East PPB; South-West PPB, and WPB, with 8, 7 and 9 boat ramps, including those with the ramp cameras, in each region respectively (Fig. 33). The regional groupings were based on knowledge of migratory habits of adult Snapper and travels distances/fishing areas of vessels using different ramps. Ramp camera effort data were matched with the harvest rate data for each region.

Boat fishing trip was the unit of effort, irrespective of numbers of anglers on a boat. Mean nominal harvest rates (number of Snapper harvested boat fishing trip^{-1}) were determined for targeted and non-targeted trips in each region and variances calculated by treating each survey of a completed boat fishing trip as a replicate. Because trip was a constant effort unit as opposed to hours fished, there was no need to account for variability in trip lengths for the catch rate estimator (i.e. ratio of means and means of ratio approach are equivalent when trip effort is constant, Pollock *et al*. 1994).

Previous creel surveys conducted between 2006-2011 with the same sampling methods, sampled weekdays and weekends. These earlier survey data were analysed to assess the potential for weekend harvest rate data to under, or over-estimate weekday harvest rates. For the two regions in PPB, these analyses (i.e. General Linear Model, negative binomial error distribution, log link function) indicated that weekday Snapper harvest rates were slightly, but significantly, higher than weekend harvest rates.

The differences were relatively small (i.e. North-East PPB, harvest rate, mean ±SD, weekday = 1.576 Snapper per trip ±2.823, weekend 1.280 ±2.443; South-West PPB, harvest weekday = 0.466 ±1.267, weekend 0.342 ±1.029). However, for WPB there was no significant difference between weekend and weekday harvest rates. In this study we did not adjust the harvest estimates to account for the likelihood that weekday harvest rates are expected to be on average higher than for weekends, because we had no concurrent data. Collection of weekday harvest rate data is recommended to improve the accuracy of harvest estimates in future. Harvest estimates presented in this study for the selected PPB ramps are therefore expected to underestimate total harvests.

Harvest estimation

Snapper harvest in numbers of fish from targeted Snapper trips each month was estimated by multiplying the effort estimate (i.e. number of 'targeted' Snapper fishing trips) for the ramp month combination with the appropriate regional nominal targeted mean catch rate. The variance of this harvest estimate was calculated as:

$$Var(X * Y) = \ var(X) * Var(Y) + Var(X)[E(Y)]^2 + Var(Y)[E(X)]^2$$

Where *X* represents the estimated effort targeting Snapper and *Y* represents the mean nominal Snapper catch rate for anglers who are targeting Snapper.

Harvest numbers for non-targeted Snapper trips were similarly calculated by multiplying the estimated non-targeted Snapper effort with the appropriate regional non-targeted catch rates. Variance of the of the non-targeted harvest numbers was computed as for the targeted harvest numbers.

The overall variance for total Snapper harvest in numbers is calculated as:

$$Var(snappertarget) + Var(snappernontarget)$$

Conversion of harvest numbers to harvest weight

Fish length data from creel surveys were considered a random sample of the harvested fish. Individual length data were converted to weights using the relationship:

$$W = aFL^b$$

where W = weight (Kg), FL = fork length (cm), a= 4.448×10^{-5} and b= 2.7889

Snapper harvest numbers were converted into harvest weight by multiplying by the mean weight of the measured Snapper for that month and the resulting variance is the product of two random variables, where *X* represents the estimated Snapper harvest in numbers and *Y* represents the mean Snapper weight.

$$Var(X * Y) = \ var(X) * Var(Y) + Var(X)[E(Y)]^2 + Var(Y)[E(X)]^2$$

The variance estimates for total harvest numbers and weights were used to calculate the standard error (SE) as the primary indicator of uncertainty in the harvest estimations.

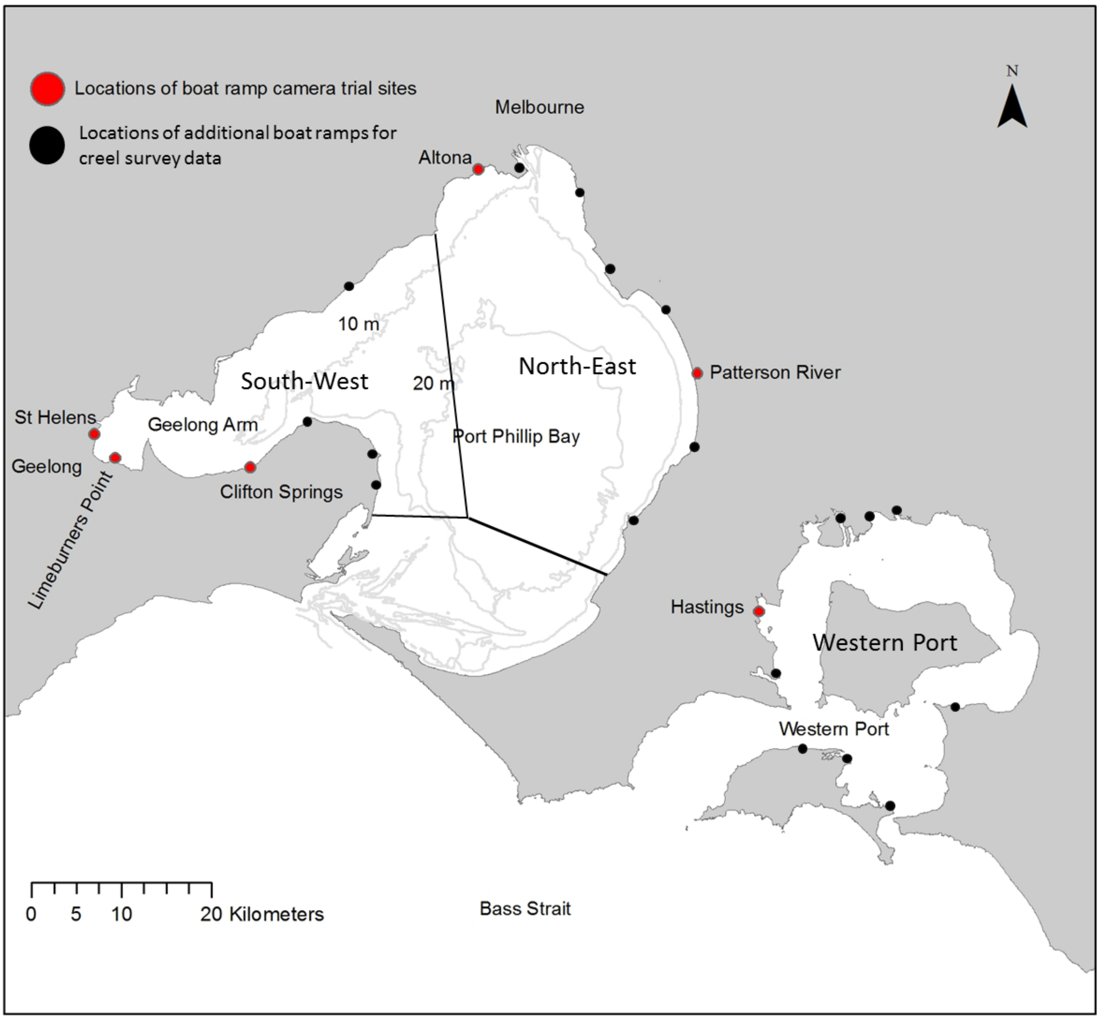


Figure 33 Map of Port Phillip Bay and Western Port showing location of boat launch facilities: labelled red dots are the launch facilities with ramp camera effort monitoring and creel surveys, black dots are launch facilities with creel surveys only.

Results

Fishing effort, catch rates and weight composition

For the Patterson River launch facility, the ticket sales data provided similar estimates of total effort to the ramp cameras, after adjustments for non-fishing vessels and season tickets (Table 6). Provided ticket sales operation and reporting continue to occur in a consistent manner, and the diel patterns of fishing effort are consistent, the ticket sales data could provide a valid source of effort data for estimating harvest and effort trends at this location. However, the ticket sales are operated by an independent provider and are not strictly controlled or monitored. Therefore, while ticket sales data provide a secondary source of information, for example if cameras fail during peak periods, it is uncertain whether they will be available and collected in a consistent manner in the long-term. In this study it was reasonable to use the ticket sales data to extend the effort time series for harvest estimations prior to 2014, and we also used the ticket sales data for effort estimation in November 2016 due to a camera malfunction (battery failure) that compromised the ramp camera data for Patterson River.

Table 6 Comparison of boat fishing launches estimated from ticket sales with those determined from boat ramp cameras in peak Snapper fishing months at the Patterson River ramp facility.

Month-Year	Daily launching passes	Cumulative season passes X 2	Total launches tickets - month	Total launches tickets adjusted for non-fishing	Fishing launches estimated from ramp cameras	Ratio ramp camera estimated fishing boat launches: ticket sales fishing boat launches
Nov-12	**6311**	**1290**	**7612**	**6851***	**NA**	**NA**
Nov-13	**5247**	**1104**	**6362**	**5726***	**NA**	**NA**
Oct-14	2815	1036	3851	3582	3938	1.10
Nov-14	**5098**	**1190**	**6288**	**5785**	**5485**	**0.95**
Dec-14	2092	623	2715	2226	2231	1.00
Nov-15	**3750**	**862**	**4612**	**4335***	**4280****	**0.99**
Nov-16	**3357**	**345**	**4092**	**3683***	**NA***	**NA**

*Adjusted for non-fishing effort by x 0.9, ** ramp camera launches estimated from sub-sampling (4WE/5WD) due to missing data 12-16th Nov (see Table 2). NA: no ramp cameras installed; NA*: images available but not analysed at time of writing.

The number of boat fishing trips at individual launch facilities in November ranged from approximately 900 trips in 2015 at St Helens, where there are three launch lanes, to 6,850 trips at Patterson River in 2012 where there are nine launch lanes (Table 7). Targeted Snapper fishing was consistently highest (ca. 90%) for trips surveyed in the North-East PPB region (i.e. Altona/Patterson River) but varied across the other regions from as low as 34% of trips in the South-West PPB region (i.e. St Helens, Limburners Pt and Clifton Springs) in 2016, to 77% in the WPB region (Hastings) in 2015 (Table 7). The lower targeted Snapper fishing effort in the South-West PPB and WPB regions is due the regionally higher availability of other target species, in particular; King George whiting, and calamari. Catch rates also varied strongly between targeted and non-targeted Snapper trips. It was therefore clear that accounting for targeted and non-targeted effort and catch rates was important in the estimation of harvests.

The mean weights varied marginally across creel survey regions and years for the peak October-December fishing period and were typically in the range of 1.7-2.5 kg per fish, which is equivalent to a length range of 50 – 60 cm total length. Snapper of this size are considered fully mature in Victorian stocks (Coutin *et al.* 2003). All regions appeared to have a slight increase in mean weight of harvested fish in 2015 compared to 2016 (Fig. 34).

Coefficients of variation (CV) were high for the target and non-target harvest rates, due to the high variability in harvest rates among surveyed trips, common occurrence of low and zero harvest rates and low sample sizes in some years. Despite this the CV for the harvest numbers and harvest weights were acceptable (mean CV 25%, Table 7) due to the high precisions of the effort and mean weight estimates.

Table 7 Summary of effort, harvest rates, and harvest total estimates for the peak Snapper fishing month of November. IS = Image sub-sampling, AS=Activity sensor, TS = Ticket sales.

Launch facility	Year (November)	Effort method	Estimated effort (No. of trips ±SE)	% Targeted Snapper trips (No. trips surveyed)	Targeted harvest rate (No. Snapper. $trip^{-1}$ ±SE)	Non-targeted harvest rate (No. Snapper. $trip^{-1}$ ±SE)	Harvest numbers (±SE)	Harvest weight (tonnes) (±SE)
Clifton Springs (2 lanes)	2014	IS	1832 ± 130	67% (45)	1.48 ± 0.48	0 ± 0	1535 ±531	2.91 ±1.03
	2015	IS	1872 ± 87	68% (60)	1.56 ± 0.35	0.26 ± 0.26	2166 ±512	4.10 ±1.02
	2016	IS	1955 ± 125	34% (79)	0.96 ± 0.41	0.12 ± 0.08	845 ±329	1.50 ±0.59
Limburners Pt (3 lanes)	2014	IS	927 ±70	67% (45)	1.48 ± 0.48	0 ± 0	777 ±270	1.57 ±0.52
St Helens (3 lanes)	2014	IS	940 ± 66	67% (45)	1.48 ± 0.48	0 ± 0	788 ±272	1.49 ±0.53
	2015	IS	902 ± 51	68% (60)	1.56 ± 0.35	0.26 ± 0.26	1043 ±249	2.23 ±0.58
	2016	AS	960 ± 27	34% (79)	0.96 ± 0.41	0.12 ± 0.08	415 ±160	0.74 ±0.29
Altona (6 lanes)	2015	IS	3092 ± 235	94% (34)	1.56 ± 0.36	0 ± 0	4486 ±1091	9.76 ±2.54
	2016	IS	5506 ± 274	86% (171)	0.93 ± 0.15	0 ± 0	4501 ±784	8.01 ±1.49
Patterson River (9 lanes)	2012	TS	6851	98% (82)	3.28 ± 0.34	0 ± 0	21514 ±2290	51.75 ±5.73
	2013	TS	5726	97% (64)	2.76 ± 0.32	0 ± 0	14819 ±1748	35.87 ±4.42
	2014	IS	5695 ± 406	89% (65)	1.25 ± 0.20	0.14 ± 0.14	5406 ±1026	10.24 ±2.01
	2015	IS	4147 ± 318	94% (34)	1.56 ± 0.36	0 ± 0	6016 ±1465	13.10 ±3.42
	2016	TS	3683	86% (171)	0.93 ± 0.15	0 ± 0	3011 ±502	5.36 ±0.96
Hastings (4 lanes)	2015	IS	2113 ± 164	77% (52)	1.73 ± 0.36	0.25 ± 0.25	2147 ±529	5.67 ±1.52
	2016	AS	3427 ± 206	69% (39)	1.59 ± 0.34	0.08 ± 0.08	3198 ±758	5.79 ±1.48
Average (min-max) CV			5% (3-8)		145% (61-221)	400% (267-481)	25% (11-39)	26% (11-39)

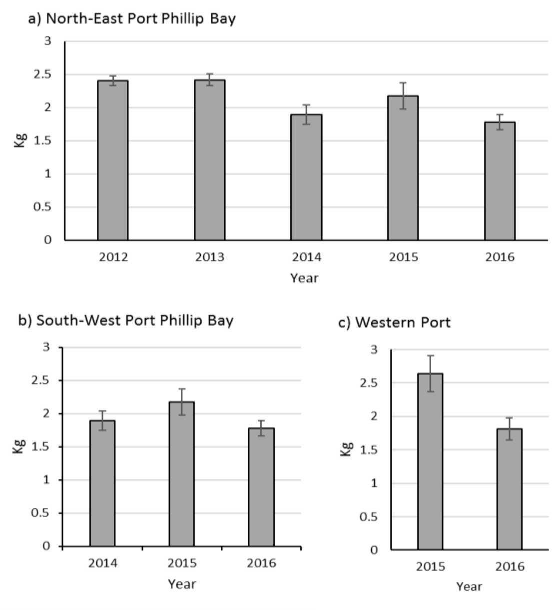


Figure 34 Mean weights (±SE) of individual Snapper harvested by anglers during October-December in three creel survey regions used for estimation of harvests from boat launch facilities.

Harvest estimates

Estimates of November Snapper harvest across the six launch facilities for the period 2014-2016 showed that harvests from Patterson River and Altona were similar, ranging from approximately 13 to 5.5 tonnes and 10 to 8 tonnes respectively. The Hasting ramp had harvest estimates of approximately 5.5 tonnes in 2015 and 2016, and ramps near Geelong (St Helens, Clifton Springs, Limeburners Pt) had November harvests from approximately 1 to 4 tonnes, with highest harvest from Clifton Springs. For the Patterson River launch facility, the estimated November Snapper harvest declined remarkably from approximately 50 tonnes in November 2012 to 10 tonnes in November 2014 (Table 7; Fig. 35).

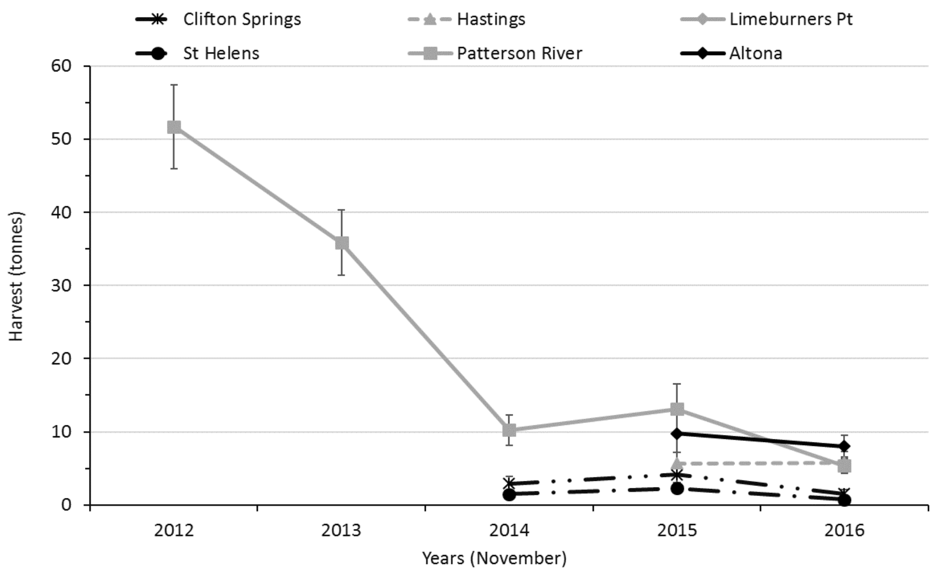


Figure 35 Estimated (±SE) total November Snapper harvests by recreational boats from six launch facilities.

At Patterson River, from 2012 to 2016, Snapper harvest rates declined to a greater extent than the estimated effort (number of trips) and average weight of harvested fish (Fig. 36 a). While effort declined by approximately 45%, and harvest rate declined by 70% from 2012 to 2016, estimated total harvested weight declined remarkably, by approximately 90% (Fig. 36 b).

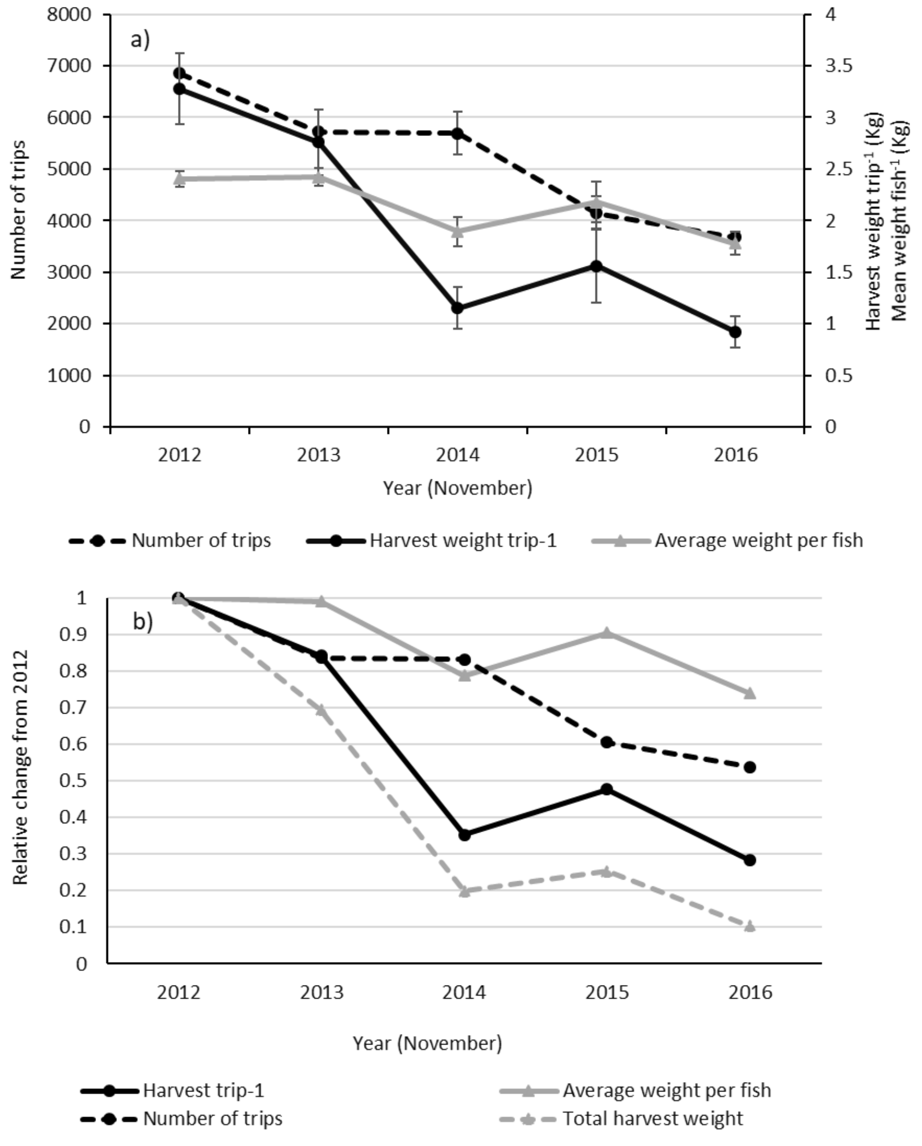


Figure 36 Patterson River launch facility: a) Trends in number of fishing trips (boat trips), harvest rate per trip and mean weight of harvested Snapper, and b) changes relative to 2012, in the number of fishing trips, harvest rates per trip, mean weights of harvested Snapper and total weight of harvested Snapper (i.e. harvest index) for November.

Discussion

This study demonstrated the integration of boat ramp camera estimates of fishing effort with creel survey data on per trip harvest rates and composition, to estimate total harvest of Snapper from boat launch facilities at a monthly scale. The method incorporated the various uncertainties associated with the effort, harvest rate and composition components of the total harvest estimation. Uncertainty around the harvest estimates was acceptable with coefficients of variation of ca. 10-40%, mean of 25%. Most of the uncertainty in the harvest estimates related to the harvest rate estimation, rather than the effort estimation. The November harvest estimates for the same years were similar at the Patterson River and Altona launch facilities, the highest capacity boat launch facilities around PPB. The Geelong region launch facilities had lower harvest estimates, as they have lower total and targeted effort, and the Hastings launch facility showed harvest estimates that were intermediate, or similar, to Patterson River and Altona. It was interesting that between 2015 and 2016 the harvest estimates were similar at Altona, and at Hastings harvest in 2016 was higher than 2015, in contrast to Patterson River where the harvest estimate declined. These differences appeared to have been largely driven by the spatial effort dynamics with increased effort through Altona (over 2000 more trips) and Hasting (over 1000 more trips) from 2015 to 2016 and decreased effort through Patterson River (approximately 500 less trips). This spatial shift in effort might reflect spatial shifts in fish availability, weather conditions, ramp conditions and or anglers choosing alternative launch locations and fishing areas for other reasons such as ramp congestion and crowding of local fishing areas. Importantly, this indicates that a harvest index for a fishery region or stock should include multiple launch facilities to ensure trends in the harvest index are representative of the fishery region or stock, rather than particular launch facilities and fishing areas.

The boat ramp camera approach collects imagery continuously, which allows the user to have full flexibility to conduct randomised and unbiased sampling, as theoretically there are no restrictions on when/how sampling can occur. While realising this flexibility in sampling has associated costs related to image processing, these costs will continue to reduce with development of activity sensing capabilities of IP cameras (chapter 1), potentially image recognition software, and improved systems for processing and managing image files and data (i.e. Greenberg and Godin 2013). While using ramp cameras to estimate boat fishing effort is clearly feasible, the conversion of effort to harvest relies on representative data on species targeting, harvest rates and length compositions for the target species and temporal-spatial strata of interest. Data on species targeting rates is essential to apportion and relate targeted effort (i.e. % of trips targeting species X) to targeted harvest rates for key species such as Snapper. For this study we used harvest rate and length composition data from a survey design that was developed prior to this project, which samples on weekend days to maximise the interview rates. Therefore, while the estimates of the numbers of fishing trips in a month were suitably accurate, the harvest rate and length composition data, and therefore harvest estimates, could be biased by the weekend sampling bias.

During the peak Snapper fishing period from October to mid-December weekday fishing is very common where anglers target the early mornings and late afternoons-early evenings (chapter 1). If weekend anglers are comprised of a different mix of experience/skill levels than weekday anglers, it may be inappropriate to use weekend harvest rates for estimating harvests from weekday effort. We are unsure of the influence of this bias or, importantly, its interannual consistency, but it is reasonable to assume that a greater proportion of anglers who fish weekdays are more avid/experienced than weekend anglers (i.e. avid anglers tend to avoid busy periods, fishing before and after work etc.), and have higher per trip harvest rates (both in numbers and mean size). It follows that the weekend harvest rates applied to the weekday effort in this study would likely underestimate harvest. Acknowledging that the harvest estimates are likely underestimates, importantly the creel data were collected under a randomised sampling approach and therefore can be assumed to be representative of relative changes across years. Assuming the distribution of total effort between weekend and weekdays is relatively consistent, the underestimation bias should be consistent, which is important for the application of the ‘harvest index’ approach.

Ideally the harvest rates and composition data should be estimated for the same strata as the effort data for expansion to total harvest estimates. Increasing the amount of harvest rate and size composition data for both weekend and weekday strata could be achieved by either expanding the creel survey sampling and/or looking at other cost-effective methods for obtaining ‘representative’ harvest rate and composition data, for example, ‘opt in’ electronic reporting systems (i.e. phone apps., electronic diaries, online reporting). Whatever approach is used it must be able to provide representative data. Representative means random sampling, often referred to as probability-based sampling (Pollock *et al.* 1997). Importantly, when collecting harvest rate and composition data for estimating harvest amounts, sampling of fishing trips within a stratum should not be biased to a particular sub-set of anglers (i.e. avidity level) or levels of fishing success for individual trips. This provides challenges for opt in (non-random) electronic reporting systems that will likely attract the more avid anglers who can maintain catch rates as stocks decline (hyperstability), and typically target/catch larger fish (size selectivity bias). Opt in reporting can also potentially suffer from under reporting of trips with low or zero harvests, or harvests of small fish, among a range of other potential biases discussed in Venturelli *et al.* (2016). The major risk is that such biases could result in overestimation of harvest levels, hyper-stability in harvest rates, and positive bias in length composition data, which could in turn lead to failure to identify declines in stock or fishery performance and inappropriate management advice.

Data from opt in methods such as phone apps./electronic diaries is likely to be valuable and worthwhile pursuing, but biases should be understood and adjusted for if used for estimating harvest amounts across a fishery. Adjusting for biases in ‘opt in’ reporting systems would likely require some form of random sampling approach to estimate the biases (Hartill *et al.* 2015). An appropriately designed randomised creel survey would seem the most informative approach to estimating the biases. Onsite surveys also have the added advantage that fish can be identified and measured by trained survey staff. Opt in electronic reporting is an attractive option for increasing the amount of recreational fishing data and the engagement of anglers in fisheries monitoring (citizen science), however, if the data is to be used to inform stock assessments and harvest management, some form of multiple approach bias estimation program is important in the early years of an opt in program, and, if necessary for the objectives of the data collection, methods for bias monitoring and adjustment should be implemented ogoing (Wise *et al*. 2013; Hartill *et al.* 2015; Stuntz *et al*. 2015; Jiorle et al. 2016).

It has often been perceived that recreational fisheries are unlikely to drive stocks to become recruitment overfished because recreational effort (or targeted effort) declines as fish availability declines and most anglers are inefficient (National Research Council 1998; Walters and Martell 2004). This assumption has been called into question (Post *et al.* 2002), and there is a need to better understand how recreational effort targeting Snapper responds to stock condition and other factors that influence or constrain effort levels (i.e. weather, ease of access, crowding, costs etc.), because active management of recreational effort is difficult and often unpopular. For the Patterson River launch facility, where effort and harvest rate data were available from 2012, there was an estimated 90% decline in the relative harvest index over 3 years from 2012 to 2014. Both harvest rate and effort declined over his period, although harvest rate declined to a greater extent. If the example for the Patterson River was indicative of the entire recreational Snapper fishery in Port Phillip Bay, then as the harvest rate declined, the overall effort would have also declined. Assuming the average effectiveness of the anglers was constant (i.e. constant catchability assumption), the result of this effort response would have been declining fishing mortality/exploitation rate as the stock availability declined, clearly a positive sign of self-regulation of effort for stock conservation. Continuation of effort and creel survey monitoring across multiple access points will allow a greater understanding of the effort response and scope for self-regulation across this fishery.

The PPB recreational Snapper fishery primarily targets spawning aggregations that migrate into the bay from coastal waters in spring (Coutin *et al.* 2003; Hamer and Mills 2017). Because of this somewhat uncertain influence of migration and aggregation behaviour, anglers may perceive that poor catch rates in a previous year where largely due to changes in migration rates and aggregation areas more so than stock declines. If this perception is predominant among Snapper anglers, their expectations for each new fishing season may not be overly influenced by their catch rates in the previous year; "each new season comes with new promise". This means that declines in angler effort may lag declining catch rates, as it takes several years of poor catch rates before individual anglers decide to stop/reduce their effort targeting Snapper. Longer time series of effort and harvest rate data would allow characterisation of the relationships between harvest rate and recreational Snapper fishing effort, and perhaps inform modelling of the responses of recreational fishing effort to resource status (Cox *et al.* 2002; Cox and Walters 2002). This is important in the context of understanding management risk and considering the necessity of options for active management of recreational effort to maintain acceptable exploitation rates over the long-term. Further, it would provide managers and stakeholders with information or predictive models to guide decisions on harvest rate or biomass targets for maintaining participation rates in the fishery and associated socio-economic benefits. This is particularly relevant in Victoria where there is a clear objective of maintaining and improving recreational fishing opportunities. Optimising the trade-off between more effort targeting Snapper and maintaining the quality of Snapper fishing expected by anglers over the long-term (i.e. quantity versus quality), is important to achieving this objective. Further, using catch rate data as a biomass proxy for management, will be more valuable when there is understanding of the levels of the biomass proxy at which recreational effort declines or increases notably (i.e. inflection points). For example, if effort drops away notably at catch rate levels well above management critical points for biomass, it would support a degree of self-regulation in the recreational fishery in relation to achieving biological sustainability objectives.

In New Zealand harvest indices are determined for three regions of the major Snapper stock (SNA 1) using ramp cameras and creel survey data. The indices are then scaled to occasional total regional harvest estimates derived from a combined aerial - access point (creel) survey approach (Hartill *et al.* 2013; Hartill and Edwards 2015). This approach allows estimation of total harvests for years when the aerial - access point estimates are not conducted and is providing a greater appreciation of the variable nature of recreational harvest and more informed stock assessment and management (Hartill *et al.* 2016). There is no recent total recreational Snapper catch estimate for the WVSS that we could use to scale harvest indices to. The application of a scaled access point harvest index to track total recreational harvest from the WVSS would require the continuation of effort, catch rate and catch length composition monitoring at, at least the three major Snapper fishing launch facilities in Port Phillip Bay (Clifton Springs, Altona, Patterson River), and the main launch facility in Western Port (Hastings). These ramps service different quadrants of PPB and WPB that have different suitability for boat fishing under different wind conditions. Addition of coastal waters ramps such as Apollo Bay and Portland (far western Victoria) would also be valuable for capturing the coastal component of the overall recreational harvest, although the coastal recreational harvest is low relative to the combined PPB and WPB recreational harvest (Ryan *et al.* 2009). If occasional total harvest estimates are not conducted in the future, the value of continuing to generate the harvest indices is in their use to indicate variation in recreational harvest pressure or relative change in harvest. This would be important for measuring the influence of management changes or other factors on harvest, and better understanding the relationship between stock status, recreational fishing harvest and self-regulation.

Ongoing application of the harvest index approach to monitoring recreational fishing pressure on the WVSS will benefit from:

1. Improving the cost-effectiveness of boat ramp camera effort monitoring, by further development and application of activity sensor software (chapter 1),
2. Improving the representativeness and spatio-temporal coverage of harvest rate and harvest composition data, including sampling on weekdays, and extending the sampling period. Trial of a phone app./electronic diary type approach would be valuable,
3. Inclusion of released and harvested fish in catch rate data and incorporation of release mortality into the harvest rate estimates and the harvest index.

Chapter 3: 'Management Strategy Evaluation' model for the Western Victorian Snapper Stock and testing of candidate harvest strategies

Introduction

Management strategy evaluation (MSE) is a simulation approach used to evaluate and compare the performance of alternative management procedures; including data collection/analysis and harvest control rules (HCRs) or other management response systems in meeting specified objectives (Smith 1994; Butterworth 2007; Rademeyer *et al.* 2007; Punt *et al.* 2016). As noted by Punt *et al.* (2016), MSE is at the interface between science and policy. While managers and policy makers are tasked with defining the desired outcomes/objectives of fishery management, MSE is the scientific tool that allows managers and stakeholders to quantify the trade-offs, risks and uncertainties among alternative management procedures in achieving the desired objectives. When conducted in the appropriate manner, MSE is the model simulation approach considered the best practice for comparing likely performance and robustness of alternate management procedures in meeting objectives (Punt *et al.* 2016). For further review of the MSE approach and terminology also refer to Rademeyer *et al.* (2007).

The Western Victorian Snapper (*Chrysophrys auratus*) Stock (WVSS) extends from approximately Kangaroo Island in South Australia to Wilsons Promontory in Victoria (Fig. 1, Hamer *et al.* 2011; Fowler *et al.* 2017). It supports recreational and commercial fisheries across these two State jurisdictions, although the largest fisheries are in Victoria, where most of the catch is taken recreationally in Port Phillip Bay (PPB) and Western Port Bay (WPB) (Fig. 1). Most of the harvest occurs during the annual spring/summer (October-December) spawning aggregations, although juvenile and sub-adult Snapper are targeted during the late summer and autumn. The fisheries in coastal waters are smaller, but in recent times have accounted for significant commercial harvests, particular along the south-east coast of South Australia (Fig. 2). The main source of commercial harvest in Victoria, PPB, is currently limited by a fixed harvest cap, and the recreational fishery is managed by size and bag limits.

An important feature of the WVSS fishery is that the dominant catch component is the recreational sector. This presents challenges to management in that recreational fishing is open access and overall harvest cannot easily be controlled using tools applied to commercial fisheries such as annual harvest or effort quotas. The intense fishery on spawning aggregations is a notable risk factor, even more so because the spawning in PPB is the major source of replenishment for the entire WVSS (Hamer *et al.* 2011). PPB is also on the doorsteps of Australia's second largest and fastest growing city of Melbourne, with the associated risks of environmental impacts and increased pressure on the bay ecosystem as a whole. Due to the confined nature of the aggregations within PPB, experienced fishers using modern fish finding technologies may continue to locate and catch fish at similar rates as biomass declines (Johnson and Carpenter, 1994; Hansen *et al.*, 2000; Post *et al*. 2002; Hunt *et al.* 2011). Therefore, while recreational effort may decline in relation to biomass declines, this may not necessarily equate to proportional declines in harvest or exploitation rates due to hyperstable density-dependent catchability, and the experienced anglers still catching a lot of fish. In aggregation fisheries such as this, it is possible that exploitation rates may not conservatively self-regulate in relation to exploitable biomass due to the experienced anglers continuing to harvest a similar volume of fish (hyperdepletion).

The biomass of the WVSS is highly influenced by variable recruitment driven by environmental influences on larval survival rates in Port Phillip Bay (Murphy *et al.* 2013; Black *et al.* 2016). Twenty-six years of continuous juvenile surveys have shown that cohort strength has 20-fold variation (see Fig 40b). Progression of strong and weak cohorts through the fishery can be seen in age structure and has been a dominant influence on stock fluctuations over at least the last 30 years, and no doubt longer. Prolonged poor recruitments during the 1980s are thought to have driven a major stock decline that led to the lowest commercial harvest on record in 1996, and a poorly performing recreational fishery (Coutin *et al.* 2003). The influence of highly variable recruitment on fishery dynamics has been recognised by managers and stakeholders as a major risk to fishery performance and sustainability. While significant recruitment pulses have occurred over the last 20 years and the fishery has recovered, a prolonged poor recruitment scenario in the face of increased fishing effort, more experienced anglers, and improved targeting effectiveness/increased catchability could see the stock rapidly decline. This is clearly undesirable for management and stakeholders, who would benefit from an understanding of the long-term risks associated with varying levels of fishing mortality under alternative future recruitment scenarios.

A key value of MSE is in its use as a risk assessment and management planning tool to test whether alternative management strategies, including HCRs for regulating fishing mortality, are likely to continue to meet management objectives over prolonged periods in the face of future uncertainties (Little *et al.* 2007). Important uncertainties might include changes in recreational pressure or selectivity, regime shifts in recruitment dynamics and or other environmental/biological processes that influence productivity. MSE can also test how robust management strategies are in the face of changes to capacity of fisheries agencies to collect certain data that are considered important for informative stock assessments (i.e. robustness to changes in assessment procedures). An obvious example relevant to recreational fisheries is poor estimation of harvests, or irregular/uncertain estimates. Importantly, MSE can be used to compare how active/adaptive harvest management strategies perform (i.e. continuous HCRs) compared to fixed approaches (i.e. constant harvests or exploitation rates), and various forms of the two approaches.

The latter capability is particularly relevant to recreational fisheries. In commercial fisheries, where harvest is often actively managed by quotas, rapid (typically annual) adjustments to harvests using continuous control rules are feasible. In recreational fisheries, due to the often large and diverse stakeholder base and the increasing political influence of organised recreational angler stakeholder groups, implementing highly active fisheries harvest management is problematic (Radomski *et al.* 2001; Pereira and Hansen 2003; Radomski *et al.* 2003). In recreational fisheries, it is more common that regulations are set for relatively long-periods of time and changed only when and if significant negative impacts on stocks are realised, i.e. reactionary rather than preventative management. Once the problem is recognised changes often take a long time to implement and have an effect, thus risking a ‘too little too late’ scenario. It is therefore important to have *a priori* understanding of the long-term risks associated with varying levels and approach(es) to managing fishing mortality, and if considered necessary, adjust strategies well before stock conservation issues materialise. MSE is the current best approach for informing this risk assessment (Punt *et al.* 2006, 2017).

Historically the WVSS fishery has been assessed using various empirical data, including commercial and recreational fishery catch per unit effort (CPUE), age and length compositions, and fishery independent trawl surveys of 0+ age recruits (Hamer and Conron 2016). The empirical assessment approach, while informative on relative stock condition, does not adequately assess biomass status and management risks associated with different fishing mortality rates. Recent development of an integrated stock assessment model (SnapAssess, appendix 3) has provided a more informed assessment of fishing mortality history, biomass status and trends, but cannot simulate and compare alternative active management strategies. While stock assessment models can provide forward simulations of biomass and uncertainty under fixed harvest amounts (assuming average recruitment) they cannot simulate the full cycle of a management procedures (Butterworth 2007; Forrest *et al.* 2018). Therefore, they cannot provide managers with the necessary information to evaluate the relative performance, risks and trade-offs among alternative management procedures, including allowable levels of fishing mortality and HCRs. With MSE stock dynamics and management strategies are simulated together, allowing evaluation of the collective performance of monitoring, analysis, and decision-making.

To facilitate a more informed and planned management approach for the WVSS fishery, this chapter aimed to:

1. Develop a Management Strategy Evaluation (MSE) model framework: SnapMSE,
2. Apply the MSE framework to compare performance and risk of alternative harvest strategies in meeting specified operational management objectives for stock biomass,
3. Test the robustness of alternative harvest strategies to changes in the underlying recruitment dynamics.

Methods

General overview of SnapMSE

The SnapMSE modelling framework (Fig. 37) was developed using the R programming language (R Core Team 2017) and can be run entirely from within any R software environment (such as the base distribution of R) or alternatively, from within an integrated development environment such as R Studio. To facilitate the operation of SnapMSE by fisheries staff with moderate experience in using R, an "MSE Control Module" was developed that allows the user to control settings for each of the separate modules, and to run the population and assessment models and overall MSE framework.

The population modelling framework used for SnapMSE is Stock Synthesis (SS3, version 3.240). SS3 is a statistical age- and length-structured population modelling framework (Methot and Wetzel 2013) that is supported, maintained, and made available by the US National Oceanic and Atmospheric Administration (NOAA) Northwest Fisheries Science Center (NWFSC). Source code for SS3 is made available to select collaborators, but the program itself, and related technical documentation and user manuals (Methot 2013; Methot *et al.* 2017) are available online or on request from the NWFSC. The SnapMSE framework stitches together and utilises R scripts and functions written specifically for this project, as well as those from various R packages designed to interface with SS3, including r4ss (https://github.com/r4ss) (Taylor *et al.* 2013) and ss3sim (Anderson *et al.* 2014). ss3sim is an R package designed to permit the use of SS3 for simulation testing. ss3sim provided functions to support linking of the operating (OM) and estimation models (EM). However, ss3sim is not capable of conducting full MSE experiments. 'Simulation testing' using ss3sim only involves specifying an OM that simulates the underlying 'true' dynamics of a fishery and fish stock, which are then estimated by a simulated sampling procedure and estimation model (EM) designed to mimic a real stock assessment. Differences between the EM estimates and the 'true' values from the OM provide a measure of performance for any candidate EMs. Full MSE, however, requires the inclusion of a management step or "management model (MM)" that receives the estimated management parameters/performance measures from the EM, for example; biomass estimates, *F* estimates, and applies a management decision or harvest control rule (HCR) that typically adjusts some aspect(s) of the fishery impact in forthcoming years, such as; fishing mortality (*F*), TACs, legal lengths/selectivity, effort levels etc.. The management adjustments are then implemented in the OM, which generates a new set of simulated "true" data on the stock and fishery status. The new "true" simulated data are then sampled by the simulated sampling procedure (SP) and the sample data are passed to the EM which generates a new set of management parameters/performance measures to which the management process is reapplied. Thus, an MSE framework implements a continuous loop process across the sub-models and the simulated sampling procedure: OM»SP»EM»MM»OM (Fig. 37) that runs for a predetermined number of simulated years. This allows not only the comparison of different simulated sampling procedures and EM configurations but also the performance of different harvest management strategies and control rules in delivering management objectives.

Significant additional R coding was required to develop the MM component and an "MSE Simulation Module" to facilitate the looping between the EM, MM and OM models. Furthermore, a "Plotting and Diagnostics Module" was developed to extract results from R objects and other SS3 output files produced by the main MSE models, consolidate data into single data frames where required and create diagnostic tables, plots and summary data on performance against specified management objectives.

The previously developed SS3 Snapper assessment model (AM) SnapAssess was used as the basis for developing and conditioning the OM and EM using data from 1978-2016 (Fig. 38). In summary, the SnapMSE modelling framework is developed around several core sub-components of code, which are structured either as discrete functions or in stand-alone scripts. Each script is a collection of functions and operations designed around a particular set of tasks in support of the overall SnapMSE framework.

Stock Assessment and MSE Modelling Components:

- Assessment Model (AM)
- Operating Model (OM)
- Simulated Sampling Procedure (SP)
- Estimation Model (EM)

Management Models (MMs)

- Harvest control rule (i.e. 'Tier 1' harvest control rule, with MEY target).
- Fixed exploitation rate

MSE Control Module

- Allows the user to control settings for each of the separate modules, and to run the models and MSE framework.

MSE Simulation Module

- Links the multiple models and modules listed above and runs a predefined number of independent population projections, assessment, sampling, and management cycles in a loop. This allow estimates of uncertainty in forecasted population outcomes and permits the running of MSE 'experiments', allowing exploration of trade-offs between different management procedures in meeting objectives.

Recruitment Dynamics Data Simulation Module

- Used to develop simulated recruitment time-series (or recruitment deviates) for forecast simulation modelling, conditioned on estimates of historical recruitment from the current SS3 Snapper stock assessment model (SnapAssess, Appendix 3) from 1980-2016.

Plotting and Diagnostic Module

- Extracts results from R objects and other output files produced by the main MSE modules and creates useful diagnostic tables and plots that can be used for ad-hoc analyses and reporting.

Access to these models, support tools, and associated source code, is currently provided via a cloud-based code hosting service at the following web links:

- Snapper MSE | SnapMSE | https://bitbucket.org/mezo-research/SnapMSE/
- Snapper Assessment Model | SnapAssess | https://bitbucket.org/mezo-research/SnapAssess/

Each link provides access to a code repository that contains source files for the models described above.

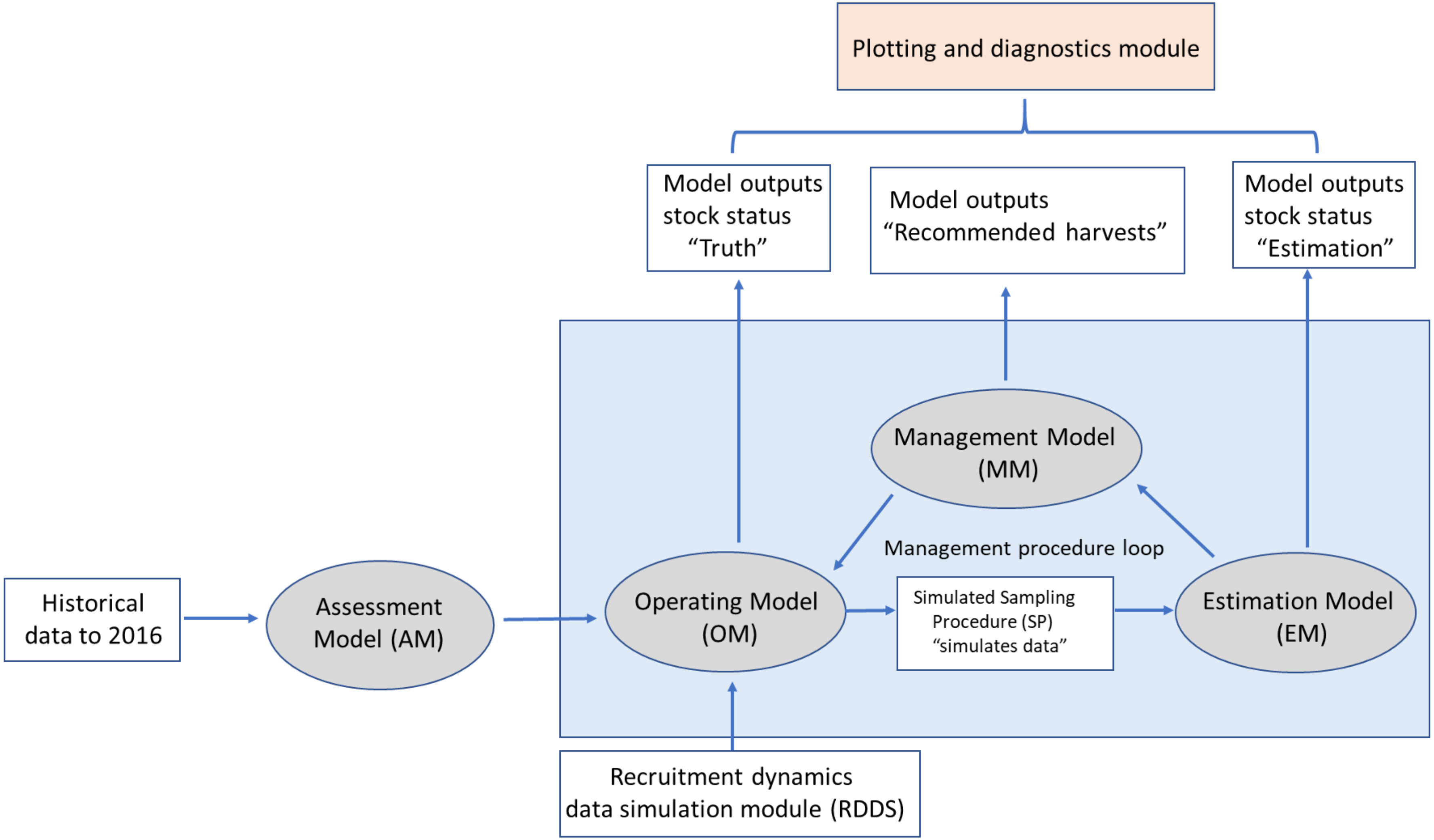


Figure 37 Schematic of the SnapMSE framework.

Model specifications

Assessment model

The SnapAssess assessment model is an age- and size-structured model implemented in SS3, version 3.240 (Methot and Wetzel, 2013). The methods utilised in SS3 are based on the integrated analysis paradigm (Maunder and Punt 2013). SS3 can allow for multiple seasons, areas and fleets. The SnapAssess model operates with a single season (fiscal year: July 1- June 30) and one area representing the WVSS. However, the assessment takes advantage of the ability of SS3 to account for multiple fleet allocations to represent the dynamics of the different fisheries that target either adult, sub-adult, or mixed life-stages. To condition the OM a stock assessment was conducted with SnapAssess using historical data from 1978 – 2016 (appendix 3, Fig. 38).

There are six fleets and a fishery independent 0+ age survey in the SnapAssess AM:

- Port Phillip Bay - Commercial longline, primarily harvests adult Snapper: **Long_Line**
- Port Phillip Bay - Commercial haul seine, primarily harvest sub-adult/juvenile Snapper: **Haul_Seine**
- Port Phillip Bay - Recreational adult, primarily harvests adults, October-December: **RR_Adult**
- Port Phillip Bay - Recreational “Pinky”, primarily harvest juvenile/sub-adults, January-April: **RR_Pinky**
- Recreational – other, includes Western Port Bay and coastal waters, harvests across the legal length range, but biased towards smaller fish compared to Port Phillip Bay long-line and recreational adult fisheries: **Rec_Other**
- Commercial – other, all waters outside Port Phillip Bay, harvests across the legal length range, but biased towards smaller fish compared to Port Phillip Bay long-line and recreational adult fisheries: **Comm_Other**
- The annual fishery independent trawl survey of 0+ age recruits in the main nursery ground (PPB): **YOY_Survey**

Recruitment is governed by a Beverton-Holt stock-recruitment relationship, parameterized in terms of the steepness of the stock-recruitment function (h), the expected average recruitment in an unfished population (R_0), and the degree of variability (deviations) about the stock-recruitment relationship (σ_r). SS3 allows the user to choose among a large number of age and length-specific selectivity patterns. Selectivity is specified in terms of length for each of the fishing fleets listed above. A logistic relationship is used for the Long_Line, RR_Adult, and Rec_Other fisheries, and the SS3 ‘Double normal’ relationship is used for the Haul_Seine, Comm_Other, and RR_pinky fisheries. The values for the parameters of SS3 are estimated by fitting to data on catches, fishery catch-rates, catch length-frequencies, survey length-frequencies and catch rates, mean lengths-at-age, and conditional age-at-length data. The population dynamics model and the statistical approach used in fitting the model to the various data types are given in the SS technical documentation (Methot, 2013). The SS3 control file for the SnapAssess base case model is in appendix 3, along with other outputs from the base case assessment used for OM conditioning. The SnapAssess model fits to length and conditional age at length compositions, CPUE time series from the Long_Line, Haul_Seine, RR_Adult and RR_Pinky fleets as well as the fishery independent YOY-Survey of 0+ age fish in the main nursery area of PPB (appendix 3, Fig. 38).

Operating Model

The OM is a simplified version of the SnapAssess AM (above). The AM and OM share mostly the same biological parameter assumptions and settings (Table 8), but have differences relating to the assumed structure of the fishery. Parameters in the OM are necessarily fixed for the MSE experiments.

The OM has three fleets:

- One fishery,
- One survey (the YOY, i.e. 0+ age fishery independent trawl survey),

- The CPUE index of abundance (longline CPUE also referred to as a survey in ss3sim).

The simulated catch history in the OM for the single fishery fleet reflects the total harvested biomass for all fisheries from the AM. The single fleet selectivity for the OM is an approximation of the combined selectivity of the main fleets in the Snap Assess AM (Fig. 39). The single fleet selectivity was approximated used a weighted average of the multiple fleets, with weighting according to the estimated proportions of the total harvest taken by each fleet. The initial *F* values that relate to the six separate fleets in the SnapAssess AM are summed to produce a single initial *F* value for the OM, which is applied to the single fishery. The historical recruitment history also comes directly from the SnapAssses AM, and is inputted to the OM. For the forecast simulation period the recruitment is input from the ‘Recruitment Dynamics Simulation Module’ (Fig. 37).

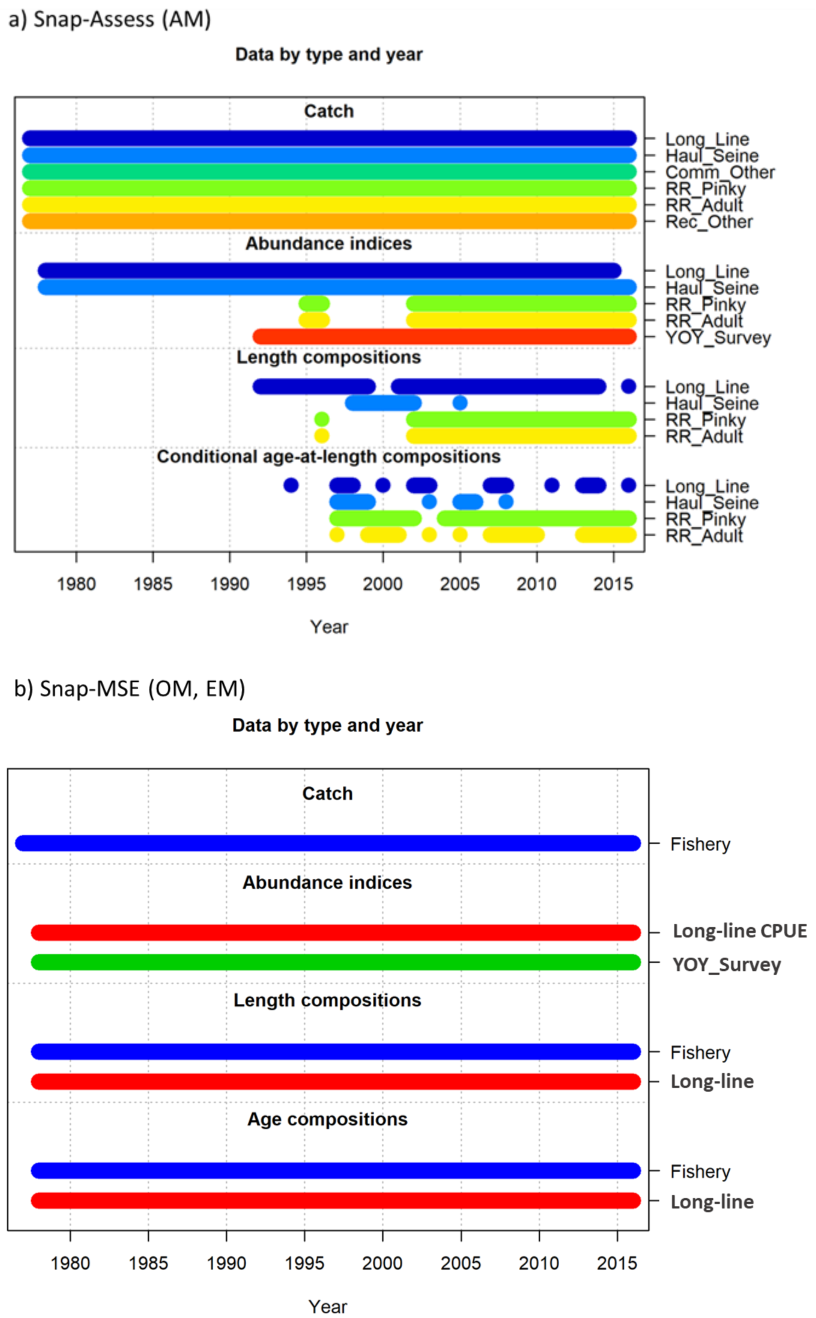


Figure 38 Summaries of data sources used in; a) the AM, and b) the OM and EM. Note: in the OM and EM the long-line fishery data (CPUE) is treated as a survey index used for model fitting, the harvests from the long-line fishery are included in the overall fishery harvests/catch. YOY-survey is the annual fishery independent trawl survey of 0+ age.

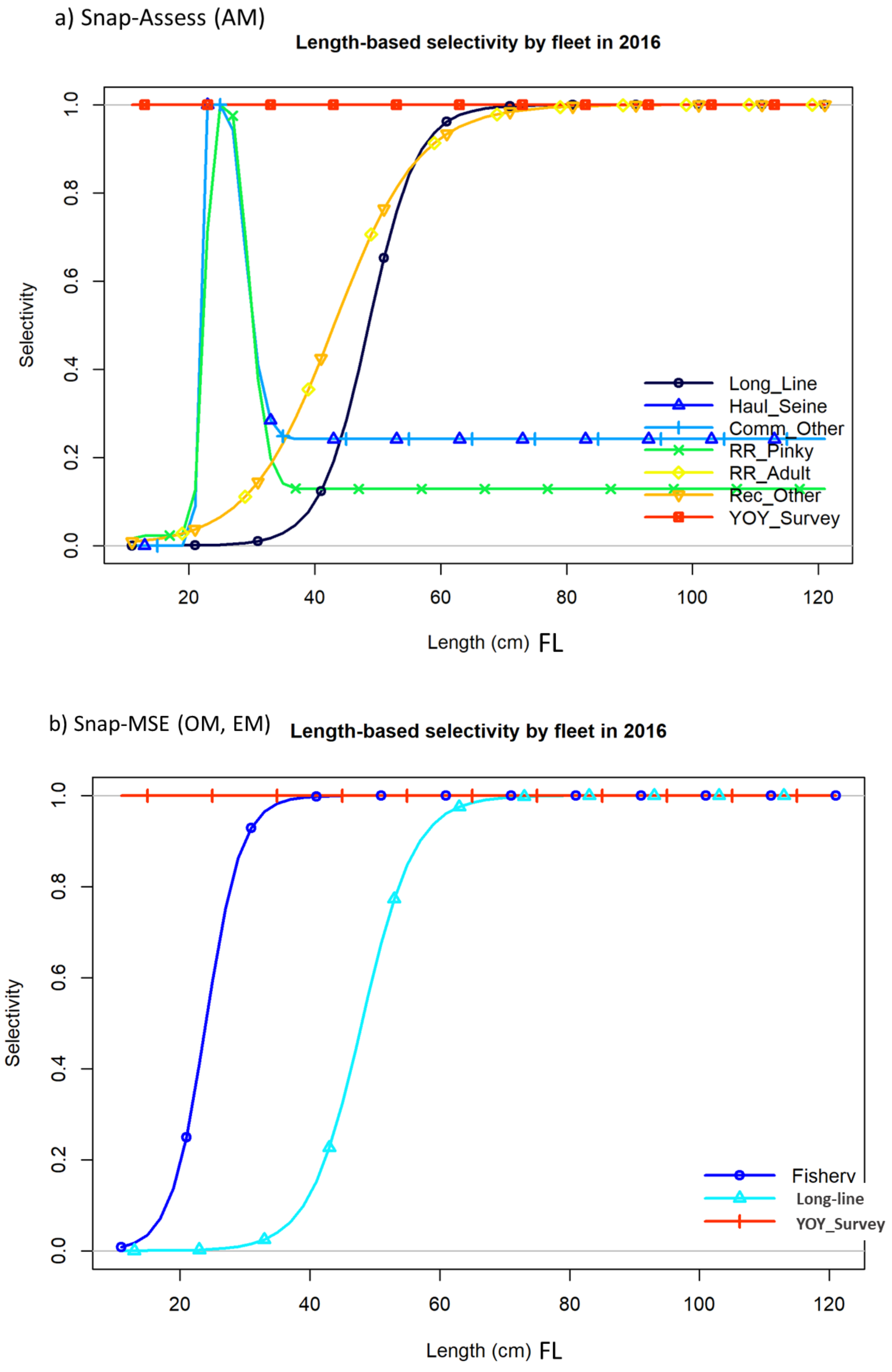


Figure 39 a) Selectivity patterns for the individual fleets in the AM, and b) the combined selectivity pattern for the single fishery fleet used in the OM and EM, and the long-line fishery used for the CPUE index of spawning biomass. Note the YOY-Survey only selects 0+ age fish (<15 cm).

Table 8 Assumed values of biological and technical parameters of the OM.

Parameter/quantity	Value	Descriptions
Time step (yr)	1	Fishery and survey data collected annually, estimated parameters calculated annually by fiscal year.
Plus-group age (yr)	32	Determined from age composition data from long-term sampling program.
Natural mortality	0.2	Estimated by the AM. Also, Then *et al.* (2015) using max age method with 32 years, M=0.16-0.204 Values of 0.15, 0.163, 0.19, 0.211 used for QLD Snapper assessments Allen et al. (2006), Campbell *et al.* (2009), Wortman *et al.* (2018). But note lower values are used in New Zealand and South Australia: 0.075 - 0.05 (Gilbert *et al.* 2006; Fowler *et al.* 2016).
Growth (Von Bertalanffy) male/female equal, fork length (FL) cm $L_{min,}$ L_{max} *k*	15 83 *k* = 0.1	Determined from age/ length data from long-term sampling program
Weight-at-length ($W=aL^b$): kg, FL (cm) *a* *b*	$a=4.448*10^{-5}$ b=2.7889	Determined from length-weight data from long-term sampling program (also see Coutin *et al.* 2003; Francis and McKenzie 2015).
Steepness, *h* (Beverton-Holt)	0.9	Steepness value is similar to other species, with high recruitment variation. i.e. 0.85, 0.9 used for New Zealand Snapper assessments (Francis and McKenzie 2015, Langley 2015), 0.9 used for blue grenadier (Tuck 2008). Uses Beverton-Holt stock-recruitment model.
Ln R_o (Virgin recruitment)	6.76	Estimated by the AM.
Length at which 50% mature Female (FL, cm), Male – NA Slope parameter	Female = 36.3 Slope: -0.25	From Coutin *et al.* (2003)
Fleet structure	1 x Fishing fleet (harvest) 2 x Survey (longline CPUE and pre-recruit survey 0+ age)	ss3sim allows specification of three fleets. In the OM, one fleet represents the fishery, which is all the harvests. Two fleets are specified as surveys and used for fitting: long-line CPUE used an index of spawning biomass, and the pre-recruit survey used as an index of 0+ age recruitment variation.
Selectivity - (logistic, time-invariant) FL (cm)	*Fishing fleet* Inf point = 24 Width = 12 *Survey: long-line CPUE* Inf point = 48 Width = 12 *Survey: pre-recruits* Upper cut-off a 15 cm, 0+ age	Fishery fleet: Based on approximation of combined selectivity of main fleets in the AM. Long-line index: Based on estimated selectivity of the Port Phillip Bay - commercial longline fleet from the AM Pre-recruit survey: only samples fish that are less than 15 cm and 0+ age
Initial F	0.05	Estimated by the AM
Recruitment deviates	-	Historical recruitment is from the AM, with 1990-2016 (main), 1980-1989 (early recruitment deviations). Simulated recruitment time series are from the recruitment dynamics data simulation module.

Simulated Sampling Procedure

The simulated sampling procedure module (SP) allows specification of the data collection program, such as; the quantity and frequency of length/age data to collect, variability around the CPUE index, and whether to have a pre-recruit survey index etc. (Fig. 37). The SP facilitates MSE experiment to investigate implications of altering aspects of the data collection programs, however, it was not used in that sense for the current experiments where the simulated sampling procedure was fixed and specified to produce a good estimation of the OM.

Estimation Model

Similar to the OM, the EM was implemented in SS3, as a simplified version of the AM with the same fleet structure as the OM. The main parameters for the EM are listed in Table 9. The EM receives simulated data via the SP from the OM on an annual basis. The stored simulated data are then used by the EM every three years to complete an assessment and recommend a harvest according to the specified harvest control rule (HCR) (i.e. the simulated assessment interval was 3 years) in the MM. The recommend annual harvest (converted to an equivalent *F*) from the MM is then extracted via the OM with the single fleet selectivity, without error (perfect management implementation), for the next three years, until the next simulated assessment. We used a 3-year interval between assessments and application of HCRs as this matches the current period between Snapper assessments, but this is a variable that could be further tested by MSE. For example, it might be sufficiently low risk to review empirical data annually, but run a full assessment every 5 years etc., depending on how management is implemented.

Recruitment dynamics module

Simulated future recruitment scenarios were generated in R by fitting an autoregressive integrated moving average (ARIMA) model of type (2,0,0) (i.e. AR (2) model) to the historical recruitment estimates from the AM between 1980 and 2016 (Fig. 40a). Over this time period there was a regime with higher frequency of relatively low recruitment years (1980-1994), and a regime with higher frequency of relatively high recruitment years (1995-2016). Parameters estimated for the AR(2) models for each of these periods were then used to generate simulated future low (Scenario C) and high (Scenario B) recruitment time-series, and the full 36 years of historical recruitment estimates was used to generate average recruitment scenarios (Scenario B). The recruitment dynamics module creates and stores user specified multiple individual recruitment time series for each MSE experiment (in this case 100) that were then used to derive the recruitment deviates by the OM.

MSE experiments

For this initial application of the SnapMSE framework, the uncertainty of most interest was recruitment variation. Fishery independent recruitment surveys of 0+ age fish have shown that recruitment of Snapper in Port Phillip Bay is highly variable (Figs. 40b) due to environmental influences on larval survival rates (Black *et al*. 2016; Murphy *et al.* 2013). Managers require an understanding of risk associated with alternate fishing mortality levels and harvest management approaches under highly uncertain future recruitment dynamics, or 'regimes'. The MSE experiments were therefore designed to assess the performance of alternative harvest control rules under different scenarios of future recruitment dynamics.

It should be noted that no stock assessment model is a perfect representation of reality and that in this study we have not included simulations that test for implications of various sources of estimation and parameter/process error. In this initial application of the SnapMSE framework we focussed on isolating the implications of recruitment dynamics, and hence the EM was a close representation of the OM. Ultimately the choice of a harvest strategy framework would need to be further informed by simulations that also included various estimation model errors, and errors in assumptions around key parameters such as natural mortality and selectivity. Furthermore, the implementation of harvest (*F*) management in the MM also assumes perfect implementation, which for a recreational dominated harvest would not be the case, especially where blunt instruments are used such as bag and size limits. Chapter 4 develops a predictive tool for estimating recreational harvest reductions associated with bag and size limit changes, but the current SnapMSE framework does not include separate recreational fleets to explicitly study implications of recreational size and harvest volume changes. As such the results of the MSE experiments are viewed in the context of risk assessment around overall levels of *F* or *U*, rather than decision making regarding choice of harvest strategies which requires more detailed evaluation in follow up studies.

Table 9 Additional parameters required by the EM to be specified for the estimation process. For the MSE experiments the EM used the same biological parameters as the OM listed in table 8.

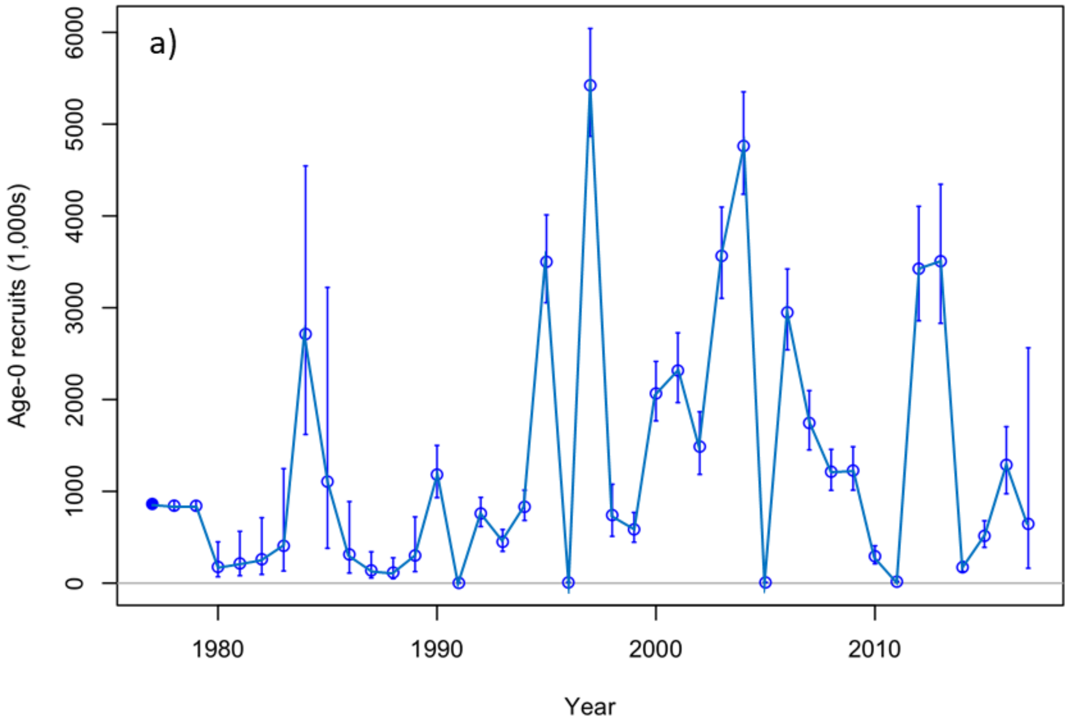
Parameter/quantity	Value	Comments
σ_r = coefficient of variation for recruitment fluctuations	0.8	Higher value applied due to known high variation in recruitment from survey data. i.e. value of 1 used for blue grenadier with extreme recruitment variation (Tuck *et al.* 2008)
Stock recruitment deviations	Constant max bias adjustment =1 applied for the EM	EM – to model end year, AM, 1990-2016 (main), 1980-1989 (early recruitment deviations)
Data weightings	0.25 on length and age for survey (longline CPUE) and fishery fleet, 10 on pre-recruit index	The high data weighting for the pre-recruit survey is due to the high confidence in this survey index.
Survey error for indices	SD = 0.05	Longline CPUE and pre-recruit (0+ age) survey.

Recruitment dynamics

The annual recruitment dynamics (i.e. relative abundance of 0+ fish) were simulated for the MSE simulation period from 2017 – 2040 using the historic recruitment time series estimated by the AM for the period 1980-2016 (Fig. 40a). Three alternative future recruitment scenarios were developed for the purposes of MSE experiments:

- Scenario A – High average recruitment: An approximation to the last 21 years (1995-2016) of historical recruitment estimates which encompasses a period of higher average recruitment and regular high recruitment events.
- Scenario B – Average recruitment: An approximation to the full 36 years of historical recruitment estimates; and
- Scenario C – Low average recruitment: An approximation to the first 15 years of the recruitment history (1980-1994), in which average recruitment was low, and high recruitment events were less frequent.

One hundred recruitment time-series were generated for each scenario experiment. Example time series of simulated recruitment deviations for each recruitment scenario are displayed in Figure 41.



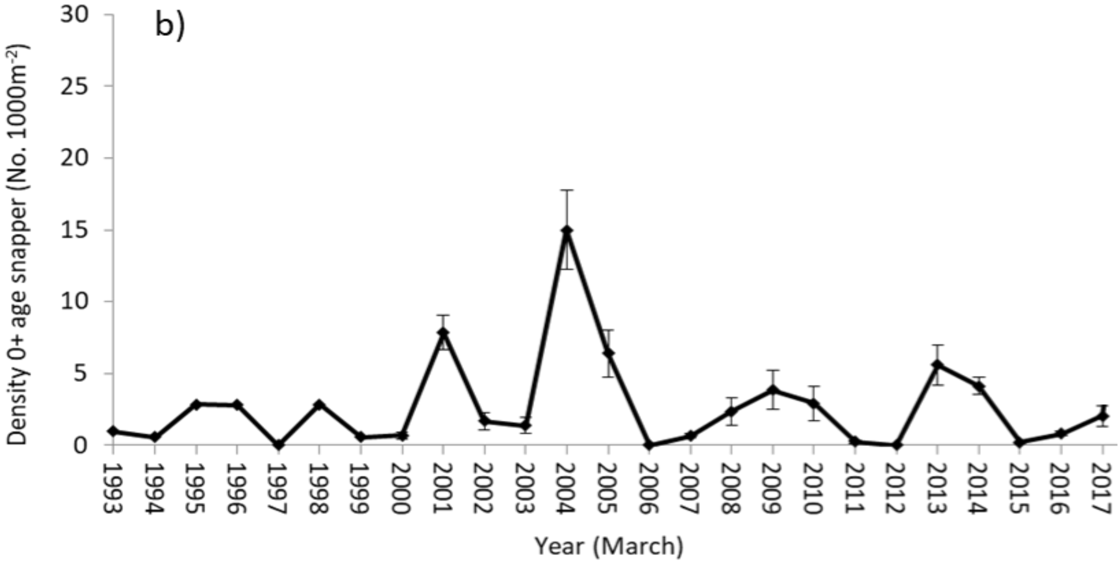


Figure 40 a) Recruitment time series (number age 0+ recruits ± 95% asymptotic intervals) estimated by the SnapAssess model, 1978-2017, b) recruitment variation of 0+ age Snapper measured by fishery independent trawl surveys (pre-recruit survey index) at seven sampling areas in Port Phillip Bay (mean density per sampling area ±SE) (1993-2017).

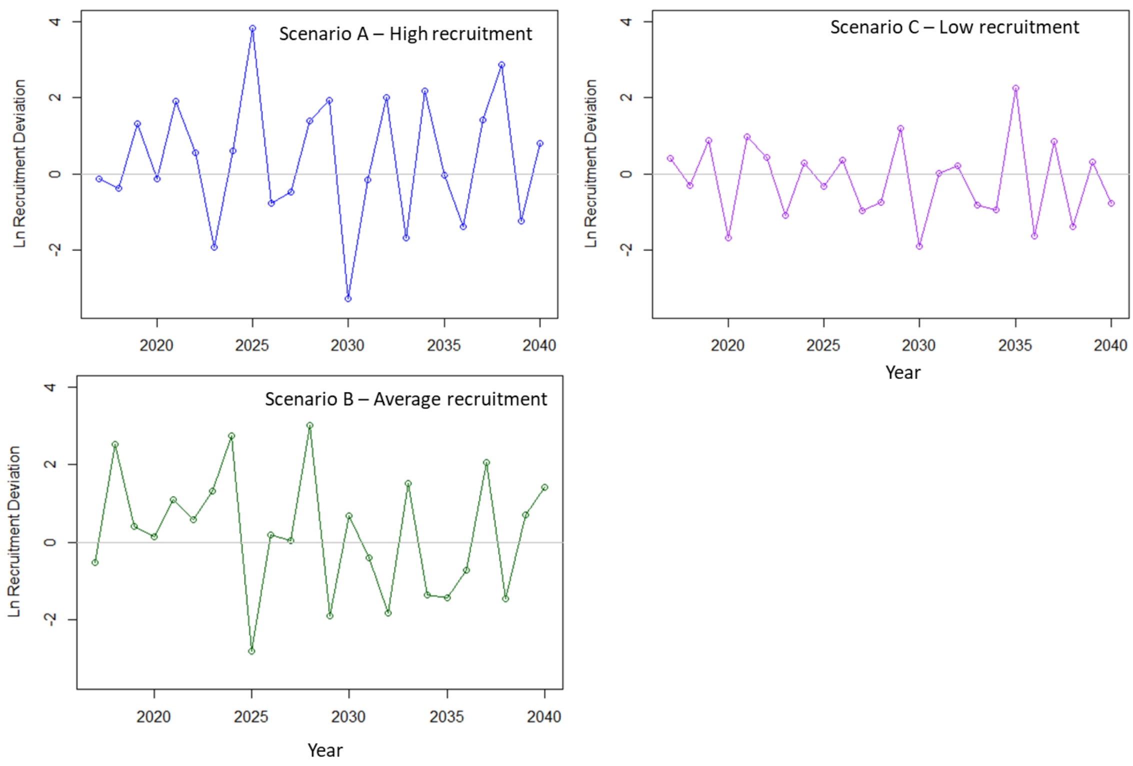


Figure 41 Examples of simulated recruitment deviations for high (Scenario A), average (Scenario B) and low (Scenario C) recruitment scenarios. The y-axis in each case is the natural log of recruitment deviations. Simulated future recruitment time-series can be shown as absolute numbers of recruits but are generated as 'log recruitment deviations' for input into the SS3 OM.

Management objectives

The trial management objectives are indicated below along with their associated operational objectives and spawning biomass reference points. Trial management objectives for this MSE study were developed based on discussions in an initial work shop with stakeholder representatives, scientist and fishery managers (appendix 5) and follow up meetings with VFA managers and policy staff, but are only for the purposes of this project and require further consideration in collaboration with stakeholders.

Two approaches to defining biomass reference points are tested:

- *"relative spawning biomass"* approach that uses the ratios of current or predicted future spawning biomass to the estimated unfished spawning biomass, B_0, and,
- a "*historical reference year spawning biomass"* approach. This measures performance based on whether the current or predicted spawning biomass is above or below levels estimated for chosen historic reference years.

The relative B_0 approach is commonly applied with an MSY (maximum sustainable yield) or MEY (maximum economic yield) management objective and harvest control rule and is provided within the SS3 model framework. The reference year approach is provided as an alternative as it is more meaningful to stakeholders who often struggle with the concept of B_0 and can more clearly relate fishery performance to periods of time through which they have actually fished. However, it should be noted that the different approaches for defining spawning biomass reference points equate to different spawning biomass levels. The way in which the reference points for spawning biomass relate to management objectives is discussed below.

The reference period for selecting reference years was 1978-2016, a period over which a suitably informed assessment could be conducted and spawning biomass indices (CPUE) are available (Fig. 38, 42). This period has also displayed substantial changes in stock biomass. Using an historical year from the reference period when the spawning biomass was estimated to be at a very low level, but was then observed to rebuild, was considered a suitable approach for identifying a spawning biomass limit reference point. We used the CPUE time series from the commercial long-line and adult recreational Snapper fisheries in PPB to identify periods of low, medium and higher catch rates, and thus assumed low, medium and higher spawning biomass (Fig. 42). The spawning biomass levels estimated by the OM for the corresponding years were then applied as historical spawning biomass reference points for the MSE projections and performance evaluations.

For this study the spawning biomass in 1997 was the lowest estimated by the AM over the reference period (Fig. 42a). The Hist_B_{LIM} reference point was therefore set at the spawning biomass determined by the OM for this year rounded up to nearest 50 tonnes. Note that spawning biomass values from the OM for the historical reference points refer to the 'total' spawning biomass including both sexes.

The historical high (Hist_B_{TARG}) biomass reference point provided a target where the fishery would be expected to be at a high level of social and economic performance but may be difficult to regularly achieve because it requires high recruitment events. We chose the reference year for the Hist_B_{TARG} based on the CPUE indices from the long-line fishery and the recreational fishery component that predominantly targets adult Snapper (Fig. 40ab), rather than historical biomass estimates form the AM, as CPUE is a more direct measure of fishery performance and is more meaningful to stakeholders. The year 2005 was selected as the Hist_B_{TARG} reference year as this was the year at which the standardised longline CPUE index (Fig. 42a) peaked after recovering from the low levels in the mid-1990s, and it also represented a period where nominal CPUE was approximately 60-70% of the 2012 peak values for the adult recreational fishery (Fig. 42b). The total spawning biomass determined by the OM for 2005 was therefore used as the Hist_B_{TARG}.

The intermediate biomass reference year is used as a trigger reference point (Hist_B_{TRIG}) representing a safe spawning biomass level above which satisfactory social and economic fishery performance would be expected, but below which concerns about the fishery state would likely be expressed requiring management consideration/review. The reference year for the Hist_B_{TRIG} was 2002, where the CPUE was roughly halfway between 1997 and 2005. Therefore, the total spawning biomass determined by the OM for 2002 was used as the Hist_B_{TRIG}.

Management objective 1: Maintain a high performing recreational fishery and a profitable commercial fishery.

Operational objectives (spawning biomass target reference points):

a) Relative spawning biomass (MEY) approach:
   - Relative spawning biomass is > 0.48*B_0 for 70% of the simulation years (0.48*B_0 is applied as an assumed proxy for MEY (DAFF 2007)).

b) Historical reference year approach:
   - Total spawning biomass is > reference year 2002 biomass, referred to as Hist_B_{TRIG}, for 70% of simulation years.
   - Total spawning biomass is > reference year 2005 biomass, referred to as Hist_B_{TARG}, for 20% of the simulation years.

Management objective 2: Prevent the stock from becoming recruitment overfished

Operational objectives (spawning biomass limit reference points):

a) Relative spawning biomass approach:
   - Relative spawning biomass is > 0.20*B_0 for 95% of the simulation years. (0.20*B0 is applied as an assumed proxy for recruitment overfished (DAFF 2007)).

b) Historical reference year approach:

- Total spawning biomass is > reference year 1997 biomass, referred to as Hist_B_{LIM}, for 95% of the time.

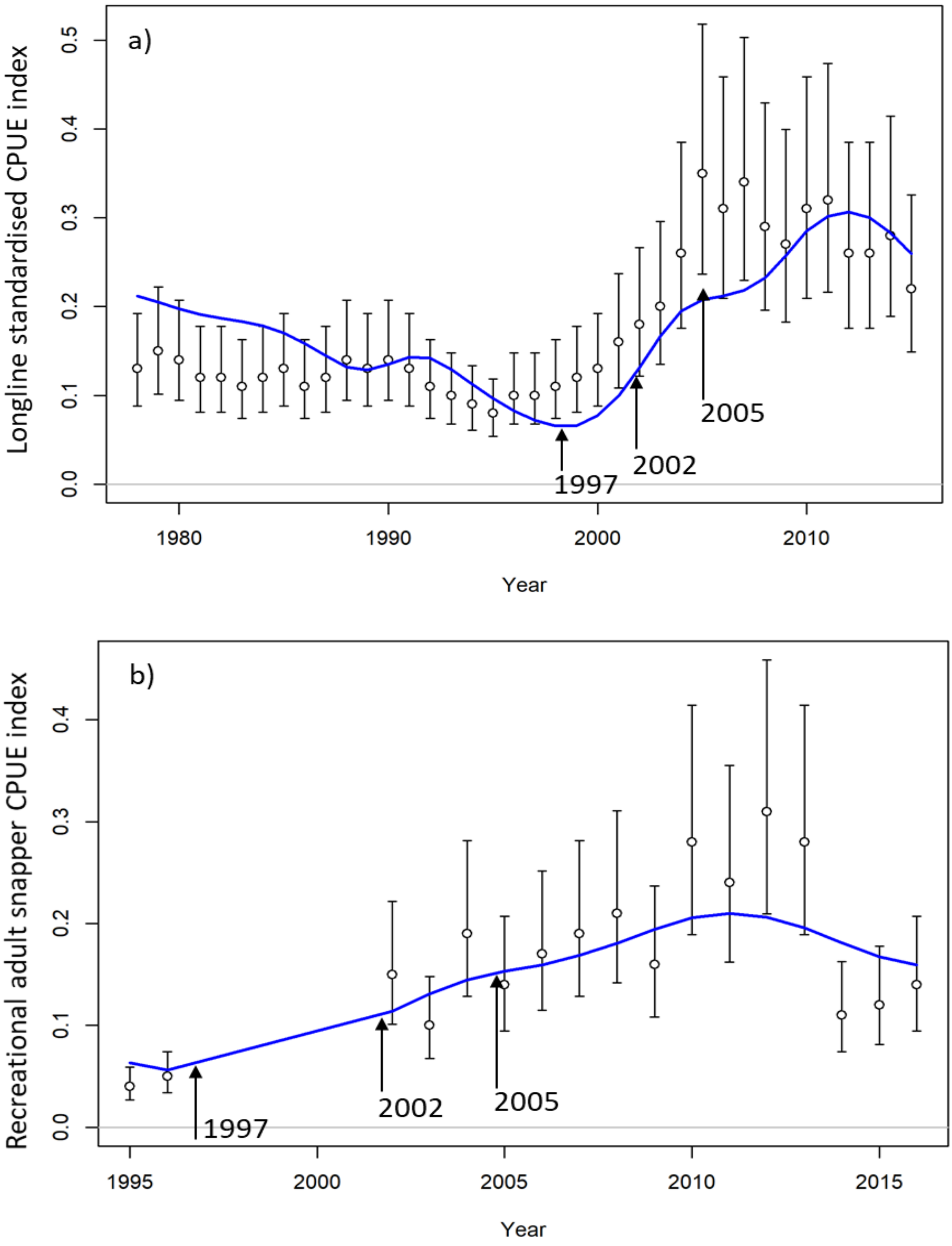


Figure 42 a) Port Phillip Bay commercial longline fishery standardised CPUE index, and b) Port Phillip Bay recreational adult Snapper fishery nominal CPUE index. Blue lines are the estimated CPUE time series fits from the assessment model (SnapAssess). Reference years used for the spawning biomass target – 2005 (Hist_B_{TARG}), trigger – 2002 (Hist_B_{TRIG}) and limit – 1997 (Hist_B_{LIM}) reference points are indicated.

The candidate harvest control rules (HCRs) were (Figs. 43, 44):

1. Tier 1 HCR (i.e. MEY target rule)
2. Constant annual exploitation rate (CER) = 10% of available (exploitable) biomass
3. CER = 20% of available biomass
4. CER = 30% of available biomass

The Tier 1 HCR can be implemented via a series of forecasting options in SS3 (Methot and Wetzel 2013). This control rule sets the fishing mortality (*F*) for the next year based on model projection of the constant *F* required to move the spawning biomass to the MEY target level (i.e. $0.48*B_0$) and maintain it at that level assuming average recruitment (expected values from the stock-recruitment relationship). The estimated *F* (i.e. F_{48}, Fig 43) to achieve MEY is then converted to a recommended annual catch (biomass). The Tier 1 rule also has a critical point if the biomass reaches $0.35*B_0$. At this point the estimated F_{48} is reduced further if the spawning biomass declines further (Fig. 43). In the MSE loop, this catch is then removed with the specified selectivity for the specified number of years between full assessments and resetting of recommended harvests.

The constant exploitation rate (CER) strategies are simpler in that the recommended annual catch for the next year is equal to the specified CER % of the currently estimated exploitable biomass. So, the Tier 1 and CER rules are different in that the CER strategies respond to estimates of the exploitable (available) biomass, whereas the Tier 1 responds to the status of the spawning biomass and the goal of achieving a spawning biomass that delivers MEY. For the SS3 framework exploitation rates are required to be input as their equivalent *F* values using the conversion equation:

$F = -\mathrm{Ln}(1-U)$; where F = fishing mortality, U = exploitation rate

i.e. 10% CER: $F = 0.105$, 20% CER: $F = 0.223$, 30% CER: $F=0.357$

For all CER strategies, if the spawning biomass is estimated to be equal or below the limit reference point by the EM, the exploitation rate is set at 10% of the estimated exploitable biomass.

Note: The annual exploitation rate is also often referred to as ‘harvest fraction’ (i.e. the percentage of fishable biomass harvested in a fishing year).

The constant exploitation rate strategies represent an assumption of self-regulation in a fishery dominated by recreational harvest, where, as catch rates decline, the recreational harvest is expected to decline in proportion so as to maintain a constant exploitation rate (see discussion). This assumes that effort is constant. In reality, it is unknown how recreational angler effort targeted at Snapper responds to changes in CPUE or availability, and many factors can influence recreational effort dynamics (Fenichel *et al.* 2013). However, because recreational anglers are not economically motivated to continue to harvest a certain amount of fish each year, it would seem unlikely that effort would increase as CPUE declines. While drivers of recreational effort dynamics are an important area for research (discussed later), the CER strategies were set to study the implications of higher fishing mortality/effort that may result overtime due to population growth, particularly around Melbourne. As such the base level of 10% for the CER HCRs was set based on the historical *F* estimates from the AM of fishing mortality ranging from approximately 0.10-0.15 and represents a ‘status quo’ scenario (Fig. 45), with 20% and 30% CER strategies representing substantially increased fishing pressure scenarios.

For the MSE experiments, while annual data collection is simulated, the estimation and harvest setting time step was set at 3 years. That is an assessment by the EM was conducted and a new annual harvest amount set by the HCR every 3 years (i.e. catches fixed for the next 3 years) over the forecast simulation period. The simulation period was from 2017 – 2040. For the purpose of the MSE experiments the recommended harvest amounts by the harvest control rules are assumed to be removed without error by the single OM fleet (i.e. perfect management implementation).

For each recruitment scenario and harvest strategy combination, 100 independent simulations with new sets of simulated recruitment time series were conducted to indicate the variability of the outcomes for each scenario.

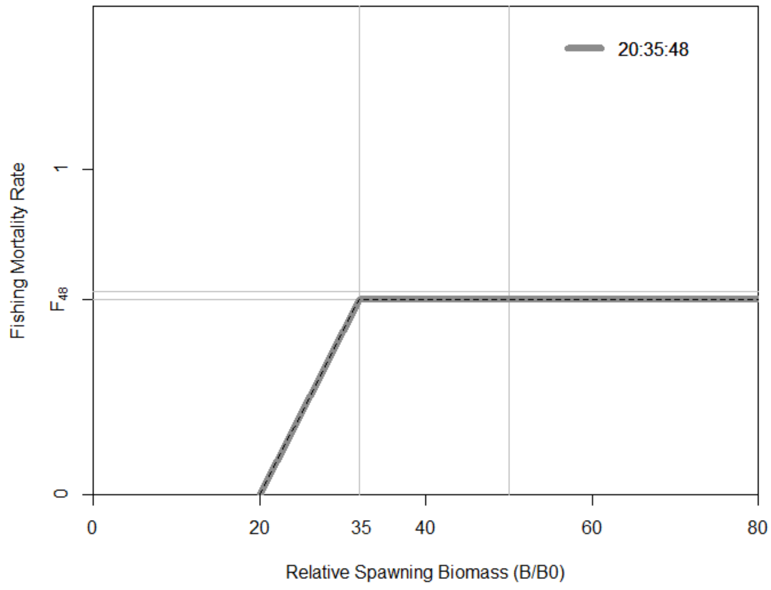


Figure 43 Tier 1 harvest control rule. This control rule sets yearly recommended harvests based on the fishing mortality (*F*) estimated to achieve a spawning biomass that would produce maximum economic yield (MEY) assumed equivalent to a spawning biomass that is 0.48 * B_0 (i.e. F_{48}). If the estimated spawning biomass drops below 0.35 * B_0, *F* is continually reduced as biomass reduces until the estimated spawning biomass passes below the limit point 0.20* B_0, when *F* is set to zero and no harvest is allowed.

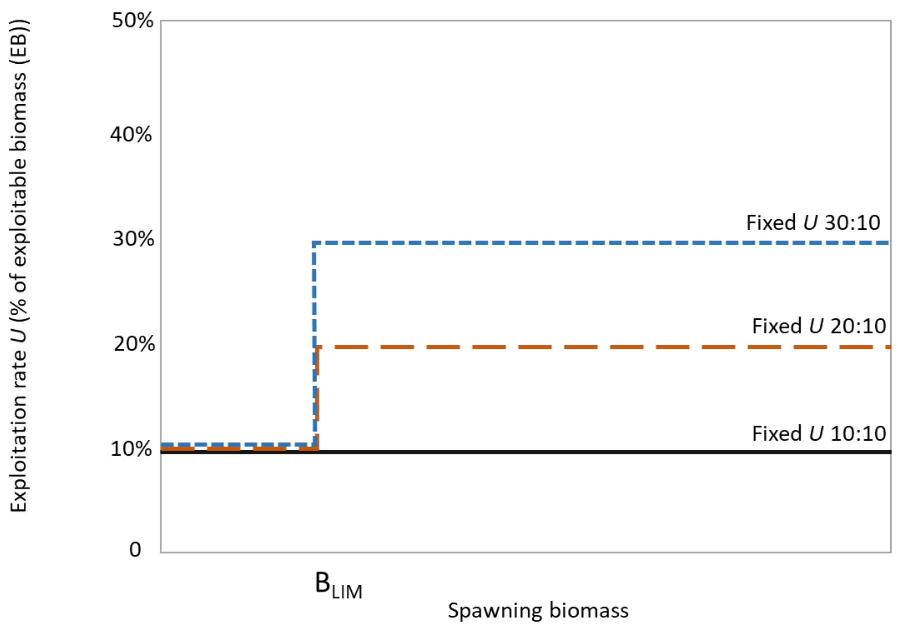


Figure 44 Fixed exploitation rate harvest control rules. Under these harvest control rules the yearly recommended harvest is set as a constant percentage of the estimated exploitable biomass when the biomass is higher than the specified B_{LIM}. When the B_{LIM} is reached the harvest is set at a constant 10% of the estimated exploitable biomass. B_{LIM} is either 0.2*B_0 or Hist_B_{LIM}.

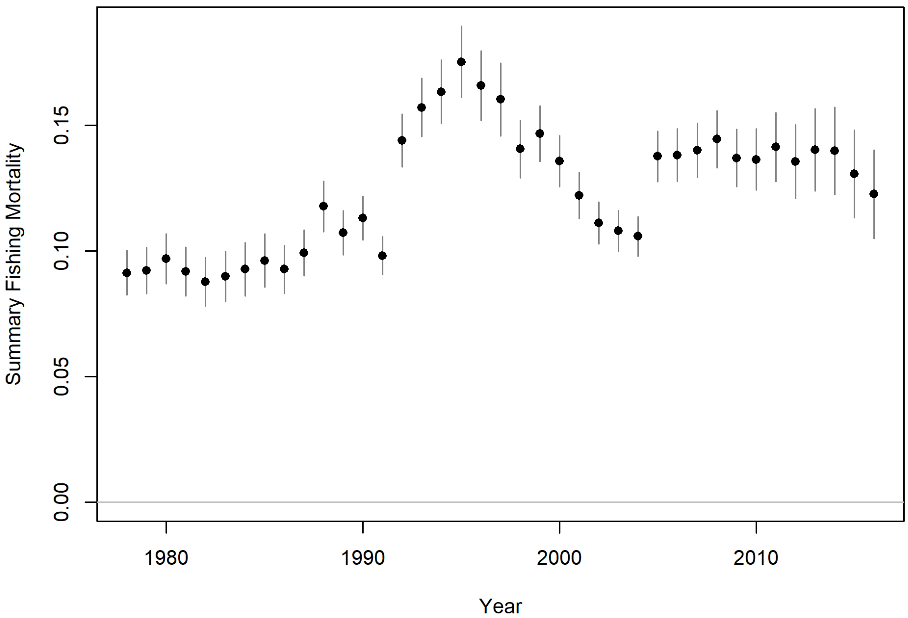


Figure 45 Estimated fishing mortality (F) by the AM for the period 1978-2016.

Results

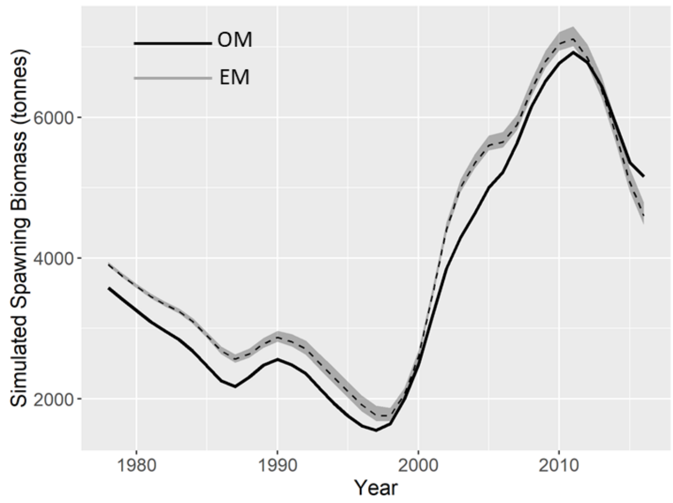
MSE model performance

The key performance measure for this MSE study was the total spawning biomass (males and females). Because the MSE studies were specifically interested in performance of HCRs under different recruitment scenarios, there was no requirement to alter the simulated sampling procedure or the EM. However, it was important that the simulated sampling procedure and the EM that were applied were realistic and could reliably estimate the biomass dynamics and quantities being determined by the OM. Figure 46a shows that the EM estimates of total spawning biomass were generally close to the OM over the historic period from 1978-2016, and importantly across a period where there was a large change in biomass. During the earlier years of the time series (until 1998) the EM tended to consistently overestimate the OM biomass, but from 2000 to 2016 the EM was very similar to the OM with no consistent bias (Fig. 46a). EM model fits to simulated length and age composition sampled from OM were also good (Fig. 47). This provides confidence that the results of the MSE simulation experiments that were focussed on recruitment uncertainty were not confounded by a poorly performing EM.

While the Tier 1 HCR works on spawning biomass estimates from the EM, the CER HCRs set harvest based on the exploitable biomass from the EM. Comparison of the estimated exploitable biomass between the EM and the OM showed very similar estimates until the last four years of the historic times series (Fig. 46b). This is most likely due to the age at recruitment to the exploitable biomass being around 4-8 years and the EM not having complete information on the strength of the recent cohorts in this age bracket. The recent year bias towards underestimation of biomass was greater for the exploitable biomass than the spawning biomass, which is comprised of older cohorts, and would be greater with stronger recent cohorts entering the exploitable biomass. However, over time the EM “catches up” as it becomes more informed. This EM lag effect is an intrinsic feature of the management process being tested in this MSE study.

As the OM represents a simplified version of the AM, it was also important to compare the biomass predictions between the OM and the AM. Figure 48 compares the total spawning biomass time series estimated by the AM (SnapAssess) and the OM over the historic period from 1978-2016. Both models clearly show the same dynamic over the 38-year time period. The only notable difference is the OM is consistently biased to estimating higher biomass than the AM. This means that the OM is assuming that the stock is slightly more productive than the AM. This difference is not important for the MSE scenario comparisons, in particular since TAC levels are converted to *F* in each management decision year, but means that the simulated spawning biomass and harvest values presented in the MSE results figures would be slightly elevated compared to what the AM would have determined. This bias was thought to be related to the SS3 bias adjustment for recruitment deviates that is applied in the AM but not in the OM (Methot and Taylor 2011).

a)



b)

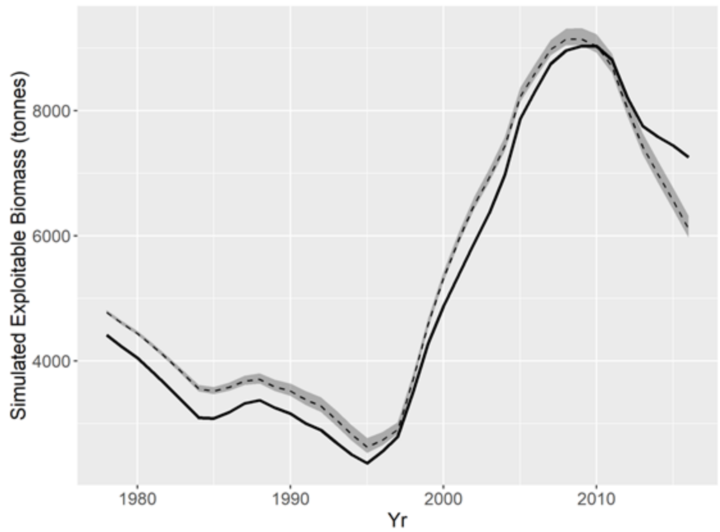


Figure 46 Comparisons of; a) total spawning biomass and b) exploitable biomass time series determined by the operating model (OM) and the estimation model (EM) from 1978-2016. The dashed line for the EM is the median value and grey band represents the range of EM estimates from the 0.05 to 0.95 quantiles.

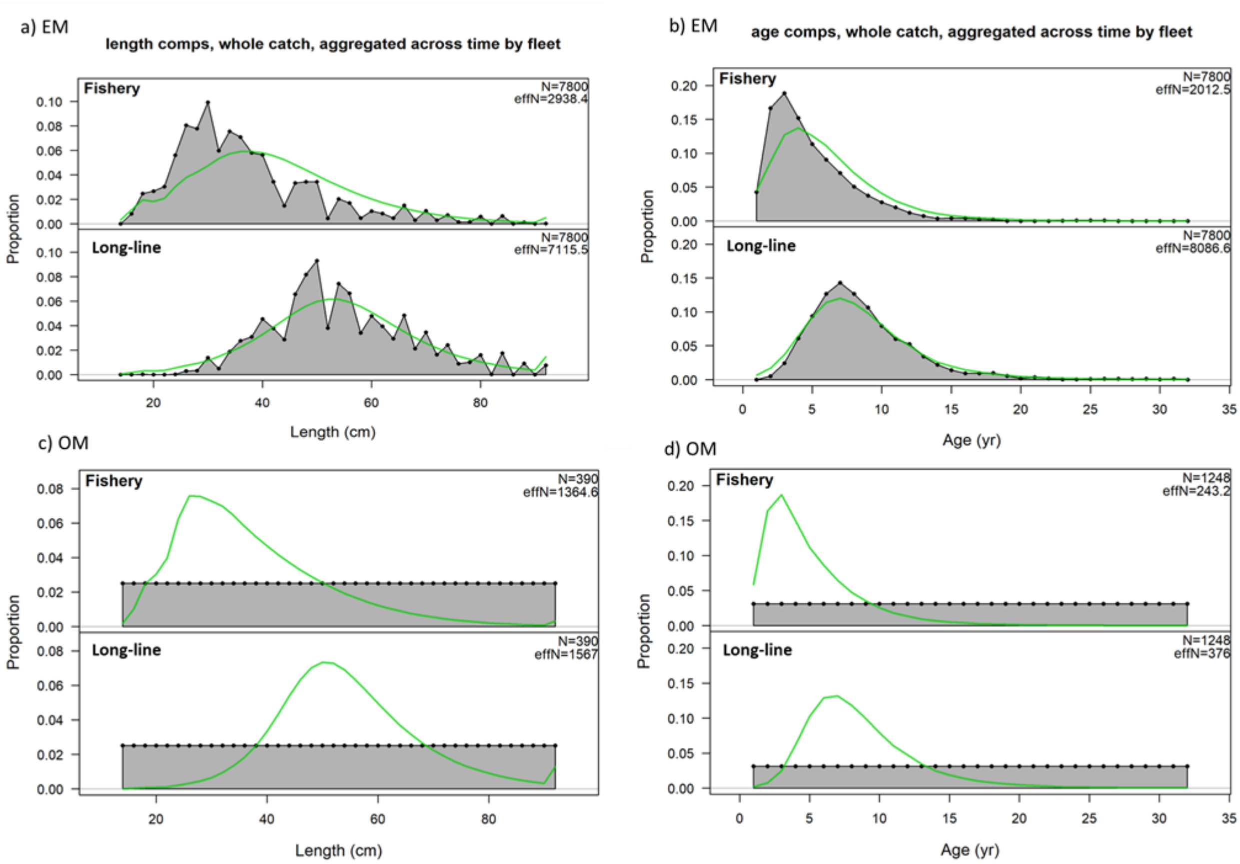


Figure 47 Aggregated EM model fits (green lines) to samples of simulated (grey) length (a) and age (b) data, sampled by the SP from the OM. Also, the expected values (green lines) for simulated length (c) and age (d) compositions from the OM for the single "combined fishery fleet" and 'Long-line Survey' used as the CPUE index of spawning biomass. Note that constant dummy values for age and length data (grey) are supplied to the OM in input files, and appear as flat lines in plots (c) and (d) and can be ignored.

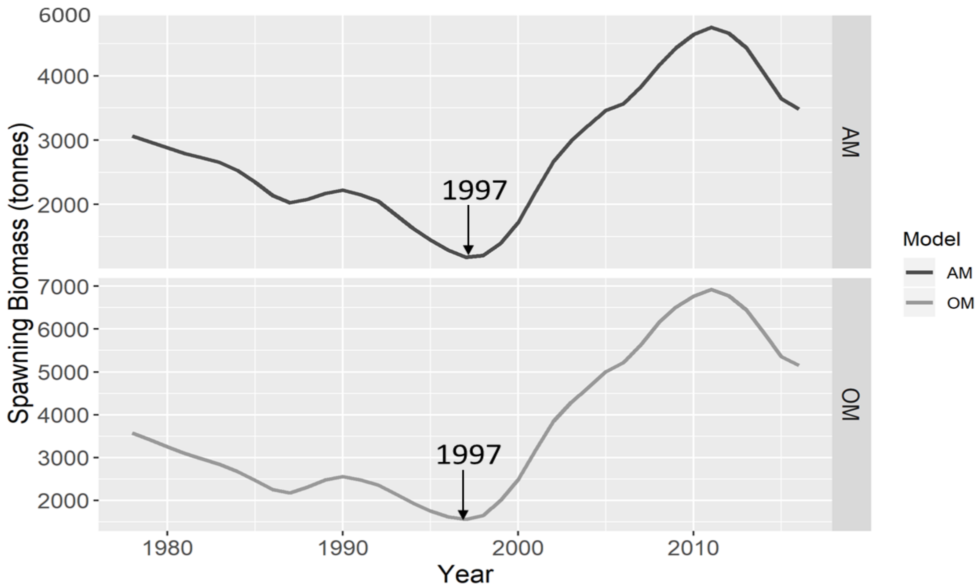


Figure 48 Comparisons of total spawning biomass time series determined by the operating model (OM) and the assessment model (AM) from 1978-2016. 1997 indicates the year of lowest estimated total spawning biomass used for the historic biomass limit reference point (Hist_BLIM).

MSE experiments

Tier 1 HCR

Recruitment Scenario A – High

MSE simulations of the Tier 1 HCR under the high recruitment scenario showed that it was effective at maintaining the spawning biomass above the MEY target reference point, 0.48*B_0, and the Hist_B_{TRIG} for 99 and 94% of the simulation years respectively. Moreover, none of the simulation runs showed spawning biomass at or below the limit reference points of 0.20*B_0, and Hist_B_{Lim} in any year (Fig. 49, appendix 4). The Tier 1 control rule also allowed the spawning biomass to exceed the historical biomass target level, Hist_B_{TARG}, for 60% of the simulation years (Fig. 49).

The Tier 1 HCR initially reduced the recommended harvests, but then set increasingly higher harvests during the simulation period, appearing to stabilise towards the end of the simulation period (Fig. 50). Despite the increasing harvests, the high recruitment stabilised the spawning biomass well above the MEY target and above Hist_B_{TARG}. The Tier 1 HCR sets *F*, and hence the recommended harvests, under the assumption of average recruitment off the stock-recruitment curve, however, due to the consistent high recruitments it continually failed to set the *F* at high enough levels to drive spawning biomass down to the MEY target as it is designed to achieve.

(Note: figures of all 100 spawning biomass simulations for each HCR and recruitment scenario are included in appendix 4)

Recruitment Scenario B - Average

Similar to the high recruitment scenario, under the average recruitment scenario the Tier 1 HCR was effective at maintaining the spawning biomass above the MEY target reference point, 0.48*B_0, and the Hist_B_{TRIG} for 98 and 90% of the simulation years respectively, and none of the simulation runs showed spawning biomass at or below the limit reference points of 0.20*B_0, and Hist_B_{Lim} in any year (Figs. 49, appendix 4). For the average recruitment scenario, the Tier 1 control rule allowed the spawning biomass to exceed the historical biomass target level, Hist_B_{TARG}, for 53% of the simulation years (Fig. 49).

The trajectory of recommended harvest and spawning biomass for the Tier 1 HCR under the average recruitment scenario was similar to the high recruitment scenario, with harvests peaking at approximately 85% of peak harvests recommended under high recruitment and starting to reduce at the end of the simulation period (Fig. 50). Similar to the high recruitment scenario, the spawning biomass stabilised at levels well above the MEY target and slightly above Hist_B_{TARG}.

Recruitment Scenario C - Low

Under the low recruitment scenario, the Tier 1 HCR was effective at maintaining the spawning biomass above the limit reference points of 0.20*B_0, and Hist_B_{LIM} for all of the simulation years (appendix 4). However, it could only maintain the spawning biomass above the MEY target reference point, 0.48*B_0, and historical biomass trigger, Hist_B_{TRIG}, for 71% and 48% of simulation years respectively, with most of these years being early in the simulation period as the stock declined from its initial higher level (Figs. 49). Unlike the high and average recruitment scenarios, for the low recruitment scenario the spawning biomass stabilised at the MEY target that the Tier 1 HCR is designed to deliver over the long-term. Spawning biomass only exceeded the historical target biomass level, Hist_B_{TARG}, for 18% of the simulation years, with most of these years also occurring at the beginning of the simulation period (Fig. 50).

The trajectory of recommended harvests and spawning biomass for the Tier 1 HCR under the low recruitment scenario showed a rapid decline, with both stabilising after about 10 years into the simulation period (Fig. 50).

10 % CER

Recruitment Scenario A – High

Similar to the Tier 1 HCR, the 10% CER harvest control rule for the high recruitment scenario maintained the spawning biomass above the MEY target reference point,0.48*B_0, and the Hist_B_{TRIG} for 100% and 99% of the simulation years respectively, and none of the simulation runs showed spawning biomass at or below the limit reference points of 0.20*B_0, and Hist_B_{LIM}, in any year (appendix 4). The 10% CER also allowed the spawning biomass to exceed the historical biomass target level, Hist_B_{TARG}, for 80% of the simulation years (Fig. 49).

Similar to the Tier 1 HCR, under the 10% CER the harvest and spawning biomass decreased initially but then increased, appearing to stabilise towards the very end of the simulation period (Fig. 48). Further, the peak of the recommended harvest was lower than for the Tier 1 control rule and the spawning biomass reached a notably higher level by the end of the simulation period under the lower harvests set by the 10% CER (Fig. 51).

Recruitment Scenario B – Average

Similar to the high recruitment scenario, under the average recruitment scenario the 10% CER was effective at maintaining the spawning biomass above the MEY target reference point (0.48*B_0) and the Hist_B_{TRIG} for 100% and 98% of years respectively, and none of the simulation runs showed spawning biomass at or below the limit reference points of 0.20*B_0, and Hist_B_{LIM} in any year (Fig. 49, appendix 4). The simulated spawning biomass exceeded the historical target biomass level , Hist_B_{TARG}, for 73% of the simulation years, slightly higher than for the Tier 1 control rule (Fig. 49).

The trajectory of recommended harvest and spawning biomass under the 10% CER for the average recruitment scenario was similar to the high recruitment scenario, with harvests peaking at approximately 85% of peak harvests recommended under the high recruitment and starting to reduce at the end of the simulation period (Fig. 51). Similar to the high recruitment scenario, the spawning biomass stabilised and remained at levels well above the MEY target and the historical target biomass at the end of the simulation period (Fig. 51).

Recruitment Scenario C - Low

Under the low recruitment scenario, the 10% CER was effective at maintaining the spawning biomass above the limit reference points of 0.20*B_0, and Hist_B_{LIM}, for all of the simulation years (appendix 4). However, it could only maintain the spawning biomass above the MEY target reference point, 0.48*B_0, and the Hist_B_{TRIG} for 82% and 53% of simulation years respectively (Fig. 49), with most of these years being in the early years of the simulation period as the stock declined from its initial high level (Fig. 51). The spawning biomass only exceeded the historical target biomass level, Hist_B_{TARG}, for 18% of the simulation years, with most of these years also occurring at the beginning of the simulation period (Fig. 51).

The trajectory of recommended harvests and spawning biomass for the 10% CER under the low recruitment scenario were similar to the Tier 1 HCR with an initial decline, then stabilising after about 10 years into the simulation period (Fig. 48). The average spawning biomass stabilised at just above the MEY target but below the historical biomass target (Fig. 51).

20 % CER

Recruitment Scenario A – High

MSE simulations of the 20% CER for the high recruitment scenario showed that it was effective at maintaining the spawning biomass above the MEY target reference point, 0.48*B_0, for 75% of the simulation years, but for only 49% of simulation years for the historic spawning biomass trigger, Hist_B_{TRIG}, (Figs. 49). The simulated spawning biomass however remained above the limit reference point, 0.20*B_0, for all simulation years, and only a few simulation years fell below Hist_B_{LIM} (appendix 4), but even with high recruitment, the spawning biomass only exceeded the historical high biomass level, Hist_B_{TARG}, for 16% of the simulation years (Fig. 49).

For the 20% CER there was an initial spike in harvest due to the 20% harvest fraction being approximately double the estimated harvest fraction at the start of the simulation period (Fig. 52). The initial harvest spike drove the spawning biomass down rapidly, after which harvest, and biomass stabilised, with the averaged simulated spawning biomass remaining above the MEY and the historical biomass trigger at the end of the simulation period, but well below the historical target spawning biomass (Fig. 52).

Recruitment Scenario B – Average

Under the average recruitment scenario, the 20% CER was effective at maintaining the spawning biomass above the MEY target reference points, 0.48*B_0 and the Hist_B_{TRIG} for only 67% and 43% of the simulation years respectively. However, it maintained the spawning biomass above the limit reference points, 0.20*B_0, and Hist_B_{LIM}, in 100% and 99% of simulation years respectively (Figs. 49, appendix 4). Similar to the high recruitment scenario, the simulated spawning biomass only exceeded the historical target biomass level, Hist_B_{TARG}, for 14% of the simulation years (Fig. 49).

Under the average recruitment scenario, the trajectory of harvest and spawning biomass with the 20% CER, declined after the initial harvest spike, with the spawning biomass stabilising at levels slightly above the MEY target and around the historical spawning biomass trigger, Hist_B_{TRIG} (Fig. 52).

Recruitment Scenario C – Low

Under the low recruitment scenario, the 20% CER could only maintain the simulated spawning biomass above the MEY target reference point, 0.48*B_0, and the Hist_B_{TRIG} for 25% and 17% of the simulation years respectively and could not achieve spawning biomass above the historical target biomass level, Hist_B_{TARG}, for any of the simulation years (Fig. 49, appendix 4). However, it maintained the spawning biomass above the limit reference points of 0.20*B_0, and Hist_B_{LIM} in 100% and 90% of the simulation years respectively (Figs. 49).

The trajectory of harvest and spawning biomass under the low recruitment scenario showed the same initial harvest spike, but the spawning biomass and harvest then dropped rapidly to levels considerably lower than for the high and average recruitment scenarios. The simulated spawning biomass stabilised at levels well below the MEY target and historical biomass trigger points, but just above the spawning biomass limit reference points (Fig. 52).

30% CER

Recruitment Scenario A – High

MSE simulations of the 30% CER for the high recruitment scenario showed that it could only maintain the simulated spawning biomass above the MEY target reference point, 0.48*B_0, for 37% of the simulation years, and 20% of simulation years for the historic spawning biomass trigger, Hist_B_{TRIG} (Fig. 49). Furthermore, the simulated spawning biomass only exceeded the historical target biomass, Hist_B_{TARG}, level for 8% of the simulation years (Fig. 49). Despite poor performance in meeting the target and trigger biomass levels, the 30% CER still maintained the spawning biomass above the limit reference points of 0.20*B_0 and Hist_B_{LIM} for 99 and 90% of simulation years respectively (Figs. 49).

For the 30% CER there was an initial spike in harvest due to the 30% harvest fraction being approximately triple the estimated harvest fraction at the start of the simulation period (Fig. 53). The initial harvest spike drove the spawning biomass down rapidly to levels just below the MEY target level and well below historical biomass trigger level (Fig. 53). Harvest and biomass then increased slightly and stabilised, with the average simulated spawning biomass remaining slightly below the MEY target, but considerably below the historical spawning biomass trigger, at the end of the simulation period (Fig. 53).

Recruitment Scenario B – Average

Under the average recruitment scenario, the 30% CER maintained the spawning biomass above the MEY target reference point, 0.48*B_0, and the Hist_B_{Targ} for only 32% and 16% of the simulation years respectively (Fig. 46). However, it maintained the spawning biomass above the limit reference points of 0.20*B_0, and Hist_B_{LIM} in 99% and 87% of the simulation years respectively (Fig. 49, appendix 4). Similar to the high recruitment scenario, the simulated spawning biomass only exceeded the historical target biomass level, Hist_B_{TARG}, for 6% of the simulation years (Fig. 49).

Under the average recruitment scenario, the trajectory of harvest and spawning biomass with the 30% CER, was similar to the high recruitment scenario, displaying the same rapid decline after the initial harvest spike, followed by the spawning biomass recovering and stabilising at levels just below the MEY target but well below the historical biomass trigger (Fig. 53).

Recruitment Scenario C – Low

Under the low recruitment scenario, the 30% CER could only maintain the spawning biomass above the MEY target reference point, 0.48*B_0, and the Hist_B_{TRIG} for 13% and 8% of the simulation years respectively, and could not achieve the historical target biomass, Hist_B_{TARG}, for any simulation years (Fig. 49, appendix 4). However, it maintained the spawning biomass above the limit reference points of 0.20*B_0, and Hist_B_{LIM} in 96% and 64% of the simulation years respectively (Fig. 49).

For the low recruitment scenario, the trajectory of harvest and spawning biomass under the 30% CER, declined rapidly after the initial harvest spike, but the initial biomass decline reached the 0.20*B_0 limit reference level and went below the Hist_B_{LIM}, before recovering slightly and stabilising at levels just above both limit reference points (Fig. 53).

Performance of Tier 1 and CER harvest control rules in meeting trial management objectives

The Tier 1 and 10% CER harvest control rules performed similarly well in meeting all the management objectives for spawning biomass under the different recruitment scenarios, except for the historical target biomass objective (20% of years > Hist_B_{TARG}) under low recruitment (Table 10). However, the 10% CER allowed spawning biomass to increase to considerably higher levels than the Tier 1 HCR for the both the high and average recruitment scenarios, and therefore appeared to be a more conservative HCR (Fig. 50, 51).

The 20% and 30% CER harvest control rules both achieved the relative spawning biomass limit (0.20*B_0) objective for all recruitment scenarios, however, the historical spawning biomass limit (Hist_B_{LIM}) objective was only achieved by the 20% CER in the high and average recruitment scenarios. The MEY target spawning biomass (0.48*B_0) was only achieved by the 20% CER for the high recruitment scenario, and no other spawning biomass target or historical trigger objectives were achieved by either the 20% or 30% CER harvest control rules (Table 10).

Finally, while we focussed on spawning biomass objectives, including biomass to produce MEY, implications of different HCRs for harvest amounts is also important to consider. The key outcome with respect to this was that the conservative Tier 1 and 10% CER rules resulted in different initial trajectories (i.e. no initial harvest spikes) and variation in the allowed harvests compared to the 20% and 30% CER rules, however, after the first 10 years of implementation the Tier 1 and 10% CER rules were allowing harvests that were only slightly less than the 20% and 30% CER rules because they were more effective at maintaining a higher biomass under each recruitment scenario (Figs. 50-53).

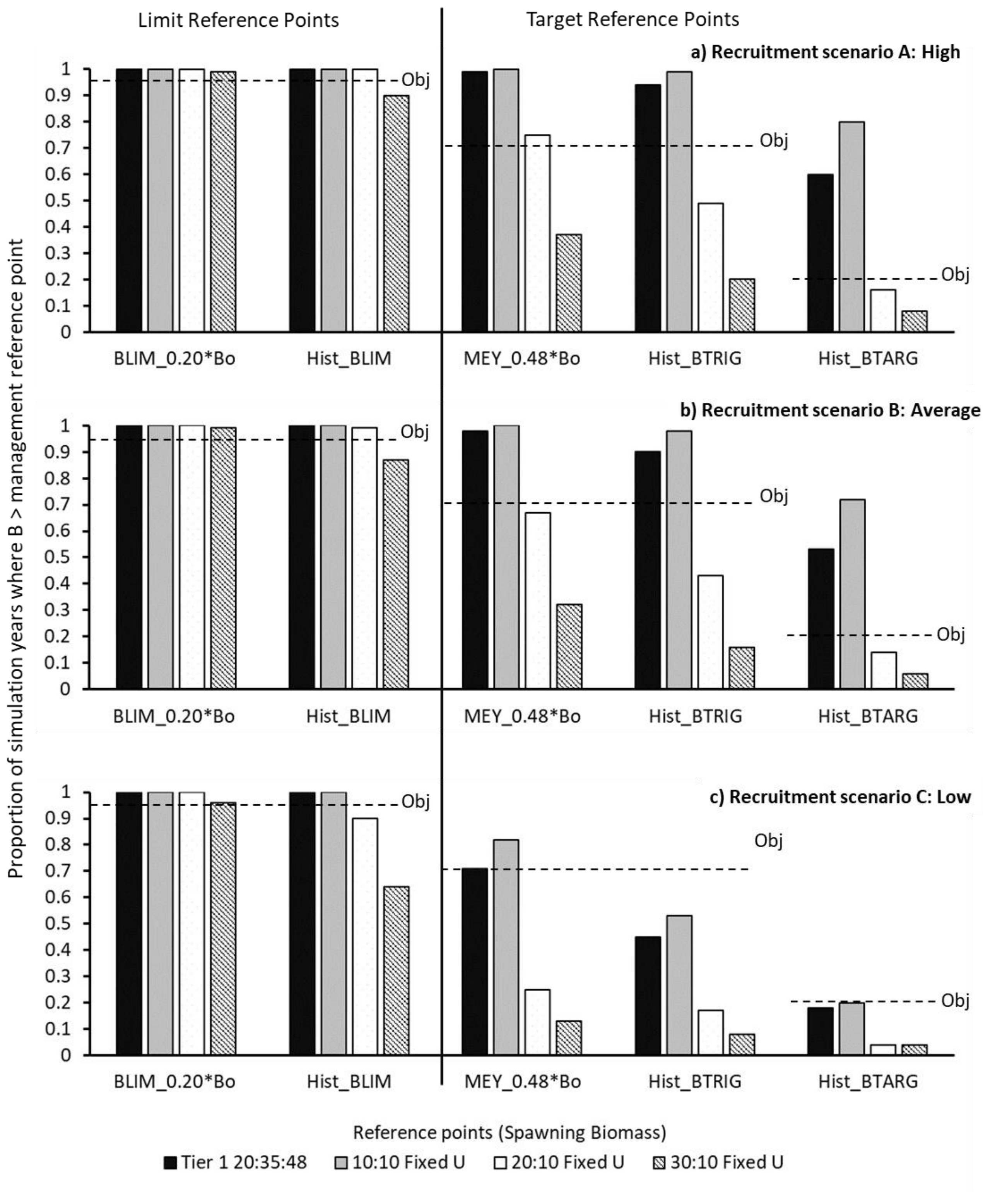


Figure 49 Summary of MSE experiment results for each harvest control rule and recruitment scenario combination in relation to the operational management objectives (Obj) for each spawning biomass reference point. The data for each scenario are the mean proportions of years across the 100 simulations (24 x projection years each) where the estimated spawning biomass was above the specified reference biomass.

Table 10 Summary of simulated harvest control rule (HCR) performance against the proposed operational management objectives for total spawning biomass under three recruitment scenarios. Y = objective met, N = objective not met.

HCR	Recruitment Scenario	'Limit Reference Point' objectives		'MEY and Historical Trigger Reference Point' objectives		'Historical Target' objective
		$0.20*B_o$ 95% of sim years	Hist_B_{LIM} 95% of sim years	MEY $0.48*B_0$ 70% of sim years	Hist_B_{TRIG} 70% of sim years	Hist_B_{TARG} 20% of years sim
Tier 1	A - High	Y	Y	Y	Y	Y
	B - Average	Y	Y	Y	Y	Y
	C - Low	Y	Y	Y	N	N
10% CER	A - High	Y	Y	Y	Y	Y
	B - Average	Y	Y	Y	Y	Y
	C - Low	Y	Y	Y	N	N
20% CER	A - High	Y	Y	Y	N	N
	B - Average	Y	Y	N	N	N
	C - Low	Y	N	N	N	N
30% CER	A - High	Y	N	N	N	N
	B - Average	Y	N	N	N	N
	C - Low	Y	N	N	N	N

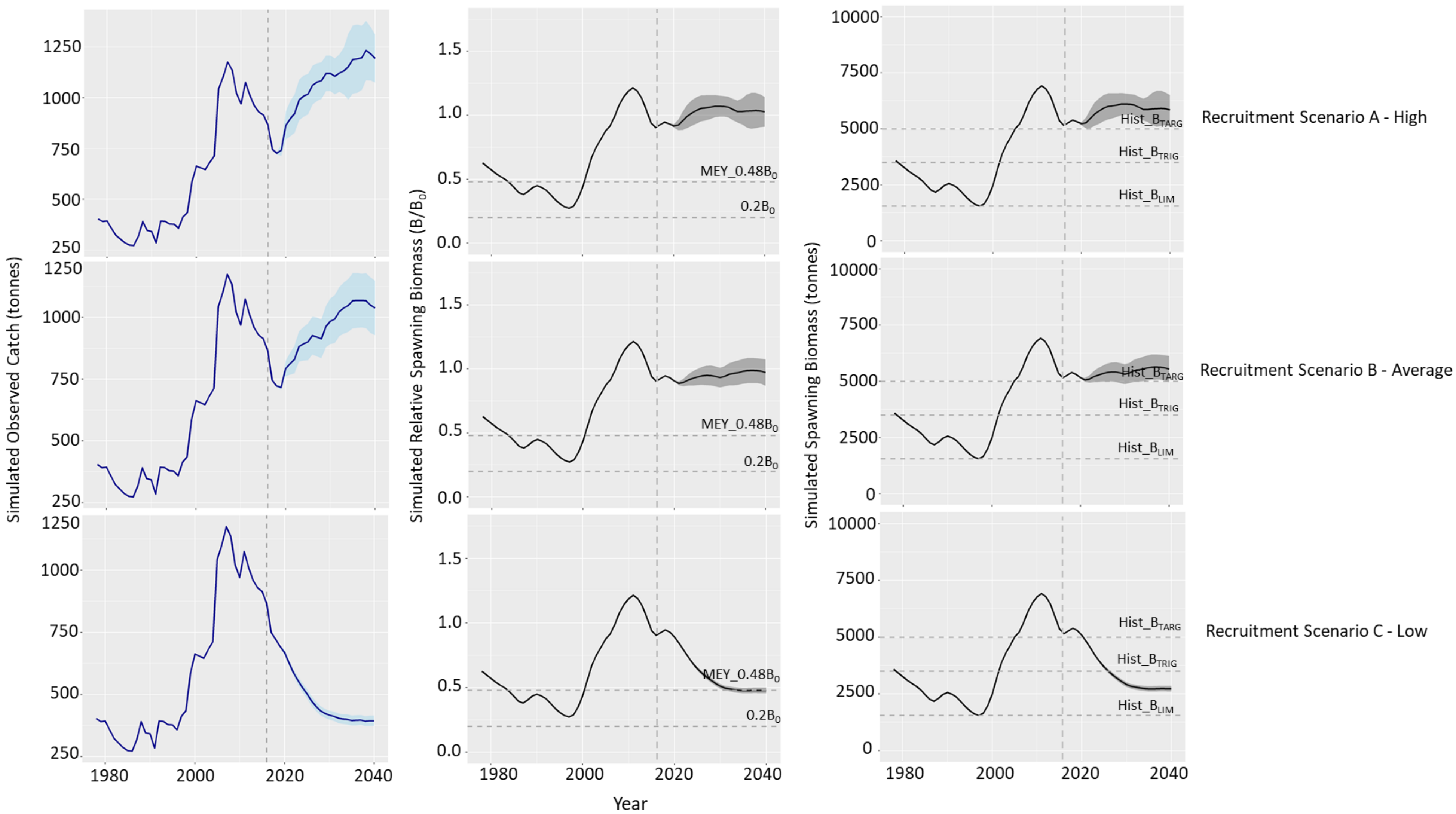


Figure 50 Simulated harvest, relative B_0 and total spawning biomass time series for Tier 1 HCR under three recruitment scenarios. The vertical dash line represents the start of the MSE simulation period.

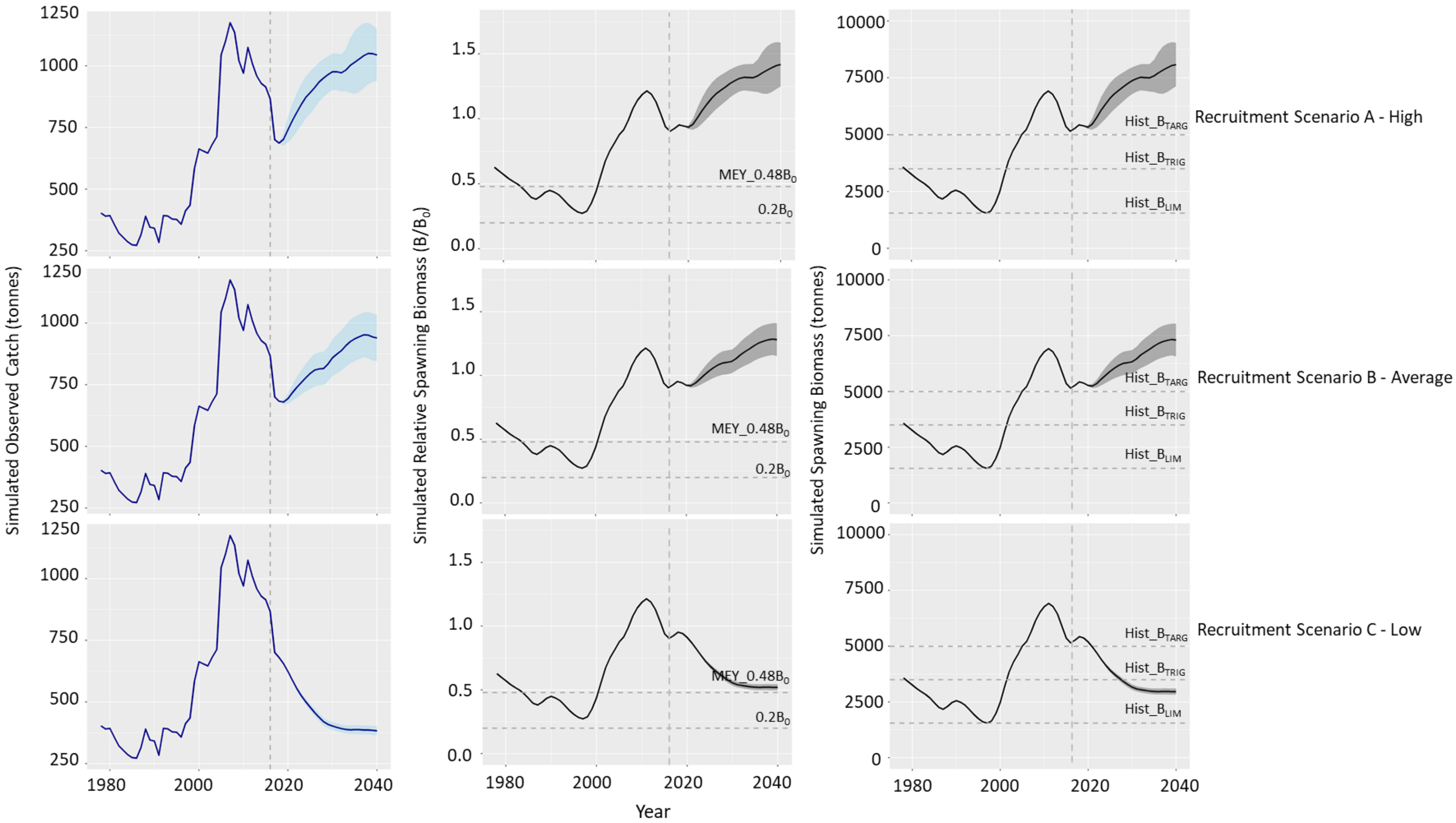


Figure 51 Simulated harvest, relative B_0 and total spawning biomass time series for 10% CER HCR under three recruitment scenarios. The vertical dash line represents the start of the MSE simulation period.

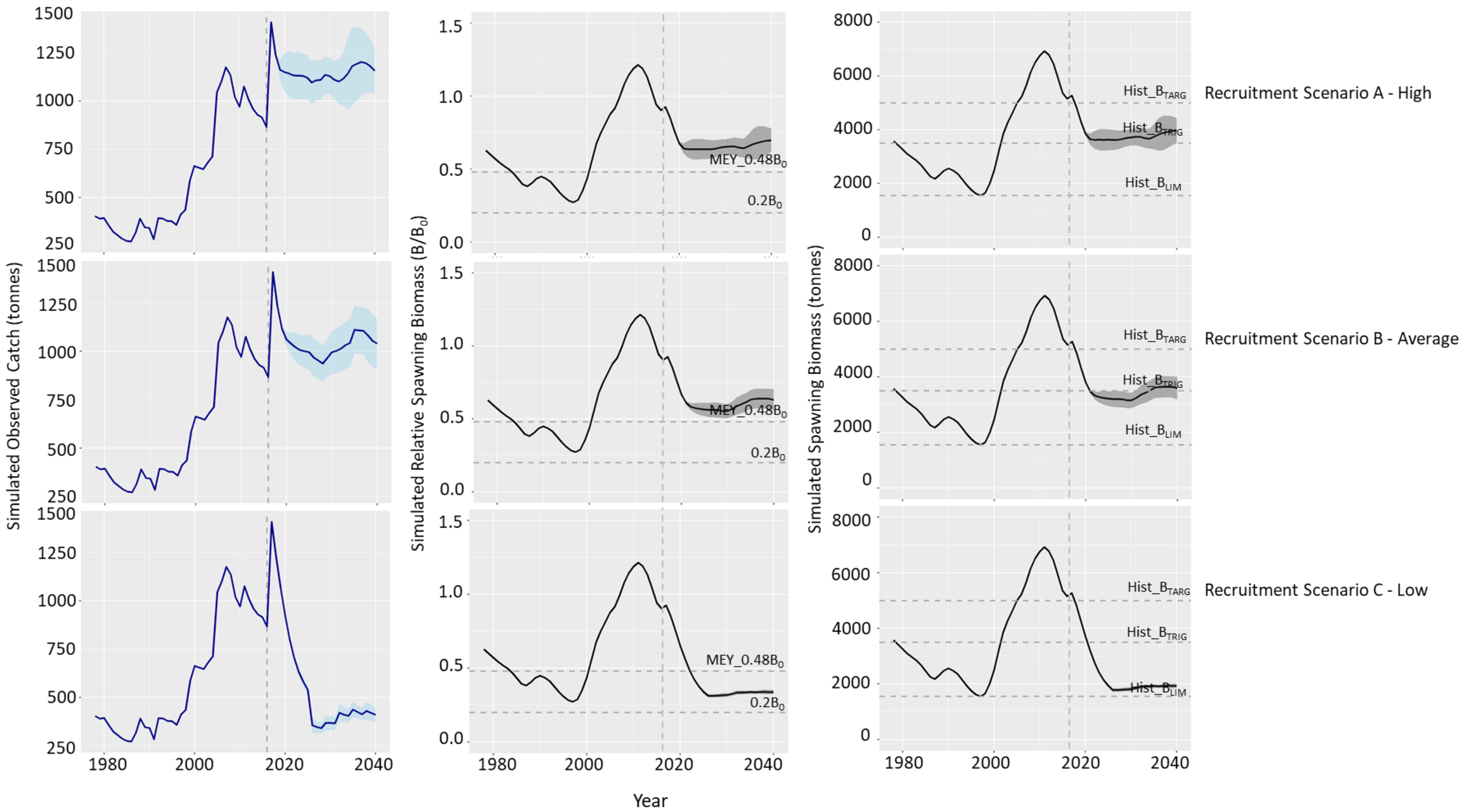


Figure 52 Simulated harvest, relative B_0 and total spawning biomass time series for 20% CER HCR under three recruitment scenarios. The vertical dash line represents the start of the MSE simulation period.

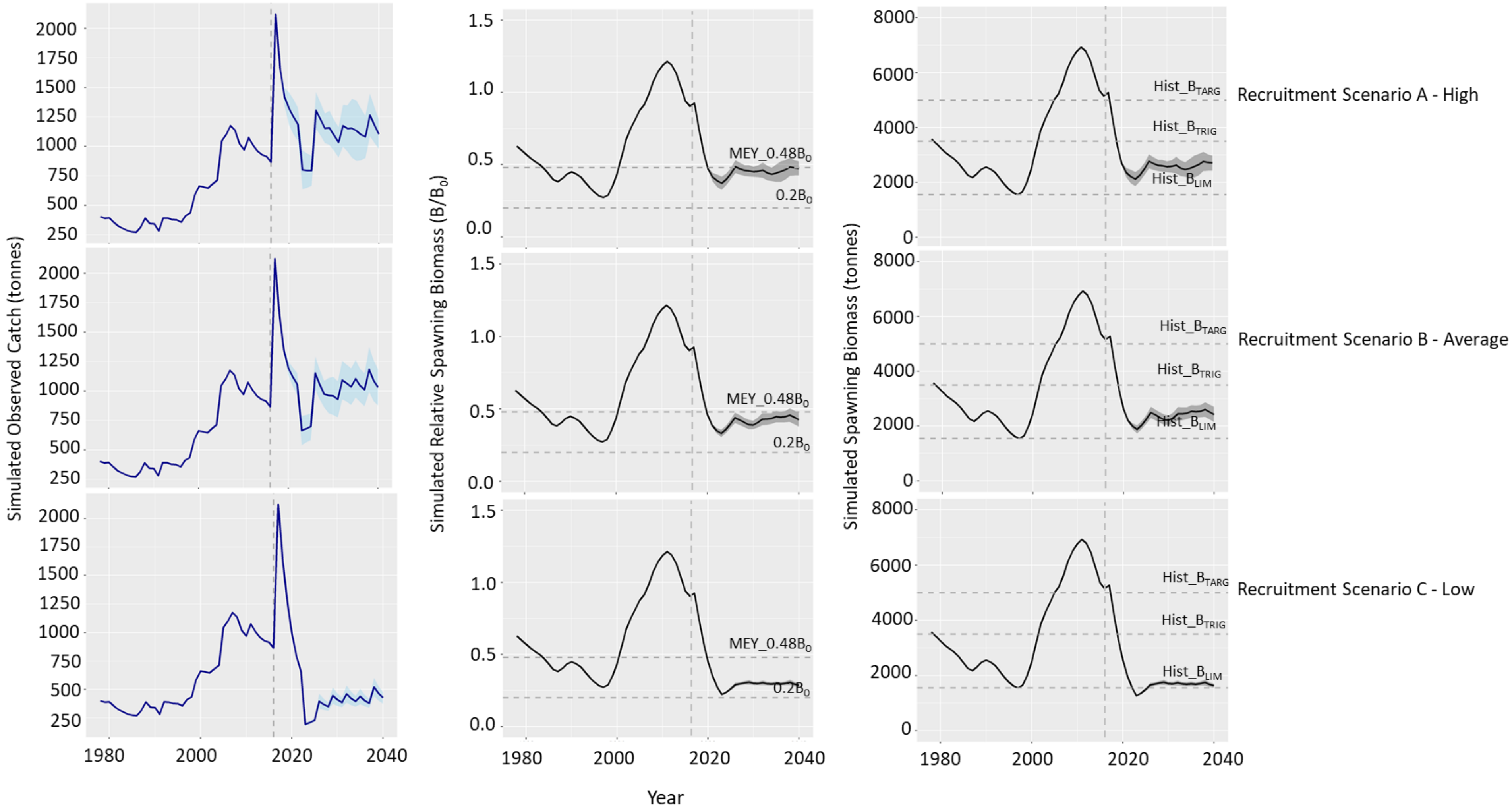


Figure 53 Simulated harvest, relative B_0 and total spawning biomass time series for 30% CER HCR under three recruitment scenarios. The vertical dash line represents the start of the MSE simulation period.

Discussion

In this chapter we have developed a novel MSE framework (SnapMSE) that utilises the SS3 population modelling framework that is operated through an R control module. SS3 has been developed, reviewed, applied and improved for well over decade and is used in many stock assessments worldwide (Methot and Wetzel 2013). SS3 was primarily developed as a stock assessment modelling framework, and while it is commonly used to conduct projections of biomass or other management parameters under fixed harvests (i.e. to inform TACs), it has rarely been incorporated into full MSE frameworks (e.g. Maunder 2014; Velero *et al.* 2016). The recent developments of ss3sim (Anderson *et al.* 2014) and r4ss (Taylor *et al*. 2013) have provided a range of valuable additional functions written in the open source and commonly used R programming language that have facilitated the expanded application of SS3 to simulation studies and improved presentation of SS3 outputs. However, the creation of a full MSE framework underpinned by SS3 required significant additional work during this project to create the connectivity and feed-back looping between an operating model (OM), sampling procedures (SP), estimation model (EM) and management model (MM) that make up a full MSE.

The SnapMSE model framework has been designed so that it can be operated entirely from within the R operating environment, making it possible for further application and exploration of MSE scenarios by fisheries scientist moderately proficient in R. Making the MSE framework "user friendly" was seen as important for it to be used in future studies by fisheries scientist, but required significant work developing simplified code and the R SnapMSE control module. Importantly, because the base models are implemented in SS3 they are reproducible by other scientists and alternative population models (OMs) can be readily created for further MSE studies by modifying the SS3 control files. Indeed, applying the SnapMSE to other fisheries is entirely feasible by modifying the base models created in SS3 and manipulating other functions written in R. SnapAssess therefore provides an example that could be applied to MSE studies more broadly taking advantage of SS3.

While there are many possible scenarios to explore with MSE, we chose to focus the first application of SnapMSE on a population process uncertainty: recruitment dynamics. Therefore, the EM and associated SP were not varied in our MSE experiments. Future MSE experiments could explore how different sampling effort/programs, survey accuracies, model configurations, assumptions and parameter values (i.e. natural mortality and steepness of the stock recruitment relationship) influence the accuracy of EM outputs and performance of HCRs in meeting objectives. Also, MSE studies could look at implications of alternative minimum legal lengths by altering fleet selectivity parameters and predictions of harvest reductions using additional sub-models such as described in chapter 4. The current version of ss3sim is limited in the number of fleets that can be included, and while we hope that capacity for additional fleets in ss3sim will eventuate, further MSE studies can use the current SnapMSE version to test implications of alternative single fleet selectivities for the performance of HCRs in achieving management objectives.

The future recruitment dynamics of Snapper in the main spawning/nursery area for the WVSS, PPB (Hamer *et al.* 2011) are highly uncertain due to the influence of climate variability. Previous declines in the PPB Snapper fishery during the late 1980s to mid-1990s appeared related to combined effects of fishing and an extended period of poor recruitment. Long-term changes in water temperature dynamics due to climate change are expected to alter the timing of optimum sea temperature windows (18-22°C) for spawning and egg survival in PPB (Pecl *et al.* 2014). Larval survival depends on availability of certain types of zooplankton prey, the production of which is related to dynamics of river flows and associated nutrient inputs into PPB (Murphy *et al.* 2013; Black *et al.* 2016). The recruitment success of Snapper in PPB therefore appears highly sensitive to match-mismatch dynamics between optimal temperature windows and optimal prey conditions for larval stages during spring/summer. The MSE experiments were designed to understand how altered recruitment scenarios or 'regimes' could influence stock dynamics, biomass and fishery performance under different HCRs/fishing mortality. The different simulated recruitment scenarios were based on recent historical recruitment variation and therefore were realistic of future possibilities. While, over the longer-term more extreme regimes may emerge, we chose not to explore regimes that were outside of recent variation (last 30-40 years). Suitably realistic management objectives for spawning biomass were also set, both for biological sustainability (limits, triggers) and fishery performance (targets). However, these objectives were set purely for this project as trial options to promote further discussion and are not written into any formal management plans or harvest strategies for the WVSS. Testing of alternative management objectives and HCRs derived with stakeholder input is an important next application of the SnapMSE tool (discussed further below).

To isolate the implications of different recruitment scenarios it was important that estimated spawning and exploitable biomass from the EM were consistent with the ‘true’ biomass levels from the OM. The EM with realistic sampling and low survey errors was generally close to estimating the 'true' OM spawning and exploitable biomass. Therefore, the comparisons of performance of the candidate HCRs under the alternative recruitment scenarios should not have been unduly influenced by a poorly performing EM. However, it was noted for the historical comparison period the that EM under-estimated spawning and exploitable biomass for the most recent four years compared to the OM. This would have the effect that the HCRs, which rely on information from the EM, under allocate harvest until cohorts are fully recruited to the adult biomass by about 8+ years age (i.e. the EM becomes better informed on their actual strength). This effect would be greater for stronger cohorts and is an intrinsic feature of the way the stock assessment-management decision process works and may add an extra level of conservatism by not allowing the “true” or full *F* under the HCRs to be applied to important strong cohorts when they are just recruiting into the fishery.

Despite the OM being a simpler version of the AM, the comparison of the spawning biomass time series for the two models over the historic period showed virtually identical dynamics and relative variation, but the OM was consistently biased to estimating higher biomass levels. This bias was of no consequence to comparing the performance of different HCRs over the projection period but means that the harvest and biomass amounts produced in the MSE experiments would be slightly higher than those that would be expected under the AM with the same biological parameters, recruitment dynamics and HCRs. However, in the MSE study it is the HCRs and spawning biomass objectives that are of more interest than the actual simulated allowable harvest levels, although these are discussed briefly below in relation to trade-offs between harvest amounts and stock conservation (spawning biomass) objectives.

The results of the MSE studies with the proposed trial objectives supported the application of the Tier 1 and 10% CER HCRs. These HCRs met the management objectives in the high and average recruitment scenarios, and also achieved the MEY objective in the low recruitment scenario. Overall, the 10% CER was the more conservative rule, setting slightly lower harvests and achieving higher average spawning biomass. However, in the high and average recruitment scenarios the 10% CER and Tier 1 HCR could have allocated more harvests as the spawning biomass was well above the MEY and historic target levels, and therefore would likely have under-achieved on economic or social performance, i.e. daily bag limits, effort or TACs could have been higher under the high and average recruitment scenarios. The higher CER HCRs of 20% and 30%, did not meet the historical spawning biomass trigger and target objectives in any of the three recruitment scenarios, and only the 20% CER could achieve the MEY objective in the high recruitment scenario, although it came close in the average recruitment scenario. Therefore, using either of these two HCRs was not conducive to meeting the performance targets, however, they maintained the spawning biomass above the limit reference points in the high and average recruitment scenarios. In the low recruitment scenario, the 20% and 30% CER HCRs pushed the spawning biomass to close to, or below, the limit reference points.

It is important to consider how relevant the chosen CER HCRs are in a current and historical sense. The AM estimated the exploitable biomass in 2006/07, when the last total recreational harvest was estimated, to be at around 5,500 tonnes (appendix 3). The total harvest, including all sources, in 2006/07 was estimated at around 750-800 tonnes (Fig. 2), equivalent to an annual exploitation rate of around 15%. The annual fishing mortality (*F*) history since 1978 estimated by the AM varied in the range 0.08 – 0.16, and the higher *F* values were estimated for the lower biomass period (mid-1990s), yet the stock managed to rebuild (i.e. the stock did not fall below a biomass from which it could not recover under conditions favourable to high larval survival rates). These levels of historic *F* are consistent with estimates from tagging studies of 0.09 per year in the late 1990s (Coutin *et al.* 2003). The *F* estimates from the stock assessment historical period are supportive of the MSE projections under the 10% CER and Tier 1 HCRs that maintained the spawning biomass well above the limit reference points, even in the low recruitment scenario. Therefore, although the OM had a simplified fleet structure and selectivity, it also indicated that maintaining the annual exploitation rate at 10-15% over the long-term would be a reasonable recommendation to meet the suggested management objectives, while accounting for recruitment uncertainty. However, under high recruitment/high biomass regimes, the 10-15% exploitation rate could be overly conservative. For a recreational fishery this may be less of issue because catch rates would be higher and catch rate is a key measure of recreational fishery performance. But for a commercial fishery forgoing an increase in allowable harvest would have an economic consequence, irrespective of the economic efficiency gains from the higher catch rates.

Despite similar performance, the Tier 1 HCR may be less suited to recreational dominated fisheries than a simple 10% CER rule. This is because MEY based policies and HCRs are more difficult to understand as they depend on the estimation of the *F* required to achieve B_{MEY} over the long-term which depends on assumptions of stock-recruitment parameters, natural mortality and average recruitment (Forrest *et al.* 2018). Average recruitment is a difficult concept for stakeholders to accept when recruitment is known to vary greatly for this species, and natural mortality and steepness of the stock recruitment function are uncertain parameters. Further, B_{MEY} as a target biomass reference point may be less meaningful to fishers because it based on the proxy of $0.48*B_0$, and the determination of B_0 itself is a difficult concept for fishers to understand and sometimes accept, and theoretically is often problematic to estimate due to lack of, or poor quality, historical data. With CER rules only the exploitable biomass requires estimation, and while this estimation has uncertainty, it is the only estimated quantity where uncertainty needs to be considered by managers and stakeholders when considering acceptable harvest levels (although uncertainty in the ability of the operational management system to constrain the harvests to the recommended levels would also be considered). The downside of CER HCRs is that they are not underpinned by the sound biological theory and application to many species/fisheries that underpins the MEY or MSY based harvest policies and HCRs (Mace 1994; Punt and Smith 2001). Therefore, applying a CER HCR without prior testing in a framework such as MSE can be risky, unless there is good prior knowledge of exploitation rates that have allowed the biomass and fishery performance to meet proposed management objectives over a suitably long timeframe.

Determining management reference points for biomass status (i.e. biomass at which the stock is deemed overfished, or at risk of becoming overfished?) using historical data from fishery dependent and/or independent sources such as CPUE, allows the stakeholders to be more actively engaged in the process of determining management reference points because they understand the data, and it is meaningful to them in relation to fishery performance. However, due to the often, contentious nature, of CPUE data, in particular accuracy of effort reporting, managers can have concerns over whether chosen CPUE reference levels are meaningful in terms of biomass status. In this case we used fishery CPUE time series to indicate historic low, high and intermediate years, that we assumed to represent low, intermediate and high productive/biomass periods. Importantly we had two sources of CPUE data, commercial and recreational, that showed the same trends and supported the choice of reference years for setting the historic biomass reference points. In terms of maintaining spawning biomass above certain critical levels where it would be deemed overfished or at serious risk of becoming overfished, the limit and trigger reference points are the most important. In this case the historical limit reference point for spawning biomass ($Hist\_B_{LIM}$) was slightly higher than the estimated $0.2*B_0$ limit reference point for a stock being overfished. The historic trigger reference point for spawning biomass ($Hist\_B_{TRIG}$) was also higher than MEY ($0.48*B_0$). Therefore, the historic limit and trigger reference points, based on selecting reference years from CPUE time series, were more conservative than the relative B_0 reference points. This is important to know and supports the use of the CPUE data for the selected reference years as empirical limit and trigger CPUE reference points for future classification of stock status (i.e. SAFS, Status of Australian Fish Stocks reporting) in the absence of spawning biomass estimates from a full integrated assessment.

Ultimately the key outcomes of MSE studies are information on risk and trade-offs among alternative levels and approaches for managing fishing mortality to achieve a set of objectives. Typically, MSE has been applied to commercial fisheries, where entry is limited, and harvest can be constrained by harvest or effort quotas (but see Little *et al.* 2009). Therefore, recommendations on managing fishing mortality from MSE studies are theoretically simple to implement by direct control of effort and/or harvest. In fisheries with large, open access, recreational components, such as the WVSS, application of harvest management systems such as quotas/TACs are typically not feasible and input control approaches, particularly, size and bag limits are applied to constrain harvest, with varying effectiveness because they do not control effort. Effort control options, such as closed seasons and areas would be expected to work with high effect because of the strong aggregation and seasonality of Snapper availability in Port Phillip Bay (i.e. McGarvey *et al.* 2010). However, spatial-temporal restrictions on Snapper fishing in Victoria would come at a high socio-economic cost, and managing recreational harvest using size and bag limits remains the preferred option. The ability of bag and size limit regulations to influence recreational Snapper harvest is explored in chapter 4.

Another issue is that harvest is not routinely measured in most recreational fisheries, including the WVSS, which complicates the use of harvest as a measure of fishing mortality in integrated assessments, and the use of harvest strategies that require direct control and measurement of harvest (i.e. recommended biological catch rules). In terms of managing overfishing risk, (i.e. is overfishing currently occurring or not?) *U (annual exploitation rate)* or *F (instantaneous fishing mortality)* estimates with trigger and upper management limits could be used to elicit a management response to reduce the risk of overfishing occurring or continuing. The MSE study provides managers with an appreciation of this risk to inform a choice of suitable trigger and limit points for fishing mortality.

In the absence of regular recreational harvest estimates, approaches for monitoring F or U may need to be developed and routinely applied. Simply watching CPUE decline, without information on current fishing mortality, will most likely lead to action being taken too late if overfishing is driving the decline, i.e. management paralysis (Walters and Martell 2004). While harvest free assessment models that estimate ‘relative’ biomass status and fishing mortality are possible (Porch *et al.* 2006), they are not freely available and would require modelling expertise and further work to develop. Empirical approaches for estimation of U and F commonly involve tagging programs (Walter and Martell 2004; Pine *et al.* 2014) or catch curves (Chapman and Robson 1960; Wayte and Klaer 2010; Thorsen and Prager 2011). The combination of these approaches to estimate U or F combined with continual effort monitoring could provide a suitable approach for ongoing monitoring of fishing mortality. While effort data is readily available for the commercial fisheries from log-books, passive electronic monitoring systems for the recreational fishery, such as ramp cameras, can provide the effort data for the recreational sector. When harvests are not directly measured, monitoring changes in effort becomes more important as fishing mortality is directly related to effort. For example:

1. Catch (C) = Exploitable Biomass (EB)*Catchability (q)*Effort (E)
2. Exploitation rate (U) = C/EB.

Therefore, U=q*E.

Theoretically, if the exploitable biomass decreases and the catchability (i.e. the number of fish that are caught from an available number/stock size with a unit of fishing effort) (Arreguin-Sanchez 1996) and effort are constant the catch will decline in proportion to the biomass decline and U will stay constant. However, if the exploitable biomass declines or even remains stable, but the effort or catchability increases, the exploitation rate will increase. Therefore, assuming average catchability is constant, measuring changes in effort can be used to indicate changes in U and F. This assumption of constant catchability in the recreational Snapper fishery requires further investigation and may need to be accounted for when using effort as a proxy for changes in fishing mortality (Walters and Martell, 2004; Ward *et al.* 2013). As stocks decline, less successful anglers are more likely to drop out and the average catchability may increase due to this “effort sorting” which may partially negate the effects of reduced overall effort. In the contrary, increasing effort as a stock becomes productive could be mostly due to less effective anglers choosing to take up or go fish again, thereby reducing the average catchability, and negating the impact of the increased effort on increasing the exploitation rate.

Recreational catchability is generally poorly understood and could be influenced by a range of factors including; angler skill and experience, technology use and gear, vessel attributes, fishing locations and times, fish aggregation patterns etc. If information on these factors can be collected and related to individual catch rate data, it could be possible to develop a catchability model using approaches such as general linear mixed models (GLMM) used in catch rate standardisations. The current Victorian creel surveys collect various auxiliary information with each interview, such as; target preference, avidity, gear, bait and hook types, location, time and date, age, and technology use, that could be used to develop catchability models with the aim of deriving an index of catchability that could be applied to individual angler trips targeted at Snapper. Target preference and angler avidity/experience likely encapsulate many of the factors that influence recreational Snapper catchability and are important in previous recreational Snapper catch rate standardisations for PPB. Bag and size limits are also a direct influence on catchability (i.e. they limit angler daily harvest and composition), but these regulations affect all anglers and would be simpler to account for in a catchability model. Estimating a catchability value associated with every creel survey trip interview would then allow the calculation of an annual recreational Snapper fishery catchability index. The combination of a catchability index combined with effort monitoring would provide an approach for tracking changes in fishing mortality/exploitation rate. A catchability index would also be useful for interpreting changes in recreational CPUE data in relation to trends in available biomass. If the chosen approach to monitoring and managing fishing mortality is to involve tracking and responding to changes in *U*, similar to the harvest index approach discussed in chapter 2, the catchability-effort combination could be scaled to occasional direct estimates of *U* using tagging studies or *F* estimates from catch curves.

While further MSE scenarios require formal testing, the scenarios tested in this MSE study suggested that an upper limit for *U* of 20% with a trigger level of 15% could be appropriate for the WVSS fishery. Exploitation rates for South Australia’s main Snapper fisheries of Northern Spencer Gulf and Gulf St Vincent have been estimated to range from approximately 5-10% since 1984 (Fowler *et al.* 2016). Despite these relatively low exploitation rates the North Spencer Gulf fishery has experienced declining effort and catch since the mid-2000’s and has been assessed as a ‘depleted’ stock under the Status of Australian Fish Stocks (SAFS) (Fowler *et al.* 2018). However, the Gulf St Vincent fishery has had increasing effort and catch and is classified as ‘sustainable’ under the same scheme. It is thought the main driver of these alternative scenarios is stochastic recruitment variation, with recent high recruitment events in the Gulf St Vincent stock and prolonged low recruitment in the Spencer Gulf. For the New Zealand Hauraki Gulf Snapper stock, the estimated exploitation rates since the 1980’s have varied between approximately 10-25%, and the stock biomass has recently been estimated to be close to the soft limit reference point of $0.2*B_0$ (Francis and McKenzie 2015). A recent assessment of the Australian eastern Snapper stock estimated *F* values of between 0.09-0.27 (i.e. *U* of approximately 9-24%) from 2012 to 2016, depending on assumptions of natural and discard morality rates, data sources and CPUE fitting indices (Wortman *et al.* 2018).

Each of these assessments used different model frameworks, production parameters (i.e. natural mortality and stock recruitment steepness), fleet selectivities and size limits, yet all estimated exploitation rates of generally less than 20% over the long-term. Interestingly, for the New Zealand assessment, exploitation rates where at around 20-25% for the Hauraki Gulf stock in the 1970-1980s and the stock declined to below the soft limit reference point of $0.2*B_0$. However, after the exploitation rates were reduced to below 15% during the 1990-2000s the biomass rebuilt to be above the soft limit but remains below the MSY target (i.e. $0.4*B_0$) (Francis and McKenzie 2015). In the Queensland assessment, most of the scenarios modelled indicated that the recent exploitation rates were likely over 15% and the stock in Queensland waters has been recently classified as ‘depleted’ under the SAFS criteria. These assessments are broadly consistent with the MSE scenarios for the WVSS in supporting a *U* upper limit of 20% and aiming for a *U* of <15%. Further, the results of the

MSE scenarios modelled in this study suggested that the HCRs that allowed higher exploitation rates did not lead to major sustained increases in allowable harvest because they result in greater biomass reduction. For example, in this study applying a 10% CER over the long-term resulted in harvests that were only marginally lower than for the 20% and 30% CER rules for the three recruitment regimes. Therefore, for a marginal additional harvest under the higher CER rules, managers and stakeholders would need to accept a disproportionately greater risk of not meeting spawning biomass objectives.

While the major aim of this project component was to develop the SnapMSE framework, and test it on relevant scenarios of recruitment, objectives and HCRs, this has largely been done without stakeholder input. The next phase of application of SnapMSE as a management planning tool will require stakeholder education of MSE initially, and then their input to:

1. Solidify management objectives, performance indicators and reference points,
2. Propose a set of alternative OMs and assessment/estimation uncertainties to further test the performance of HCRs, against objectives, include additional HCRs if warranted, and test alternative selectivities,
3. Consider testing further recruitment scenarios that include extreme low recruitment events and alternating rather than continuous regimes,
4. Consider options for monitoring and controlling fishing mortality by the recreational sector.

Chapter 4: Development and application of SnapMat: a management advice tool that uses recreational creel survey data to predict impacts of bag and size limit adjustments on retained Snapper catches

Introduction

The most commonly applied approaches to regulation of recreational fishing harvest is the application of legal minimum lengths (LML) or “size limits” for harvest and daily per angler harvest limits or “bag limits” (Radomski *et al.* 2001; Woodward and Griffin 2003; Van Poorten *et al.* 2013; Gwinn *et al*. 2015). These approaches are often referred to as ‘blunt’ because they only limit the daily harvests of individual anglers and not the total harvest which is driven by the overall effort across many anglers. Despite this, fisheries managers when faced with the need to regulate impacts of recreational fishing on fish stocks, continue to rely heavily of these tools. Recently ‘harvest strategies’ have been promoted as the best practice formal frameworks for guiding management of fishing mortality and have been implemented in many commercial fisheries (DAFF 2007; Smith *et al.* 2007; Sloan *et al.* 2014; Smith *et al.* 2014). In shared recreational/commercial fisheries, or recreational only fisheries regulation of harvest (i.e. fishing mortality) under harvest strategy frameworks is problematic (Radomski 2003). This is because, unlike commercial fisheries which are often limited access with quota systems, most recreational fisheries are open access with no definitive tool(s) for regulating overall effort/harvest. Decisions around changing or implementing size and bag limits to regulate recreational harvest/fishing mortality should ideally be made with some informed predictions of the likely impact of the changes (Van Poorten *et al*. 2013). How likely is it that proposed size and bag limit changes can produce desired changes in harvest, would the changes required to make the necessary impacts be acceptable by anglers and continue to meet socio-economic objectives, and can different regulation changes achieve similar results but with different socio-economic impacts? Answering these questions will benefit from development of analytical tools that can predict the implications of size and bag limit regulation changes for harvest and socio-economic objectives.

Fortunately, recognition of the socio-economic value of recreational fisheries, the need to manage recreational fisheries sustainably, and the contribution of recreational harvest to overall fishing mortality (McPhee *et al.* 2002; Cooke and Cowx 2006; Ihde et al., 2011), has led to implementation of monitoring programs for many recreational fisheries worldwide. Most of these programs collect data on catch rates, size composition and fishing effort trends, along with various other data that describe the anglers themselves, gears used, target preferences and more. These data are mostly used to develop indices of both stock (i.e. biological) and fishery (i.e. socio-economic) status and performance. However, there is potentially added value to these data in relation to predicting impacts of regulatory changes.

Data on the numbers of fish harvested (i.e. retained) per angler trip and their length compositions could be useful for predicting the implications of changes to bag and size limits (i.e. Attwood and Bennet 1995). Assuming the most recent retained catch rate and length composition data for a target species is representative of the next fishing year/season, and that effort will not change markedly, applying alternative bag and size limit regulations to the recently collected harvest rate and size composition data may be used to predict the influences on overall harvest levels. Impacts of release mortality can also be factored into the estimation procedures. For most creel data sets, this approach is possible when the goal of the regulation changes is to reduce harvest, however, if accurate data on the size and numbers of released fish per angler trip is also available it could be possible to estimate impacts of less conservative regulations that aim to allow increased overall harvests. Importantly, this approach is purely numerical/empirical which has the advantage of few assumptions. This type of retrospective size and bag limit study can provide indicative estimates of harvest changes in response to different size and bag limits, and if the changes likely to be required would be acceptable given other socio-economic objectives. It is however important to consider how bag and size limit changes might influence incentives/motivations and behavioural responses of anglers that could have secondary or unintended impacts on effort (Woodward and Griffin 2003; Van Poorten *et al.* 2013). Monitoring of harvest trends overtime is therefore still important in validating predictions of harvest changes and identifying the influence of other angler response variables to size and bag limit changes.

Snapper, *Chrysophrys auratus*, are an important recreational target species in Victoria. Most of the recreational harvest is taken by boat-based anglers from two bays; Port Phillip Bay (PPB) and Western Port Bay (WPB) (Ryan *et al.* 2009) that are part of the 'Western Victorian Snapper Stock' (WVSS) (Fig. 1). The recreational fishery has a major focus on spawning aggregations that occur from spring to early summer (Coutin *et al.* 2003). Total catch surveys during the 2000s indicated that recreational harvests from the WVSS were in order of 400-600 tonnes/year (Ryan *et al.* 2009). The current recreational harvest is unknown. Commercial catches are also significant in Victoria but have recently been capped in the main PPB fishery, are unlikely to exceed approximately 100 tonnes overall, under the current arrangements, and have been significantly less in recent years.

Maintaining a biologically sustainable and a well performing WVSS fishery depends on being able to effectively manage fishing morality across both the recreational and commercial sectors. Controlling harvest for the commercial sector is technically straight forward with limited entry and harvest caps (or quotas). There are no spatial or temporal restrictions imposed for fisheries management purposes for Snapper in Victoria. Bag and size limits continue to be the preferred approach for regulating recreational Snapper harvests. The current recreational regulations (in place since 2007) allow for a maximum of 10 Snapper to be harvested per person per day, all harvested fish must be ≥28 cm (also applies to commercial harvests) and only three retained fish can be ≥40 cm total length. The WVSS stock and associated fisheries are currently considered sustainable (Fowler *et al.* 2018; Victorian Fisheries Authority 2017). The stock biomass is sensitive to highly episodic recruitment. Maintaining adult biomass above levels where average recruitment starts to decline will require active management of fishing mortality in relation to recruitment variability. The most recent adjustment to size and bag limits were made in response to high harvest rates to address concerns around socially acceptable individual recreational daily harvest amounts and illegal take for sale, rather than to reduce overall harvest for stock conservation objectives (Department of Primary Industries 2007).

In this study we develop an analytical tool that estimates how different size and bag limit options would impact recreational harvests. These estimations can provide managers with comparisons of the effectiveness of alternative size and bag limit approaches for achieving desired changes to recreational harvests in the upcoming year/season. The approach is designed to inform decisions on feasibility of applying size and bag limit changes to achieve harvest reductions recommended by management, and to explore trade-offs among different regulation changes in relation to social objectives for the fishery. For example, trade-offs between reducing take of smaller versus larger fish. We use the extensive boat-ramp creel data set collected for the recreational Snapper fisheries in PPB and WPB over the last 10 years, however, because the data is limited with respect to numbers and sizes of released fish, we only consider the impacts of changes aimed at harvest reduction outcomes for the boat-based fishery. We create the size and bag limit management advice tool, SnapMat, implemented in the open-source statistical programming language R (R Core Team 2017). This tool allows for simultaneously modifying legal minimum lengths (LML), total bag limits, secondary harvest limits (sub-bag limits and sizes) of fish above specified lengths higher than the LML and applying slot limit regulations.

Methods

Creel data

Creel data were obtained from the Victorian Fisheries Authority's boat-ramp creel survey program, that has continuously surveyed boat fishing parties at launch facilities around PPB and WPB (Fig. 54) since 2002. The creel survey program is a stratified random sampling design with strata defined by spatial zones, and daytime periods (morning and afternoon). Sampling was restricted to weekend days for the most recent years used in this study (i.e. 2010 onwards). All ramps within a spatial zone were sampled on a survey day. Random sampling was conducted by prior determination of the time and sequence of visiting boat ramps among sample days. Wait times at each ramp within a zone also varied according to the relative fishing effort occurring at each ramp, to reach a trade-off between covering all ramps in a zone but also obtaining sufficient numbers of interviews (i.e. less time at low activity ramps). This was justified as the main aim was collecting harvest rate and size composition data rather than estimating effort. The total retained catch for each fishing party was identified, counted and, for a random selection of interviews, measured by the interviewer. The fishing effort data for each surveyed trip includes the number of anglers and time spent fishing by each party. Target species were indicated by the fishing party, as well as other demographic information, gear and bait types, technology used, information on released fish, and approximate fishing location. The surveys run from late October until April, capturing most of the annual recreational Snapper fishing effort (see chapter 1).

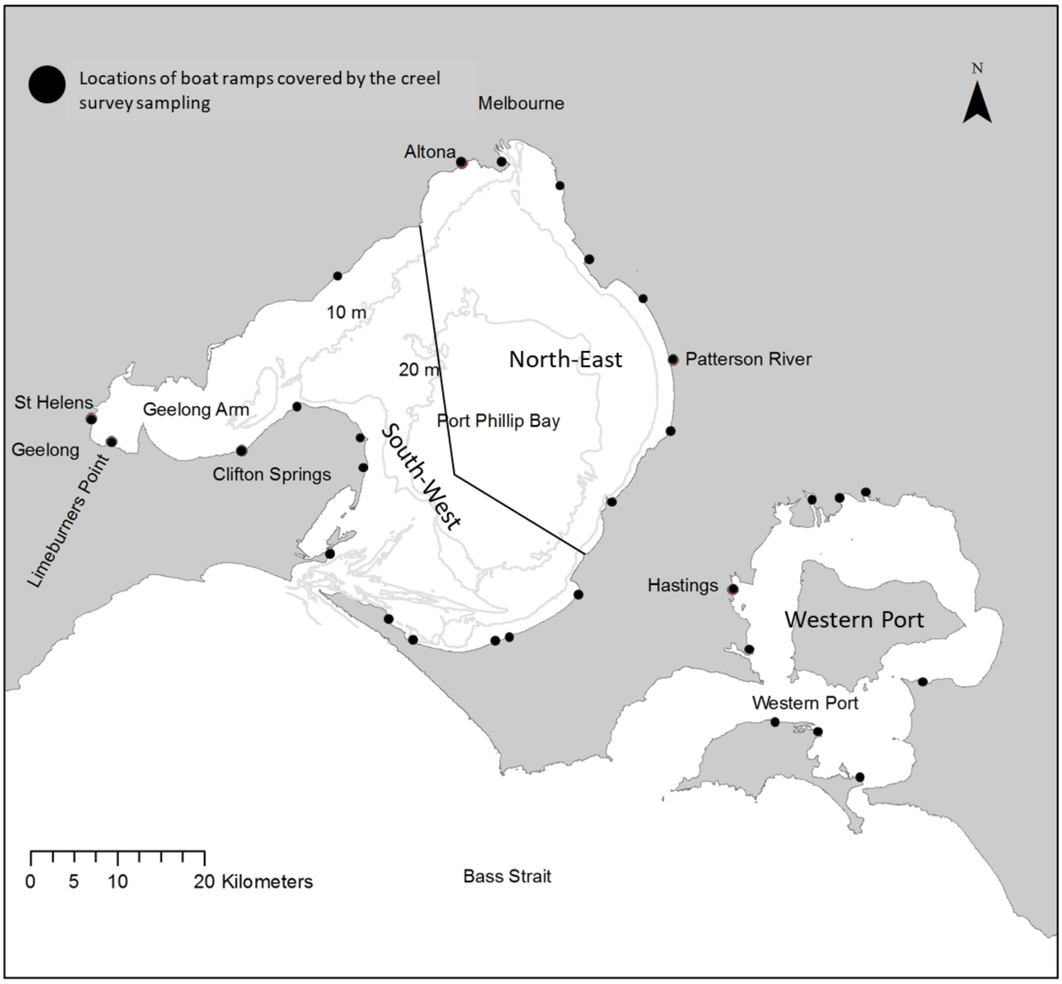


Figure 54 Map of Port Phillip Bay and Western Port showing locations of boat ramps where creel survey data were collected, and sub-regions that were used for the size-bag limit simulation study.

Logic

The logic behind this approach (Fig. 55) assumes that the creel survey data represent a representative random sample of retained catch numbers per angler trip (i.e. angler bags) and length compositions of retained fish for specified regions and time periods. The angler bags are accumulated, apportioned to length compositions (as per the survey data length composition) and converted to total numbers and biomass for the original random creel sample. Application of a length and/or bag limit regulation change can then be applied to the 'original' sample data. Assuming that the fishing effort that was applied to generate the original sample data is similar under the new regulation, the impacts of the regulation changes can be determined by subtracting the numbers of fish that would have had to be 'returned' or 'not caught' from the original sample had the alternative size and/or bag limits been in place. After this process of 'returning' fish from the original sample data, a new set of angler bag data is created and used to calculate an 'adjusted number' of retained fish, that is also converted to an 'adjusted biomass' using the 'adjusted length frequency' distribution if length regulations were also altered. Post-release mortality (PRM) is accounted for by calculating the numbers of fish that would have been returned due to the changed regulations. PRM was applied by using the appropriate length composition, and grouping the returned numbers into those above and below 40 cm TL (i.e. juvenile and adult Snapper). The numbers assumed to have died after release are then calculated using pre-specified release mortality rates for Snapper above and below 40 cm TL (below). The numbers dead after release are converted to biomass and added to the 'adjusted harvest numbers and biomass. This produces the final adjusted harvest numbers and biomass accounting for PRM that are then ratioed to the original numbers and biomass to determine the % reduction in harvest. The reduction in harvest determined for the creel survey data is assumed to represent the % reduction likely for the entire population of angler trips.

If there is also a recent estimate of exploitable biomass and total harvest, the harvest change can be interpreted in terms of exploitation rate change if this is used as a key performance measure in management.

Because the approach involves simulating the return of undersize fish to the water, post-release mortality should be incorporated into the estimates of reduced harvests. Based on studies of post-release survival for juvenile Snapper in Victoria (Grixti *et al.* 2010) and New South Wales (Broadhurst *et al.* 2012) that showed >90% post-release survival for shallow mouth hooked fish we applied a PRM of 10% for fish <40 cm total length (TL). For fish ≥40 cm TL there have been no studies of post-release survival in Victoria. Studies on other Snapper populations show variable impacts of capture and release on survival rates of larger Snapper depending on a range of factors including hooking location, treatments such as venting, reproductive state and capture depths (McGarvey 2004; Lenanton *et al*. 2009; Butcher *et al.* 2012; McLennan *et al.* 2014). Because recreational Snapper captures in PPB and WPB are generally in depths <20 m we chose a PRM rate for adult Snapper (≥40 cm TL) of 20%, consistent with the lower bounds of estimates for untreated released fish from these studies.

The logic diagram presented in figure 55, describes the approach and formed the basis for the Snapper management size and bag limit simulator, referred to as SnapMat written in the R programming language (R Core Team 2017). The SnapMat R script is included in appendix 5.

Management simulations

Recreational harvest regulations for Snapper include an LML, a total bag limit, and a sub-bag harvest limit. A sub-bag harvest limit refers to a limit on the number of Snapper that can be harvested per person per day, within the total bag limit, that are equal to or above a certain length (referred to as the 'sub-bag length'). The sub-bag limit and length regulation aims to limit individual harvest of larger mature fish, while also allowing anglers to harvest smaller sub-adult Snapper in higher numbers. A slot limit is an extreme form of the sub-bag limit where the sub-bag limit is zero. Thus, the manager has the option to alter four variables: 'LML', 'total bag limit', 'sub-bag length', and 'sub-bag limit'. The current regulations for individual recreational daily harvest of Snapper in Victoria are: total bag = 10 fish, LML = 28 cm, sub-bag length = 40 cm, sub-bag limit = 3 fish. Alternative scenarios for each of these four variables were tested. Results are presented as predicted % change in retained catch in biomass and numbers of fish.

Fishing effort, harvest length composition and harvest rates can vary regionally due to Snapper habitat preferences, movement and aggregation behaviour. Therefore, the creel data were aggregated according to three regional strata based on prior knowledge of these aspects: two in PPB (south-west, north-east regions), and WPB (Fig. 54). Each simulation of a regulation change was applied to each region to compare the impact of regulation changes. Further, because the recreational Snapper fishery has two components; an "Adult" fishery that targets larger spawning fish (typically > 40 cm TL) from October – December and a "Pinky" fishery that target smaller sub-adult/juvenile fish (typically < 40 cm TL) from January-May, the impacts of regulation changes were simulated for these two fishery components.

For this study we chose to test a range of plausible management changes (n = 19 scenarios) that involved modifying individual (single lever changes) and multiple (combined lever changes) components of the current size and bag limit regulations.

The 19 simulated management changes were:

Single lever changes, holding all other limits as current:

- Increased LML: 30, 35, 38 cm
- Decreased total bag limit: 8, 6, 4
- Decreased sub-bag length: 38, 36 cm TL
- Decreased sub-bag limit: 2, 1

Combined lever changes, holding all other limits as current:

- Increased LML: 30 cm, decreased total bag limit 6
- Increased LML: 30 cm, decreased sub-bag limit 2
- Increased LML: 35 cm, decreased total bag limit 6
- Increased LML: 35 cm, decreased sub-bag limit 2
- Increased LML: 30 cm, decreased total bag limit 6, sub-bag limit 2
- Increased LML: 35 cm, decreased total bag limit 6, sub-bag limit 2
- Increased LML: 30 cm, decreased total bag limit 6, sub-bag limit 1
- Increased LML: 35 cm, decreased total bag limit 6, sub-bag limit 1
- Slot limit, 35-65 cm, total bag limit 4

The simulated regulation changes were initially applied to creel data collected over the last 4 financial years 2014/15, 2015/16, 2016/17 and 2017/18 (referred to as 2014-2017), as an indication of impacts on harvest relevant to the recent fishery status. Recreational CPUE and length composition has been relatively stable over this period (i.e. Fig. 56).

Impacts of regulation changes on reduction of retained catches will vary temporally depending on catch rates (i.e. proportions of angler trips that catch the bag limits) and length compositions (i.e. recruitment pulses entering the fishery) of the available stock. To explore how regulation changes impacted retained catches under different scenarios of stock abundance and length composition, we compared the above 19 scenarios for the "Adult" and "Pinky" fishery components in PPB and WPB between the 2014/15-2017/18 period and the most recent peak recreational catch rates from 2010/11-2013/14 (i.e. Appendix 3, Figs. 9,10).

Finally, while the SnapMat tool predicts impacts of implementing more conservative regulations than current, we also considered whether the 'current' regulations were likely to be constraining 'individual' daily catches by summarising creel data on numbers of released fished and the reasons for their release. This was also done for the 2014/15-2017/18 and 2010/11-2013/14 periods separately.

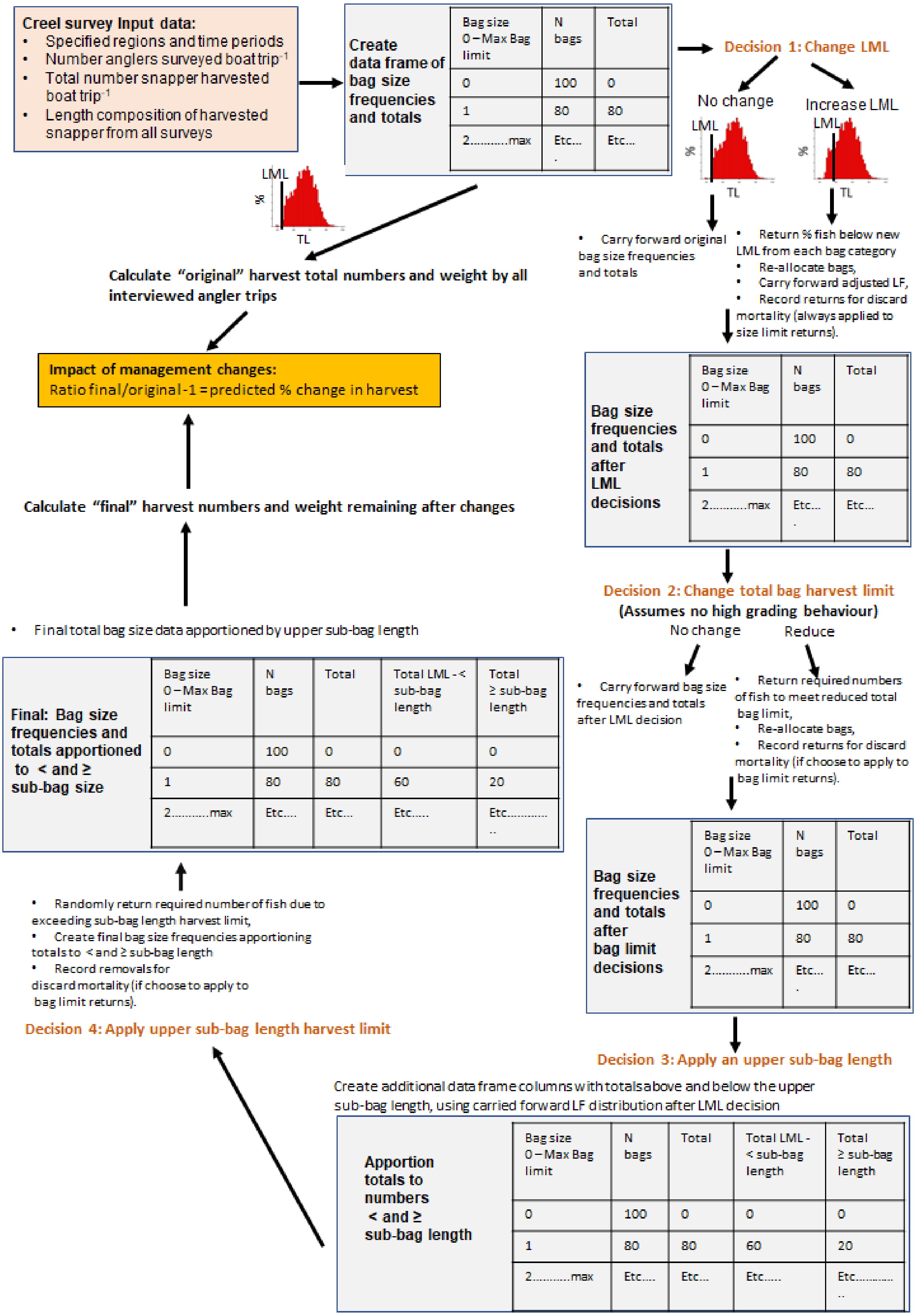


Figure 55 Logic diagram describing the flow of steps in the SnapMat model for predicting impacts of size and bag limit changes, including the sub-bag length option, on recreational harvests.

Results

Simulated regulation changes for Port Phillip Bay 2014/15-2017/18

Adult fishery: Simulation of the 19 regulation changes on creel survey data from PPB between 2014/15-2017/18 showed that for the "adult" fishery increasing the LML and reducing to the sub-bag limit were the most effective single lever changes for reducing retained catch (including PRM). Increasing the LML from 28 cm TL to 35 cm and 38 cm TL, was predicted to reduce retained catch in number by 25% and 35% respectively, with retained biomass reductions predicted to be lower, at 7% and 12% respectively, due the small size of fish being returned under an increased LML (Fig. 57a). Total bag limit adjustments had negligible impact because surveyed anglers rarely achieved bags of over 4 fish (Figs. 56, 57). Reduction of the sub-bag limit (i.e. fish ≥40 cm TL) from 3 (current regulation) to 1 was required to achieve any notable impact, and only achieved a reduction in retained catch of 14% by numbers and 21% by weight (Fig. 57a). Of the 19 regulations simulated, the largest reduction in retained catch in numbers and biomass for the adult fishery was with the slot limit rule, that achieved a 43% and 53% reduction in catch by numbers and weight respectively. This was greater than for the increased LML to 35 cm, total bag limit 6 and sub-bag limit of 1, that achieved the next largest reductions of 43% by numbers and 33% by weight, noting the total bag limit reduction would have contributed little to this reduction (Fig. 57a). The impacts of the various simulated regulation changes were very similar for the south-west and north-east regions of PPB (Fig. 57a).

Pinky fishery: For the "Pinky" fishery, there was clearly no influence of changing the sub-bag limit as very few fish over 40 cm are caught in this fishery component (Fig. 56, 57b). The total bag limit reduction from 10 to 4 did achieve a notable reduction in retained catch of 23% for both numbers and biomass, but reduction from 10 to 6 only achieved an 11% reduction. (Fig. 57 b). Changes to LML had the greatest impact for the Pinky fishery, with increased LML from 28 to 30, 35 and 38 cm TL resulting in reductions in retained catch numbers of 22%, 71% and 85% respectively, however, because the returned fish are small, the reduction in retained catch by weight are lower at 9%, 38% and 54% respectively (Fig. 57b). The slot limit rule, while not reducing catch in numbers as much as the 38 cm LML, did reduce the catch in biomass by a greater amount (Fig. 57b).

Simulated regulation changes for Port Phillip Bay 2010/11-2013/14

Adult fishery: The impacts of simulated regulation changes for the PPB creel survey data for the "adult" fishery from 2010/11-2013/14, when catch rates were higher than the recent 2014/15-2017/18 period, differed mostly in relation to the increased LML and reduced sub-bag limits. For the 2010/11-2013/14 period increasing the LML had less effect on the retained catches. For example, the LML increase to 38 cm TL for 2010/11-2013/14 resulted in a 15% reduction in retained numbers and 6% reduction in retained biomass, compared to 35% and 12% for 2014/15-2017/18 (Figs. 57a, 59a). The other notable difference was for the reduced sub-bag limit. For the 2010/11-2013/14 period, reducing the sub-bag limit from 3 to 2 and 1 resulted in reductions of retained catch in numbers and biomass of 12% and 13%, and 35% and 39% respectively. These reductions were approximately double those achieved for the 2014/15-2017/18 period (Figs. 57a, 59a). For the 2010/11-2013/14 the slot limit rule performed similarly to the sub-bag limit reduction to 1 and produced approximately 10% less reduction in catch numbers and biomass than for the 2014/15-2017/18 period, because most of the catch was within the slot limit (Figs. 57a, 59a). The greater impacts from reducing the sub-bag limit in 2010/11-2013/14 suggest that the sub-bag limit was having an effect of constraining individual daily harvests over this period.

Pinky fishery: For the "Pinky" fishery in PPB, there were minor differences between the impacts of the regulation changes between 2010/11-2013/14 and 2014/15-2017/18. The % reductions in retained catches due to the LML increases, total bag reductions and slot limit were predicted to be slightly lower for 2010/11-2013/14 than 2014/15-2017/18 (Figs. 57b, 59b).

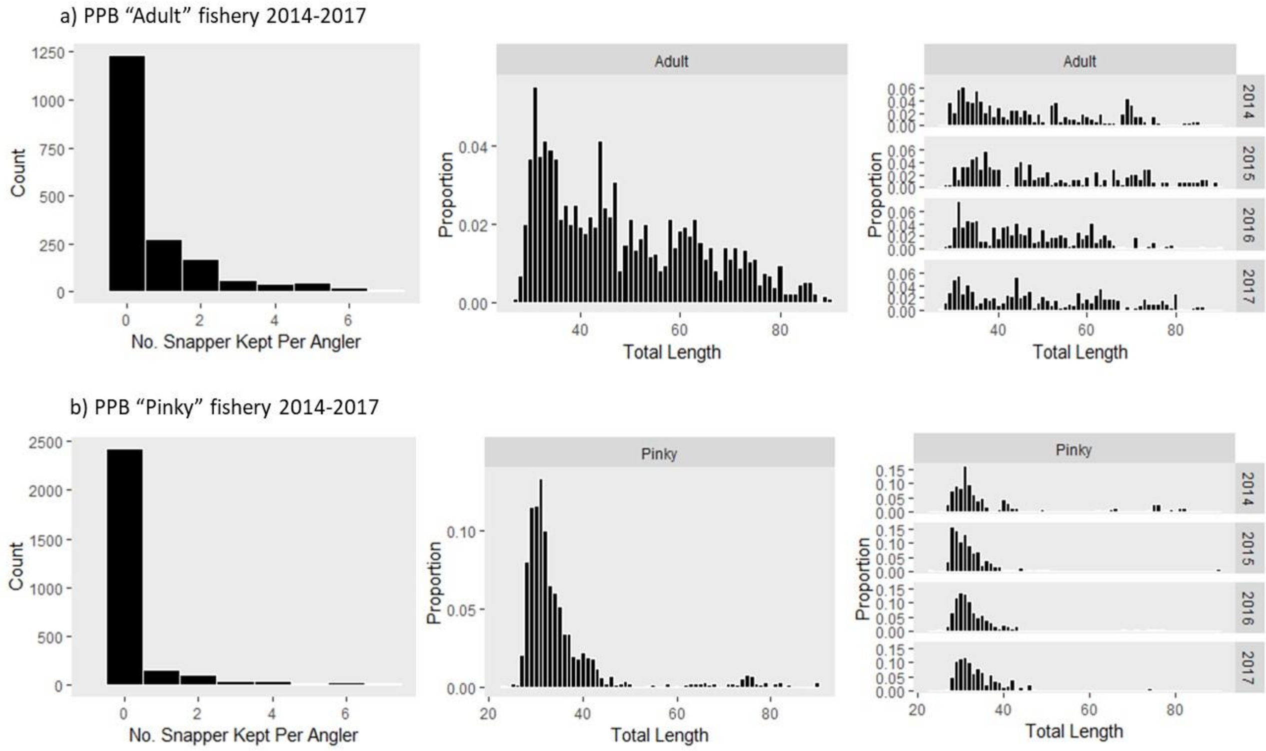


Figure 56 Port Phillip Bay: Creel survey data summaries 2014/15-2017/18 of (left) counts of angler retained bags (i.e. No. Snapper Kept Per Angler), and length composition or retained catches (pooled across years – centre, by year – right). a) Adult fishery (October-December), b) Pinky fishery (January-May).

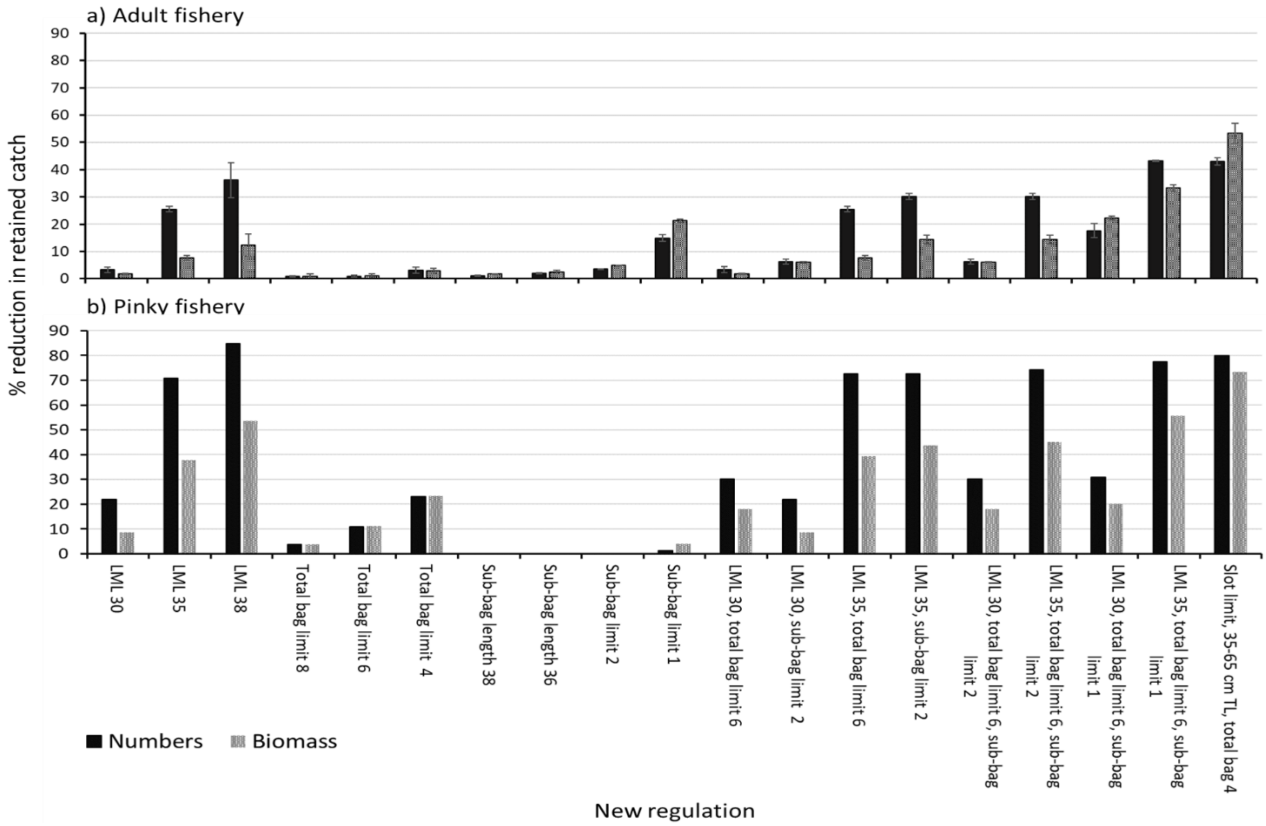


Figure 57 Port Phillip Bay: Predicted impacts of new regulations on recreational Snapper harvest based on creel survey data collected from 2014/15 – 2017/18, a) Adulty fishery (mean ± range of north-east and south-west regions, Fig. 54), b) Pinky fishery.

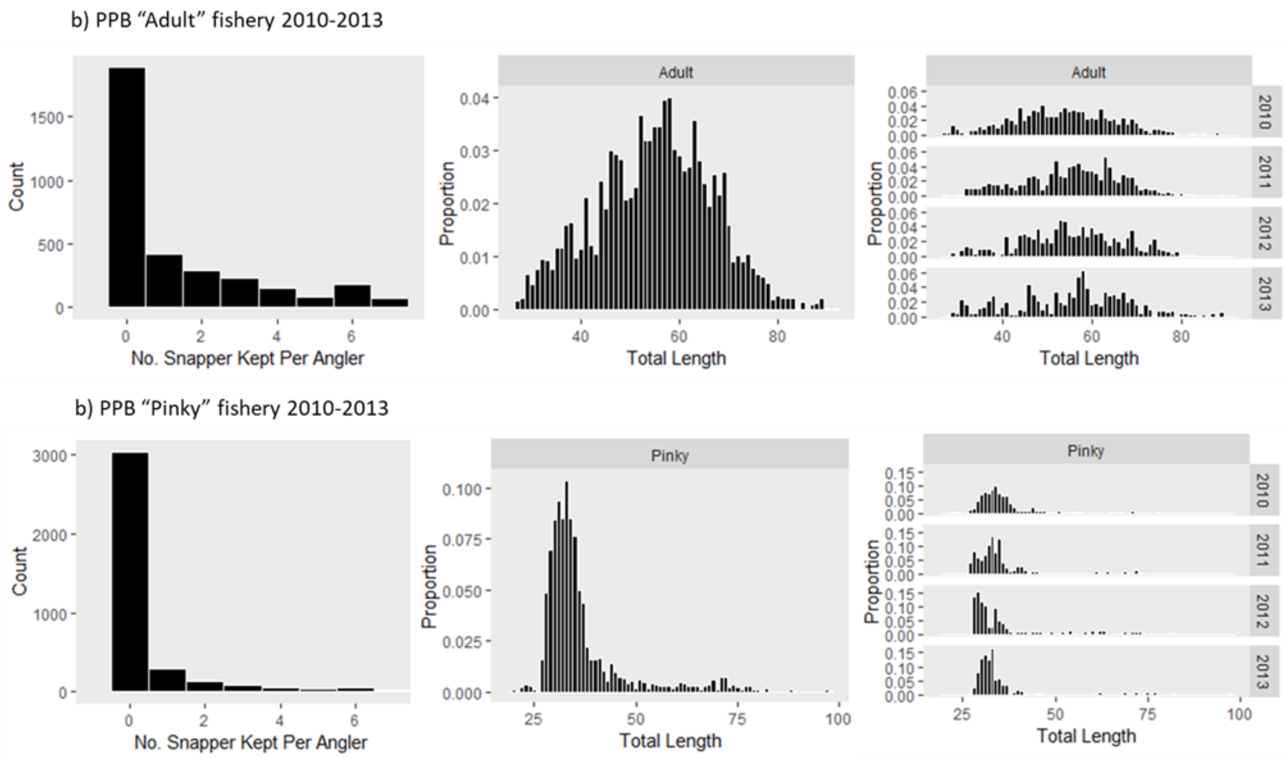


Figure 58 Port Phillip Bay: Creel survey data summaries 2010/11-2013/14 of (left) counts of angler retained bags (i.e. No. Snapper Kept Per Angler), and length composition or retained catches (pooled across years – centre, by year – right). a) Adult fishery (October-December), b) Pinky fishery (January-May).

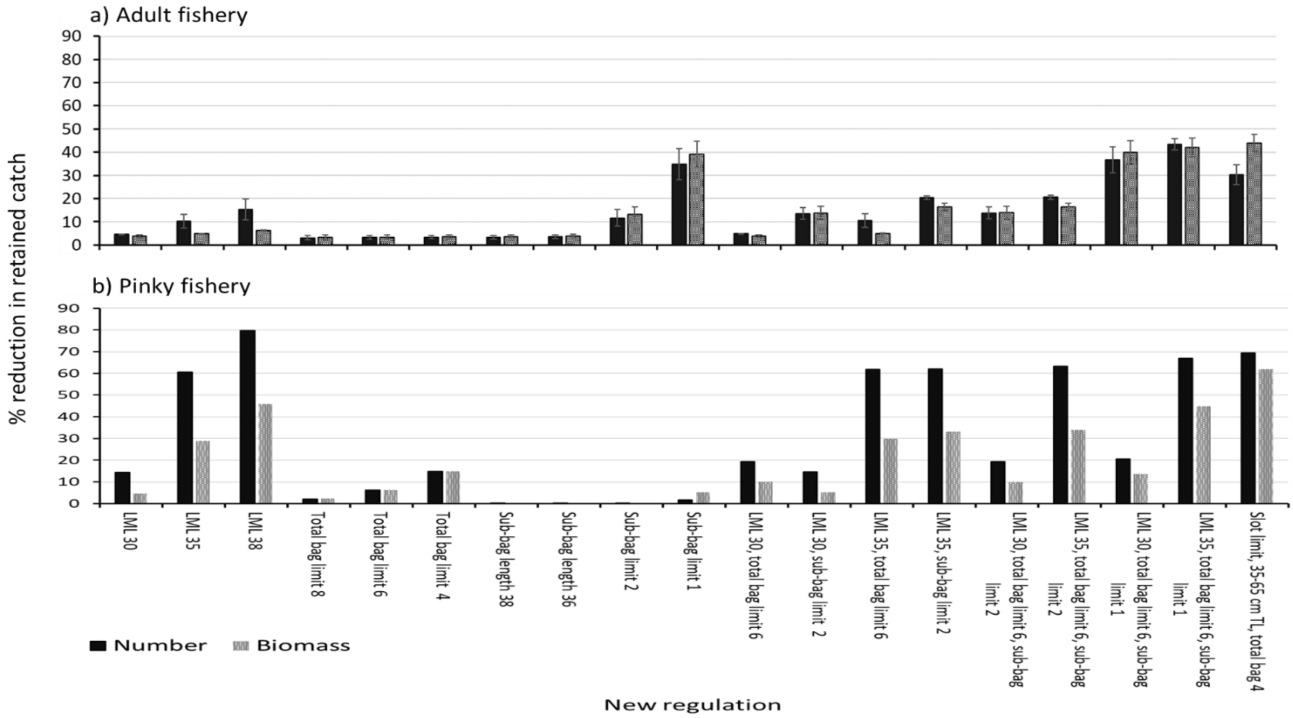


Figure 59 Port Phillip Bay: Predicted impacts of new regulations on recreational Snapper harvest based on creel survey data collected from 2010/11 – 2013/14, a) Adult fishery (mean ± range of north-east and south-west regions, Fig. 54), b) Pinky fishery.

Simulated regulation changes for Western Port Bay 2014/15-2017/18

Adult fishery: Simulation of the 19 regulation changes on creel survey data for the "adult" fishery in WPB between 2014/15-2017/18 showed generally similar impacts on retained catches to PPB. The greatest impacts on retained catch numbers were observed for the increased LML changes (Fig. 61b). Similar to PPB, the largest combined reduction in retained catch numbers and biomass were for the slot limit (30% and 42% respectively) and the LML 35 cm, total bag limit 6, sub-bag limit 1 scenarios (34% and 27% reduction respectively), mostly attributed to the LML increase and sub-bag limit reductions (Fig. 61b).

Pinky fishery: For the Pinky fishery in WPB, increasing the LML achieved the largest reduction in retained catches, i.e. 38 cm LML resulted in 66% reduction in catch by numbers and 44% reduction by weight (Fig. 61b). However, the reductions were lower than for PPB (Figs. 57b, 61b).

Simulated regulation changes for Western Port Bay 2010/11-2013/14

Adult fishery: For the "Adult" fishery in WPB, there were only minor differences between the impacts of the simulated regulation changes between 2010/11-2013/14 and 2014/15-2017/18, with slightly larger reductions in retained catches due to the reduction in the sub-bag limit for the 2010/11-2013/14 period (Figs. 61a, 63a).

Pinky fishery: For the WPB "Pinky" fishery in 2010/11-2013/14, the impacts of the regulation changes were generally predicted to be greater than for 2014/15-2017/18 (Figs. 61b, 63b). For the LML increases, while the 30 cm LML had minor impact (15% reduction in numbers), the 35 cm and 38 cm LMLs reduced the retained catch in numbers and weight by 71% and 50%, and 84% and 64%, respectively (Fig. 63b). For the 35 cm LML, the reductions for 2010/11-2013/14 were approximately 40% and 30% higher in number and biomass than for the 2014/15-2017/18 period (Figs. 61b, 63b).

Summary of released Snapper reported during creel surveys

For the PPB and WPB "Pinky" fisheries, and for both time periods, over 98% of the released Snapper reported in creel surveys, were released due to being undersized (Fig. 64 ab).

For the Port Phillip Bay "Adult" fishery, during the 2014/15-2017/18 period, virtually all Snapper reported as released in creel surveys were reported as released due to being undersized. However, in the 2010/11-2013/14 period, almost 20% of released Snapper were reported as being released for reasons other than undersize, with approximately 10% released due to being over the bag limit (Fig. 64a). For the WPB "Adult" fishery, in both time periods over 90% of released Snapper were reported as released due to undersize, with approximately 5% released due to catch and release fishing (Fig. 64b).

Overall the LML was clearly important in protecting juveniles in these two bays, but the bag limits were not binding for most anglers.

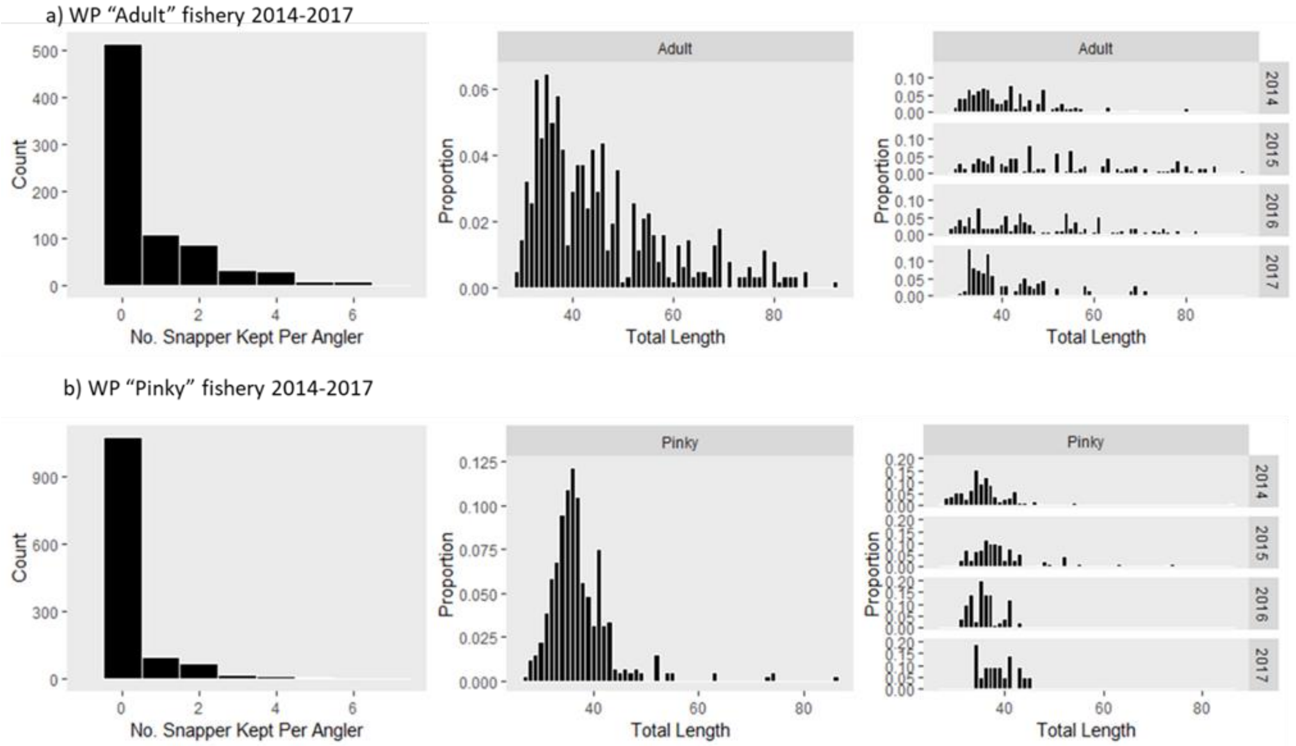


Figure 60 Western Port Bay: Creel survey data summaries 2014/15-2017/18 of (left) counts of angler retained bags (i.e. No. Snapper Kept Per Angler), and length composition or retained catches (pooled across years – centre, by year – right). a) Adult fishery (October-December), b) Pinky fishery (January-May).

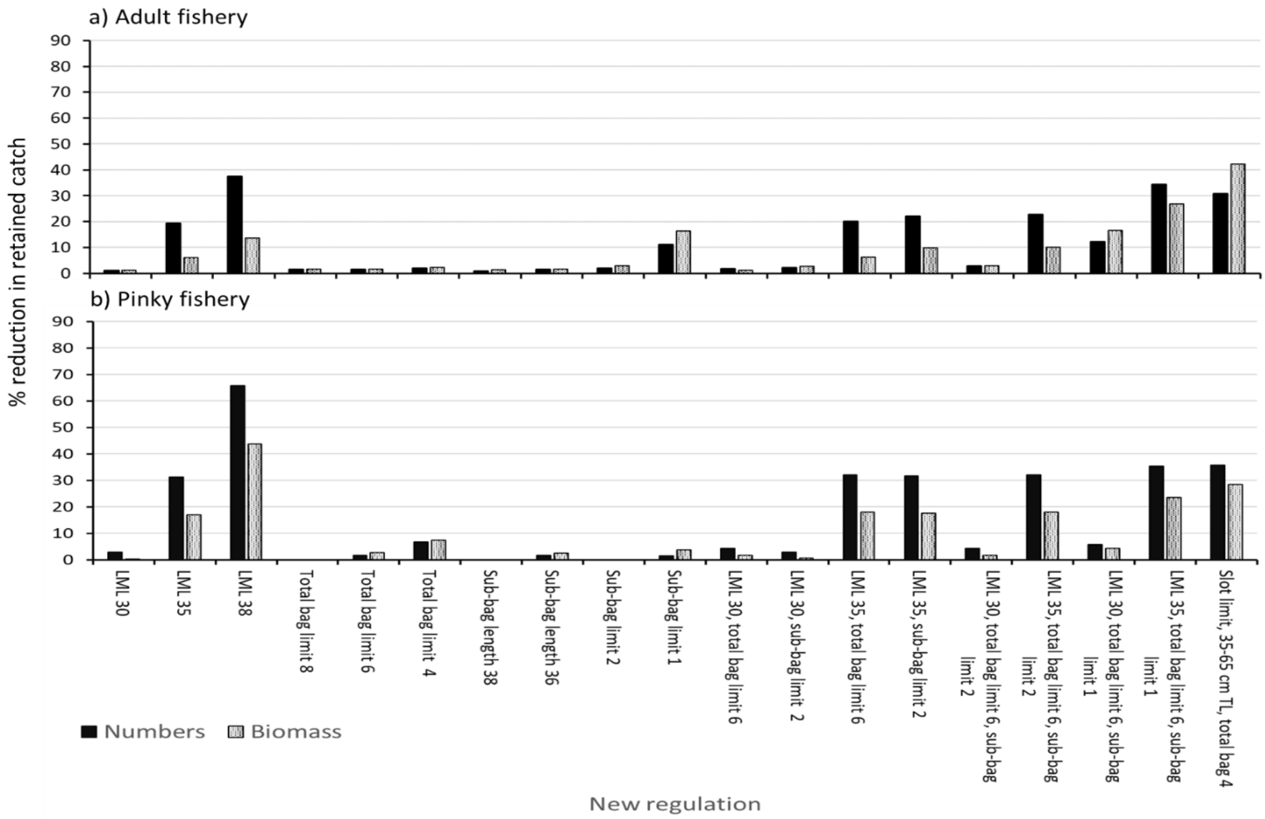


Figure 61 Western Port Bay: Predicted impacts of new regulations on recreational Snapper harvest based on creel survey data collected from 2014/15 – 2017/18, a) Adulty fishery, b) Pinky fishery

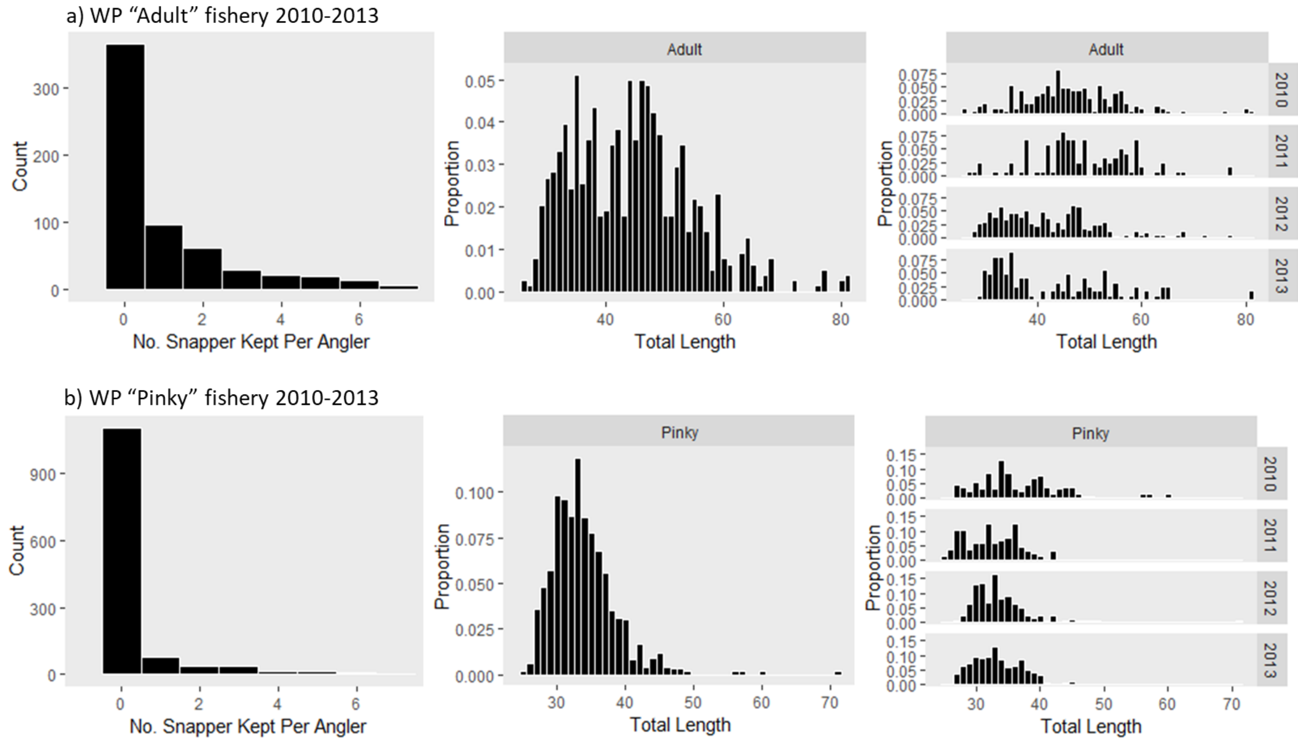


Figure 62 Western Port Bay: Creel survey data summaries 2010/11-2013/14 of (left) counts of angler retained bags (i.e. No. Snapper Kept Per Angler), and length composition or retained catches (pooled across years – centre, by year – right). a) Adult fishery (October-December), b) Pinky fishery (January-May).

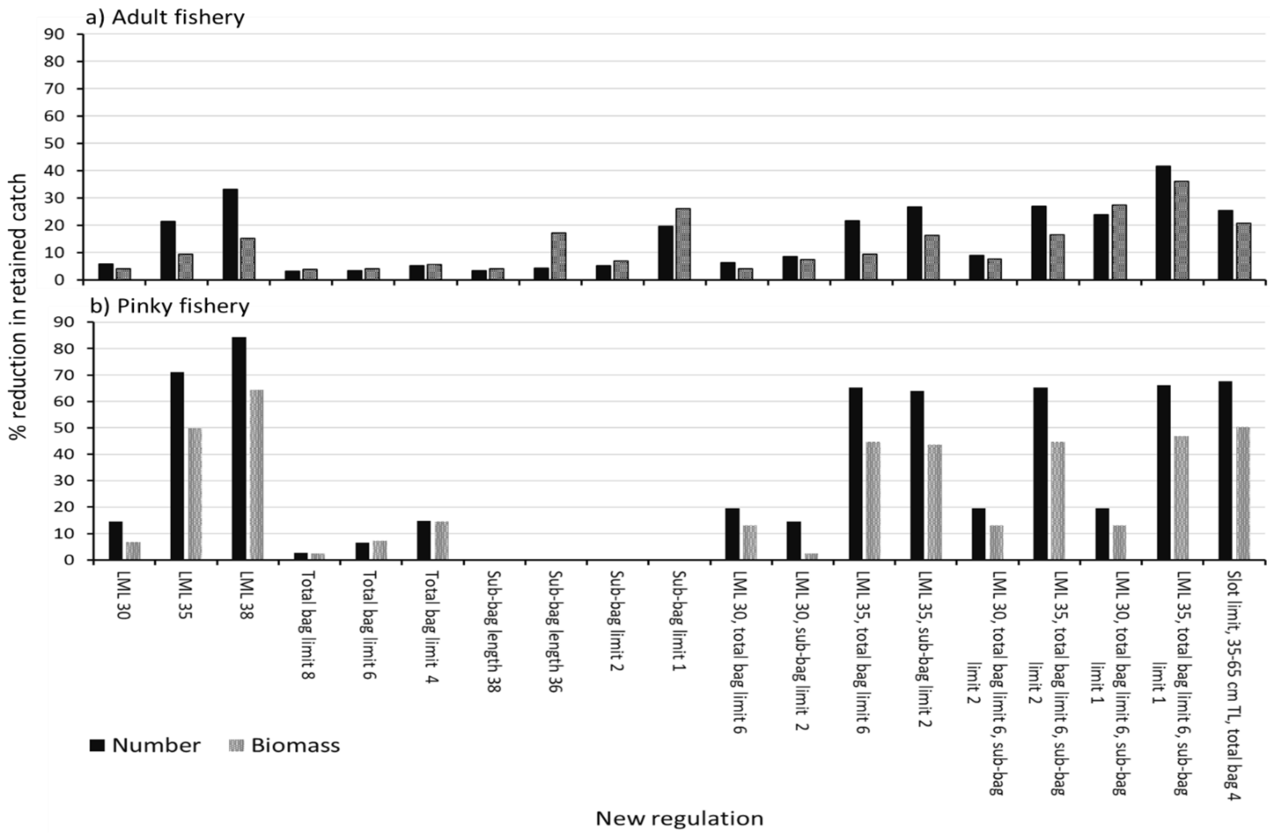


Figure 63 Western Port Bay: Predicted impacts of new regulations on recreational Snapper harvest based on creel survey data collected from 2010/11 – 2013/14, a) Adulty fishery, b) Pinky fishery.

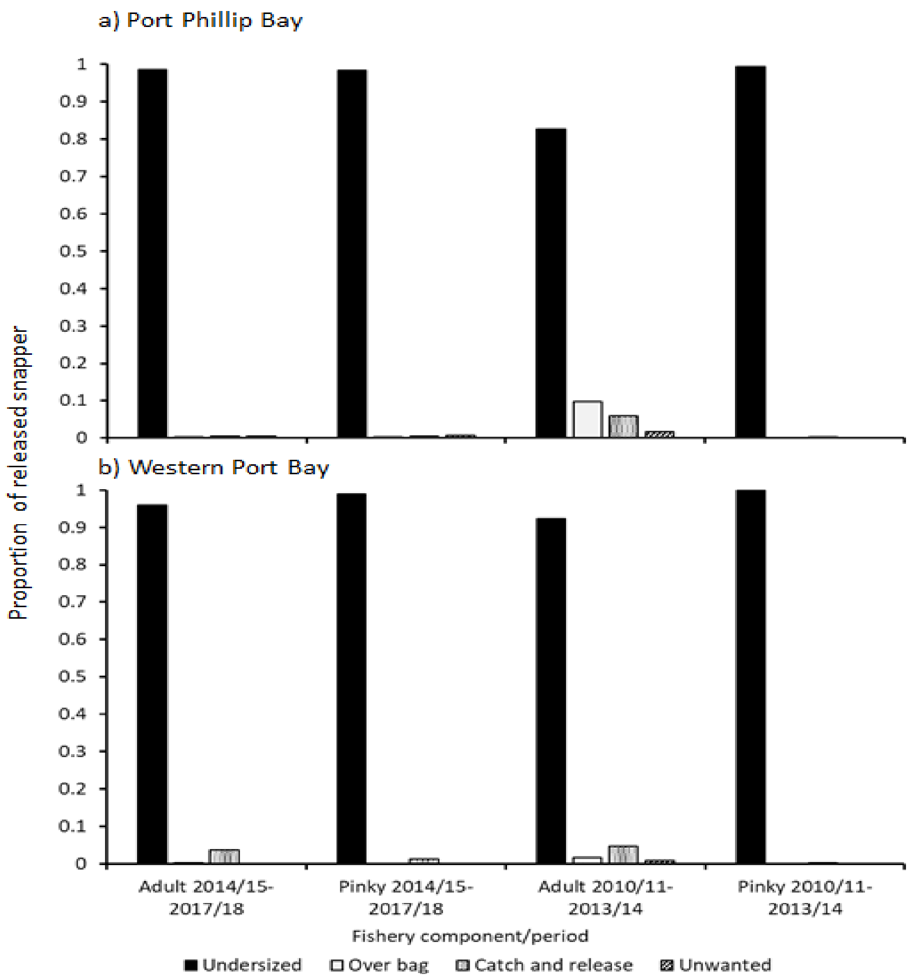


Figure 64 Proportions of Snapper that were reported as "released' and their reason for release reported from creels surveys in; a) Port Phillip Bay, and b) Western Port Bay, for two time periods and the "Adult" (October-December) and "Pinky" (January-May) fisheries.

Discussion

In chapter 3 we created and applied a Management Strategy Evaluation (MSE) model framework to explore risk associated with alternative fishing pressure and recruitment dynamics for the WVSS. The MSE simulated active management procedures aimed at constraining fishing mortality/exploitation rates within specified limits to achieve management objectives. This simulation modelling assumes that there is a management system capable of regulating recreational Snapper catch. The premise for the development and trialling of SnapMat was that at some stage managers will be required to consider changes to size and bag limit regulations for recreational Snapper fishing on the WVSS as the preferred first options to reduce fishing mortality.

Using creel data collected over the recent 4 year period (2014/15-2017/18), the single lever regulation changes in involving LML increases or bag limit reductions, showed that increasing the LML was generally more effective at reducing retained catches in numbers under the recent stock conditions (i.e. recent length composition and catch rates). Changes to either the total or sub-bag limits would have to be severe to achieve notable reductions in retained catches, because for most anglers the bag limits were not binding, but when combined with increased LML had potential to make notable reductions in retained catch both in numbers and biomass. The slot limit rule (total bag of 4 fish between 35 – 65 cm) tested had the greatest combined impact on reducing retained numbers and biomass for the important PPB adult fishery. The limited influence of reducing bag limits was consistent with low numbers of surveyed anglers catching the total or sub-bag limits over recent years, and few surveyed anglers releasing Snapper due to being over the bag limits. However, for the higher catch rate period (2010/11-2013/14), there was clearly a greater impact of the sub-bag limit changes on catch reduction for the adult fishery, reflecting more angler daily catches being limited by the sub-bag limits. This suggest that the sub-bag limit of 3 will increasingly constrain individual angler catches of adult fish as the stock size increases.

Predictions of catch reduction by SnapMat are estimated in numbers and biomass, and the choice of LML and bag limit, or combined approaches including slot limits, will be influenced by the objective of the catch reductions. These objectives will link back to the management objectives for the stock and fishery, and an understanding of the condition of the stock and fishery at the time. For example, depleted spawning biomass or truncated age/length compositions might mean an objective of increasing protection of the current spawning biomass. Such an objective would consider the impacts of regulation change on reducing the harvest of larger mature fish and would focus on the sub-bag limit /slot-limit lever and the biomass metric which equates to egg production. Alternatively, if there was a strong new cohort entering the fishery that could drive recovery from a depleted state, or even just improve the fishery performance from a current average state, increasing protection for the recent recruits could be the objective, even if this may seem contradictory to high juvenile abundance. In this case approaches such as LML increases and total bag limit reductions would be favoured to reduce catches of smaller fish, focussing on reduction in catch numbers rather than biomass. Fortunately for Snapper, catch and release mortality of small Snapper is very low, making LML increases and total bag limit reduction particularly attractive for reducing recreational catches of smaller juvenile and sub-adult Snapper (i.e. < 40 cm TL).

It is obvious that bag limit reductions will have limited impact on reducing recreational catches in scenarios where few angler trips achieve the bag limits (i.e. bag limits are not binding). This is typically the case when stock abundance has been allowed to decline to unsatisfactory levels. While slot limits and extreme bag limit reductions; in this case reducing the sub-bag limit for larger Snapper from 3 to 1, or the total bag limit from 10 to less than 4, may reduce retained catches even in depleted stock situations, such severe reductions can be difficult for stakeholders to accept and may reduce the incentive to go Snapper fishing. While this may be a desired outcome in terms of stock sustainability objectives, it would sacrifice socio-economic objectives due to poor participation in recreational fishing, particularly if alternative target species are not available. In these situations, LML increases might be considered more favourable by stakeholders, however, they can fail in preserving the important current spawning biomass. In situations of stock depletion there will typically be a need to increase the conservation of both small fish (i.e. the future spawning biomass) and the current spawning biomass, necessitating application of both LML increases and reducing sub-bag limits for larger fish. Slot limits that specify a size range between which fish can only be harvested are an extreme case of the sub-bag limit being reduced to zero. Slot limits are typically used to allow smaller fish to have an opportunity to spawn before being vulnerable to harvest, while also protecting the larger spawning fish to promote increased egg production and or numbers of large “trophy” fish for catch and release. We estimated the impact of one slot limit scenario that we considerable reasonable, and out of the 19 scenarios we explored, and it did appear to perform most favourably in predicted reductions of catch in both numbers and biomass for the pinky and adult fisheries in both bays and for the two time periods. A slot limit will, however, require more fish to be released, particularly larger fish that can be subject to poor handling and higher post-release mortality. If slot limits were to be considered, local studies of catch and release mortality of larger Snapper would be recommended.

Ultimately, if managers do primarily rely on size and bag limits to reduce recreational fishing mortality on Snapper, implementing changes when stock declines are forecast by stock assessments rather than waiting until stocks are depleted is important so that that ‘modest’ changes can actually reduce catches and hopefully limit the rate of decline, thus, providing greater opportunity for stock recovery from sporadic strong recruitment events. In the case of the WVSS, where a reliable 0+ age recruitment index is available, and stock assessment is well informed by commercial and recreational catch rate and composition data, declines in stock biomass can be forecast ahead of time, allowing early intervention. However, formal management systems are required to dictate when reviews of recreational regulations should occur for stock conservation or fishery performance objectives.

While the SnapMat tool, using contemporary creel survey data, can provide managers and stakeholders with a quantitative prediction of likely immediate impacts of size and bag limit regulation changes, they should not lose sight of the fact that size and bag limit changes do not directly influence effort (Cox *et al.* 2002; Beard *et al*. 2003; Post *et al.* 2003). It is therefore important to evaluate the impacts of regulation changes, not only on catch reduction objectives, but also on angler effort and behaviour. Failure to consider how angler effort (i.e. numbers and lengths of fishing trips) and behaviour (i.e. high grading, non-compliance, retain or release etc.) might respond to regulation changes may lead to ineffective regulations that fail to meet objectives of fishery management. Modelling approaches and social/angler surveys can potentially be applied to predict how angler effort and behaviour is likely to respond to size and bag limit regulation changes and how these responses might vary between different angler types (i.e. avid versus non-avid occasional anglers) (Cox *et al*. 2002; Fenichel *et al.* 2013; Lee *et al.* 2017). However, the lack of empirical information to condition models and expertise to create them, as well as the time lags to obtain results when changes are urgent, can make these predictive approaches impractical for operational management. Simpler qualitative risk assessments, informed by anglers, might be useful for incorporating likely angler responses into decisions on bag and size limit changes. We advocate treating regulation changes as management experiments (Post 2013) and having suitable monitoring programs in place to evaluate the impacts of changes on recreational catches, effort and behaviour. This will importantly increase the empirical data on relationships between various regulation approaches and angler responses (Arlinghaus *et al.* 2013). Monitoring of targeted Snapper fishing effort is therefore important to account for any short-term changes in effort that might either negate or enhance the intended effects of regulation changes informed by using the SnapMat approach. Targeted creel survey questions can also be used to assess changes in angler behaviour in relation to Snapper fishing after regulation changes.

SnapMat provides a conceptually simple approach to providing quantitative predictions of the impacts of size and bag limit changes on recreational Snapper catches. It depends on creel survey data and the assumption these data represent a random sample of fishing trips. The current creel survey data are collected on weekends and so are less likely to sample avid anglers who often fish weekdays, when fewer other fishers are on the water, and have higher catch rates and catch larger Snapper, and who may be more constrained by the size and bag limit rules. The implications of this under-sampling of avid anglers would be that the predicted catch reductions are underestimates. Statistical procedures could be developed to adjust creel survey data to account for this bias. The bag and size regulation changes tested in this study are based on what were considered by the authors as reasonable without constraining the fishery to the point of virtual closure. Alternative regulations that could also constrain or reduce recreational catches such as boat limits were not modelled in this study but could easily be considered with minor modifications to the SnapMat R script. Finally, while the scenarios examined in this study suggest there is scope to apply size and bag limit regulations to reduce recreational catches in the main fisheries for the WVSS, such regulations that restrict the catch of individual anglers, while providing some resilience, may not prevent overfishing if fishing effort increased to critical high levels. Other management options that involve restricting recreational Snapper fishing effort, such as spatial and temporal closures and harvest permits could be considered if the stock was to become severely depleted and size and bag limit changes were insufficient to achieve required reductions in fishing mortality.

Chapter 5: Framework for approaching cross-jurisdictional management of the western Victorian Snapper stock

Introduction

Many fish stocks are distributed across jurisdictional management boundaries. Often referred to as “straddling or migratory stocks”, management in one jurisdiction can have implications for biological, social and economic outcomes in other jurisdictions (Campbell and Hanich 2015). Ideally, management strategies and governance systems for these stocks should be developed with collaboration across jurisdictions. In many cases, however, jurisdictional management arrangements and fisheries fleets are well established prior to a comprehensive understanding of stock structure becomes available. Irrespective of whether each jurisdiction has its own management strategy, operational arrangements, and fleet structures/fishing methods, alignment of high-level management goals and objectives across jurisdictions is important to promote equitable responsibility and expectations for managing fishing impacts on the stock as a whole. Cross-jurisdictional collaboration on stock assessments, data sharing, and strategic research is common for straddling stocks in Australia and has been encouraged by the National reporting framework for stock status, “Status of Australian Fish Stocks” (Stewardson *et al.* 2016). Formal agreements, policies, acts or otherwise, to guide or obligate jurisdictions to develop cross-jurisdictional management strategies or plans, and formally collaborate on management issues for straddling stocks are however rare. Collaboration on management of straddling stocks lags behind the progress made in stock assessment and strategic research.

In Australia, the Offshore Constitutional Settlement Act 1997 (OCS) is the main piece of legislation that governs cross-jurisdictional management and sharing of marine resources. However, the OCS only considers cross-jurisdictional matters between the Commonwealth and the States (including the Northern Territory). Collaboration on cross-jurisdictional management of fish stocks among states continues to provide significant challenges in Australia. This was recognised in the recent Productivity Commission inquiry into regulation of the Australian marine fisheries and aquaculture sectors (Productivity Commission 2016). A key point made in this review was that where the rules of jurisdictional systems are inconsistent or do not sufficiently consider each other, there are higher risks of over- and under- fishing, unequal treatment of fishers, administrative inefficiency and compliance costs. Further the recent report “National Guidelines to Develop Fishery Harvest Strategies” Sloan *et al.* (2014), discusses the importance of collaboration among jurisdictions for straddling or highly migratory stocks, *“In the absence of effective regulation, trans-boundary or migratory fish may be particularly susceptible to overfishing. Transboundary governance and cooperation are therefore needed”*. There are currently no formal agreements between Victoria and any other States to govern or guide cross-jurisdictional fisheries management.

The recent study of Fowler *et al.* (2017) has confirmed the cross-jurisdictional nature of the Western Victorian Snapper Stock (WVSS) (Fig. 1). The western boundary for this stock delineated by Fowler *et al.* (2017) is at Kangaroo Is. in South Australia and the eastern boundary is thought to be at Wilsons Promontory in central Victoria (Coutin *et al.* 2003; Hamer *et al.* 2011) (Fig. 1). The WVSS supports a highly valued recreational and commercial fishery in Victoria and has recently supported significant harvests by the South Australian Marine Scalefish Fishery (SA-MSF) in coastal waters off south-east South Australia (Fig. 2). In Victoria, recreational and commercial fishers consistently target the WVSS, particularly during the spring/summer spawning aggregations in Port Phillip Bay (PPB) and Western Port Bay (WPB). However, it appears that targeted Snapper fishing along the south-east coast of South Australia is opportunistic depending on the local availability of Snapper, and the operational choices of operators in SA-MSF that may be independent of local fish availability.

The study by Fowler *et al.* (2017) suggested that availability of Snapper in commercial quantities off south-east South Australia is influenced by juvenile recruitment levels in PPB (Victoria). PPB is the main spawning and 0+ age nursery area for the WVSS, and it is thought that intermittent strong cohorts move into south-east South Australian waters in sufficient numbers to support profitable commercial targeting. This happened most recently from 2005/06 – 2014/15, when the catch from the south-east coastal region increased from 5 tonnes in 2004/05 to a peak of 225 tonnes in 2009/10, declining back to less than 5 tonnes by 2015/16 (Fig. 2). Overall, during this period approximately 900 tonnes of Snapper were harvested by the SA-MSF from the WVSS in South Australian waters. Furthermore, over the same period approximately 420 tonnes of Snapper were harvested from the WVSS by Commonwealth licensed operators in waters adjacent to Victoria and South Australia. The total commercial harvest from the WVSS by State licensed commercial operators in Victorian waters during this same period was approximately 1,220 tonnes, mostly taken in PPB. Therefore, just over half of the commercial harvest from WVSS over this period was taken by non-Victorian jurisdictions.

The recreational harvests from both States over this same period are unknown but estimates for Victorian waters for 2006/07 (the start of the commercial harvest peaks) were in the order of 600+ tonnes, mostly from PPB and WPB (Ryan *et al*. 2009). In comparison the peak annual commercial harvest, across all jurisdictions, between 2005/06 – 2014/15 was approximately 400 tonnes in 2009/10 (Fig. 2). Due to the low population base and exposed coastal waters along the south-east region of South Australia, recreational Snapper catch is thought to be very low (i.e. < 20 tonnes per year, Fowler *et al.* 2016) compared to Victoria. The Victorian recreational harvest from the WVSS is clearly much greater than all other sources of harvest, underlying the high recreational importance of the WVSS in Victorian waters.

Historically, the main harvests and interests in the WVSS have been with the Victorian commercial and recreational sectors. Stock assessment and management has been focussed on Victorian fisheries harvests and data. The recent multi-jurisdictional harvests have raised the need to develop a collaborative approach to assessment and management of the WVSS resource. This is important to ensure that the overall sustainability of the stock is maintained, while considering the fishing impacts and interests of the fishing sectors in both Victoria and South Australia and the differences in operational management in each State. Snapper is also a State managed species under the OCS and the growth of Snapper harvest by Commonwealth licensed operators in the 2000s was against the intent of the OCS and highlighted limitations of the OCS. Review of the OCS as it pertains to Snapper and development of approaches to limit Commonwealth harvest would also be important to protect the interests of the State Snapper fisheries in the future. To this end the Australian Fisheries Management Authority (AFMA) has worked with the South-East Trawl Fishing Industry Association (SETFIA) to implement an approach to limit Commonwealth licenced harvests of Snapper in waters relevant to Victoria (AFMA 2018).

This chapter aims to develop a simple framework for guiding the cross-jurisdictional assessment and collaborative management of the WVSS across the Victorian, South Australian and Commonwealth jurisdictions. It does not consider formal resource allocation or sharing, but has the key objectives to:

1. Review jurisdictional management objectives, fisheries management approaches and settings that apply to the WVSS,
2. Develop a formal Memorandum of Understanding (MOU) to guide the collaboration of the Victorian and South Australian jurisdictions on stock assessment and management issues,
3. Develop a framework for guiding the operation of the MOU.

Methods

Review of jurisdictional management objectives, fisheries management approaches and settings that apply to the WVSS

The key areas for this comparative review were:

- Management objectives,
- Fisheries and regulatory approaches,
- Data collection and monitoring to inform stock assessment and management.

'Memorandum of Understanding' for the collaboration of the Victorian and South Australian jurisdictions on stock assessment and management issues

Drafting of an MOU occurred via several preliminary phone meetings and a one day drafting workshop between Victorian Fisheries Authority (VFA) and Primary Industries and Regions South Australia (PIRSA) / South Australian Research and Development Institute (SARDI) management and science representatives. The MOU collaborative approach was requested by the Victorian and South Australian Fisheries Management Alliance in early 2017 as a preferred approach over formal agreements on resource allocation between States or a multi-jurisdictional harvest strategy framework.

The drafting meeting initially reviewed fishery and stock status information and the progress of this FRDC project. A representative from the Australian Fisheries Management Authority (AFMA) provided an update on progress with the industry-imposed trip limits and move on rules to limit Snapper harvests by Commonwealth operators and expressed the view that the rules were working adequately in limiting harvests, which was supported by harvest data. While the MOU was specifically between Victorian and South Australia, the operational framework below includes consideration of the Commonwealth harvest component (data to be provided annually by AFMA). The afternoon was primarily involved with drafting the MOU. MOU drafting meeting agenda is included in appendix 7.

Framework for collaborative assessment and management of the WVSS

A draft framework to guide the operation of the MOU was developed that aimed to capture the flow of activities and responsibilities required. The draft framework was reviewed and endorsed by the responsible fisheries managers in the VFA and PIRSA. Comments were also received by AFMA.

Results

Review of jurisdictional management objectives, fisheries management approaches and settings that apply to the WVSS

Victoria

Management plans: There is no fisheries management plan for the Victorian jurisdiction that specifically considers the WVSS and its associated fisheries. A general set of management guidelines that include limit, trigger and target reference points for key stock performance indicators is in development. These guidelines are expected to be completed in 2019 and aim to provide direction on management response in relation to stock status indicators for key species such as Snapper (T. Jeavons, VFA fisheries manager, pers. comm).

Management goals and objectives: "Draft" goals and objectives (below) have been developed for inshore fin-fish fisheries, but specific objectives or operational objectives for performance indicators for the WVSS and fisheries have not been developed.

Goal 1) Biological sustainability: To ensure the sustainable use of bay and inlet fisheries resources in order to maximise current and future community benefits

Objectives:

1) Ensure that fishing effort and catches of key target and by-product species are maintained at sustainable levels that avoid recruitment and growth overfishing
2) Monitor and assess the status of key species and determine the effects of recreational, indigenous and commercial fishing on these species
3) Monitor and assess the performance of the fisheries and implement adaptive management strategies in response to significant changes in fishery indicators

Goal 2) Habitat/environment: To advocate for the protection and maintenance of essential fish habitat and environmental conditions for the bay and inlet fisheries

Objectives

1) Improve understanding of habitat and environmental conditions essential for maintaining healthy fish stocks and fisheries
2) Partner with agencies to advocate for the protection of essential fish habitat (and therefore fishery values) and adaptation to changing environmental conditions

Goal 3) Socio- economic: To maximise the social and economic benefits of the bay and inlet fisheries to regional communities

Objectives

1) Regional communities have access to fresh, local seafood and a range of recreational fishing opportunities
2) Community members understand, participate in and support bay and inlet fisheries management arrangements

South Australia

Management plans: There are general management plans for the commercial, recreational and charter fisheries in South Australia:

- Management Plan for the South Australian Commercial Marine Scalefish Fishery 2013 (PIRSA 2013)
- Management Plan for Recreational Fishing in South Australia" (PIRSA 2017).
- Management Plan for the South Australian Charter Boat Fishery (PIRSA 2011)

These management plans describe governance procedures, goals and objectives, and systems for triggering management responses in relation to stock status indicators (i.e. quasi harvest strategies). They also specify harvest allocation arrangements between recreational, charter and commercial sectors for keys species including Snapper.

Management goals and objectives: The goals and objectives specified in the management plans for the commercial and recreational sectors are consistent. The goals and objectives below are taken from the Management Plan for the South Australian Commercial Marine Scalefish Fishery 2013.

High level goals

1) Ensure the Marine Scalefish Fishery resources are harvested within ecologically sustainable limits

2) Optimum utilisation and equitable distribution of the Marine Scalefish Fishery resources

3) Minimise impacts on the ecosystem

4) Cost effective and participative management of the Marine Scalefish Fishery

Snapper fishery management objectives

1) Ensure long-term sustainable harvest of Snapper
2) Maintain catches within agreed allocations for each sector
3) Improve economic efficiency and financial returns to the commercial fishery
4) Minimise impacts of fishing activity on ecosystem
5) Take account of the objectives of other sectors (e.g. the recreational sector)

Fisheries and management settings

Victoria and South Australia

The key fisheries components and associated management settings for the Victorian and South Australian jurisdictions are summarised in tables 11 and 12.

AFMA - SETFIA agreement

The Australian Fisheries Management Authority (AFMA) and the South East Trawl Fishing Industry Association (SETFIA) have entered into an arrangement for the management of Snapper caught by Commonwealth Trawl Boat concession holders in waters relevant to Victoria or landed in a Victorian port (AFMA 2018). The aim is to allow incidental catches of Snapper in waters relevant to Victoria in excess of the 200 kg trip limit to be landed instead of discarded without creating incentives to target Snapper. A fixed 200 kg trip limit applies to waters around Port Phillip Bay heads (Fig. 65). The arrangement between AFMA and SETFIA only applies to waters relevant to Victoria and to trawl methods, AFMA provides Commonwealth harvest data by all fishing methods from waters relevant to the WVSS adjacent to Victoria and South Australian (Fig. 66).

Details of the AFMA-SETFIA Snapper harvest agreement are included in AFMA (2018) (https://www.afma.gov.au/sites/g/files/net5531/f/uploads/2018/04/SESSF-Management-Arrangements-Booklet-2018-FINAL.pdf). In summary, outside the fixed 200 kg trip limit zone around Port Phillip Heads, Snapper catches greater than 200 kg cannot be landed without a SETFIA approval number (this is subject to various conditions). The arrangement will cease if the combined total catch of Snapper taken by Commonwealth trawl operators from the eastern and western zones of waters relevant to Victoria (Fig. 64) is more than 35 tonnes in any one SESSF fishing season, i.e. 1 May to 30 April of the following year. If the arrangement ceases, the 200 kg trip limit remains in force.

The AFMA-SETFIA arrangement only applies to Victorian waters and trawl caught fish, and the 35 tonne trigger for applying the blanket 200 kg trip limit applies to all waters relevant to Victoria. Therefore, specified harvest reporting zones will be applied to Commonwealth Snapper harvest data to separate out the WVSS harvest from Victorian and South Australian waters. These harvest reporting zones are displayed in figure 66.

Develop a formal Memorandum of Understanding (MOU) to guide the collaboration of the Victorian and South Australian jurisdictions on stock assessment and management issues

The signed MOU is attached in appendix 8.

Develop a framework for guiding the operation of the MOU

The agreed operational framework for the MOU is outlined in figure 67.

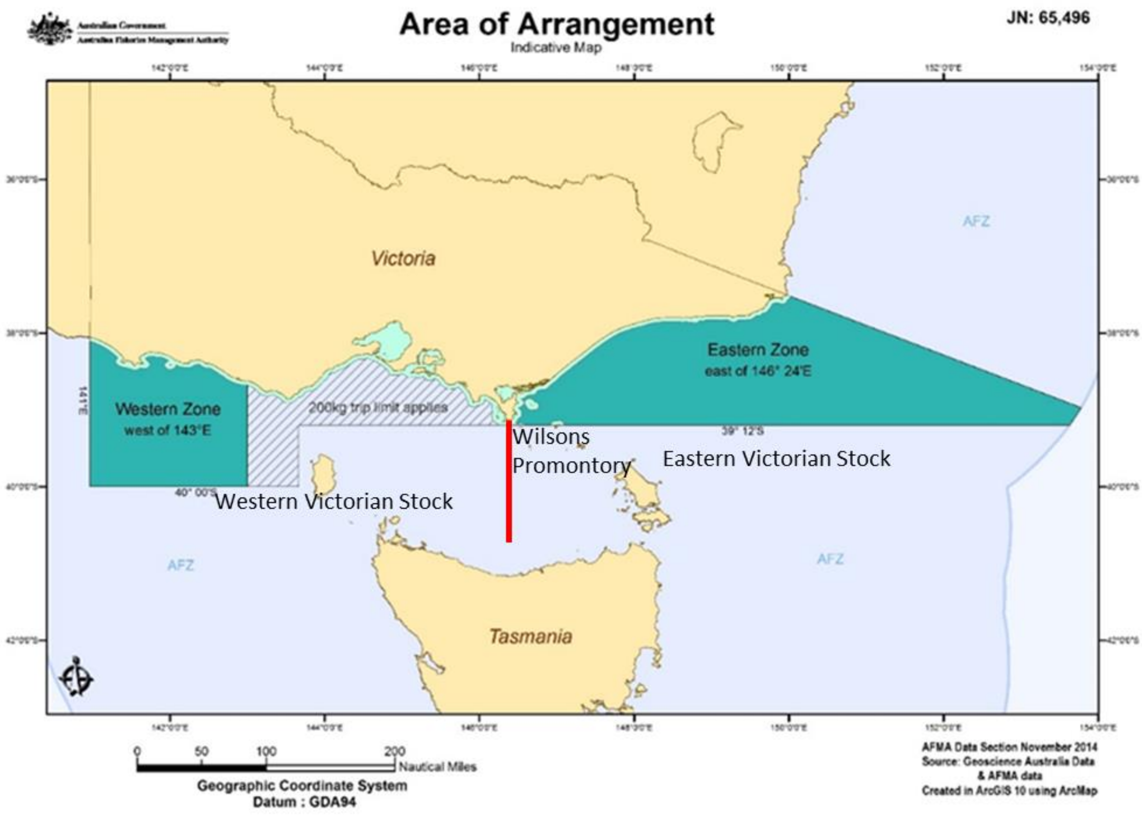


Figure 65 Map showing the spatial zones relevant to the AFMA-SETFIA Snapper harvest agreement for waters relevant to Victoria.

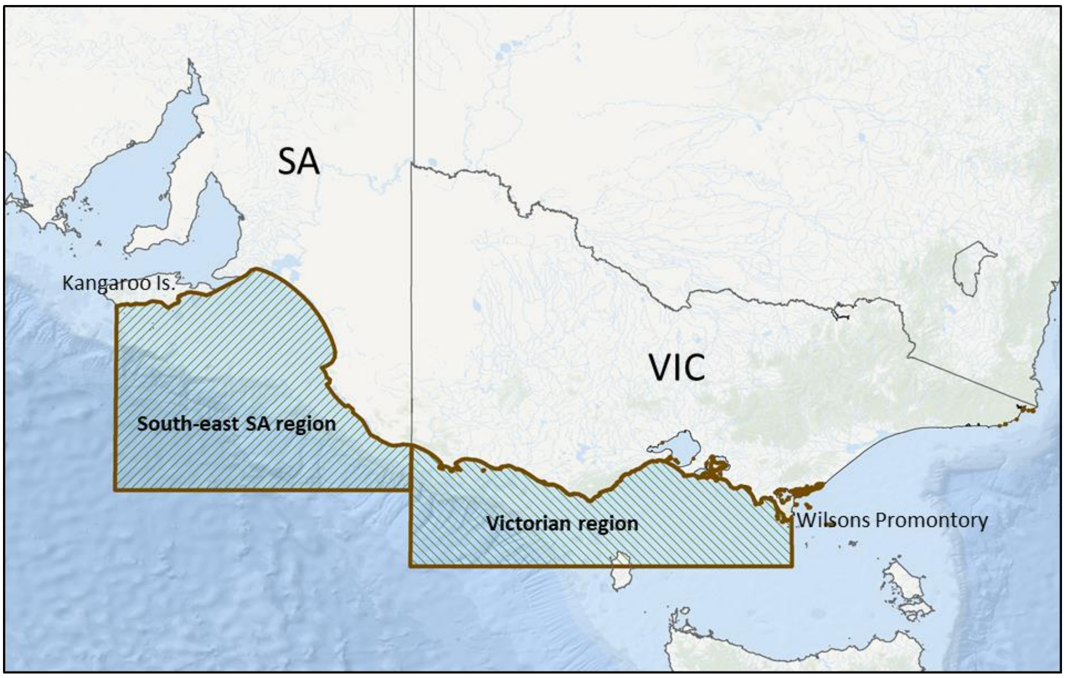


Figure 66 AFMA Commonwealth Snapper harvest report zones for the WVSS in waters relevant to Victoria and South Australia. Victorian region: 140.950000° to 146.440000°, -38.100000 to -39.800000°. South-east SA region: 136.700000° to 140.950000°, -35.600000° to -38.700000°.

Table 11 Summary of fisheries and management settings relevant to the WVSS under the Victorian management jurisdiction.

[a)] Other commercial fisheries that have entitlement to harvest western stock Snapper include the central and western zone rock lobster fisheries, the harvest from these fisheries are minor and considered a bycatch.
[b)] Excluding marine protected areas, aquaculture zones, or other areas that exclude fishing but are not imposed for targeted Snapper management.

Sector	**Licences/fisheries**	**Gear**	**Spatial-temporal management** [b)]	**Minimum size limits** (TL = total length)	**Harvest limits**	**Effort limits** (i.e. limits to individual effort – days)
Commercial [a)]	Port Phillip Bay Western Port Fishery (PPBWPF) (9 licences active, capped at 8 licenses from 2022)	**Longline:** A maximum of 400 hooks that can be deployed at any one time on no more than two long-lines**. Traps:** 6 fish traps allowed. **Handlines/rod and reel:** PPB - 6 lines allowed, no more than 3 hooks or one bait jig per line. WPB - 9 fishing lines with no more than 3 hooks or 1 bait jig. **Nets:** Various mesh and seine nets are currently allowed in Port Phillip Bay (excluding Corio Bay). All netting methods will be removed by 2022.	No closed areas or times specifically targeted at Snapper management.	28 cm TL	88 tonne total annual cap for commercially harvested Snapper in Port Phillip Bay. 11 tonnes allocated to each of 8 licences.	None
	Ocean Access Fishery (OF) (180 licences, 50 active Statewide, but few actively targeting Snapper)	**Longline:** one line with no more than 200 hooks. **Handline/rod and reel:** 6 lines allowed, no more than 3 hooks per line. **Nets:** Seine net up 650 m, up to 10 mesh nets not exceeding 2000 m.	Restricted to coastal waters (i.e. excluding Port Phillip Bay and Western Port). No closed areas or times specifically targeted at Snapper management.	As above	None	None
	Victorian Inshore Trawl (VIT) (54 licences, 11 active but not currently targeting Snapper)	Trawl net or combination of trawl nets: total head line length of all nets in use must not exceed 33 meters.	As above	As above	35 tonne total annual harvest cap. 50 kg trip limit if cap is reached.	None
Recreational	Statewide recreational licence required unless exempt.	Maximum of 4 lines per person, with maximum of 2 hooks or 1 bait jig	No closed areas or times targeted at Snapper management.	As above	Daily per person harvest limits: 10 Snapper, of which only 3 can be ≥ 40 cm TL. No boat limits.	None
Charter	All charter customers require Statewide recreational licence required unless exempt. No fisheries related licenses are required to operate a recreational charter fishing vessel. No catch and effort data reporting are required. Number of charter operators uncertain.	As above for individual anglers. No overall limits on number of lines per vessel.	As above	As above	As above, there are no boat limits for recreationally harvested Snapper on charter boats in Victoria. Personal daily limits apply as above.	None

Table 12 Summary of fisheries and management settings relevant to the WVSS under the South Australian management jurisdiction.

a) Other commercial fisheries that have entitlement to harvest Snapper in the SE region are the Southern Zone Rocklobster and Lakes and Coorong fisheries, although the harvest from these fisheries are very minor and considered a bycatch.
b) Excluding marine protected areas, aquaculture zones, or other area that exclude fishing but are not imposed for targeted Snapper management.

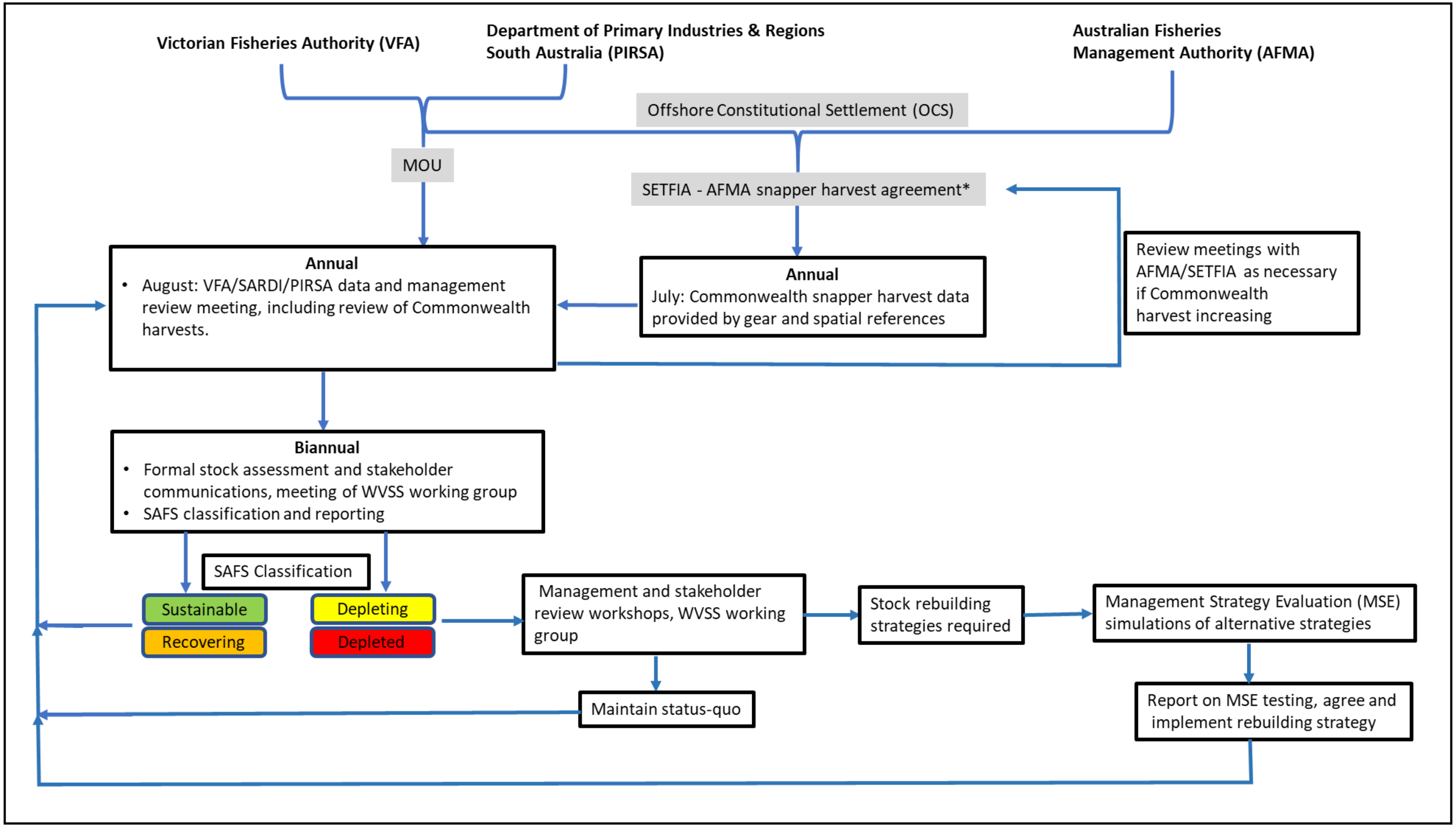
Sector	**Licences/fisheries**	**Gear**	**Spatial-temporal management controls** [b]	**Minimum size limit** (TL = total length)	**Harvest limits**	**Effort limits** (i.e. limits to individual effort – days)
Commercial [a]	Marine Scalefish Fishery (MSF) (309 licences Statewide, 25 licences targeted Snapper with longline in the south-east in 2010, in 2015 declined to 11 licences, and by 2016 < 10 licences targeted Snapper in the south-east region).	**Longline (as applies in south-east fishery region):** maximum of 400 hooks deployed at any one time. Number of longlines permitted depends on individual licence conditions. **Rod and handline:** one of the following combinations of rods and handlines: - up to 2 rods - up to 2 handlines, or - one of each. Each line can have one of the following: - up to 3 hooks attached separately, - up to 5 hooks joined together.	**Closed season:** State-wide midday 1 November to midday 15 December. **Closed areas:** no closed areas in south-east coastal region specifically targeted at Snapper management.	38 cm TL	350 kg/day, individual trips are limited to 5 days duration with max. of 1050 kg per vessel per trip.	None
Recreational	No recreational license	**Rod and handline:** each person can have one of the following combinations of rods and handlines: - up to 2 rods - up to 2 handlines, or - one of each. Each line can have one of the following: - up to 3 hooks attached separately, - up to 5 hooks joined together.	As above	As above	Daily per person limit of 5 Snapper from 38 to 60 cm TL, and 2 Snapper > 60 cm TL. Daily boat limit applies when 3 or more people onboard: 15 Snapper from 38 to 60 cm TL, and 6 Snapper > 60 cm TL.	None
Charter	Charter Boat Fishery license is required, and provision of catch and effort data to SARDI. 92 charter fishing licences Statewide, Snapper is a primary target species, number actively targeting Snapper in the south-east unknown.	As above	As above	As above	**Up to 3 passengers daily per person limits apply**: 5 Snapper from 38 to 60 cm TL, and 2 Snapper > 60 cm TL. **4 to 6 passengers**: boat limit of 15 Snapper from 38 to 60 cm TL, and 6 Snapper > 60 cm TL. **More than 6 passengers**: daily per person limits 3 Snapper from 38 to 60 cm TL, and 1 Snapper > 60 cm TL.	None

Table 13 Summary of data available to inform cross-jurisdictional stock assessment for the WVSS

Jurisdiction	Data available for stock assessment
Victoria	**Fishery Dependent:** *Harvests*: Commercial annually, last recreational estimate 2006/07, no regular total recreational harvest estimates are planned, trends in relative harvest may be derived in future from integrating boat ramp camera, creel survey and phone app. reporting data. *CPUE:* annual from recreational creel surveys and diary anglers (catch per fisher hour or fisher trip) Port Phillip Bay and Western Port Bay, commercial long-line Port Phillip Bay (kg per hook lift). *Length and age composition:* annual recreational and commercial samples, Port Phillip Bay and Western Port Bay. **Fishery Independent:** *Surveys:* Annual pre-recruit surveys in Port Phillip Bay (0+ age fish).
South Australia	**Fishery Dependent:** *Harvests:* Commercial annually, last recreational estimate 2013/14, recreational harvest estimates are committed to occur every 5 years. *CPUE:* Commercial (Kg per fisher day) for longline and handline. *Charter*: harvests and catch rates, numbers of released fish above and below legal size/bag limits. *Age and length composition*: sporadically collected from commercial catches. **Fishery Independent:** N/A
Commonwealth	**Fishery Dependent:** spatially referenced, annual harvest data for all waters relevant to the WVSS in Victoria and South Australia. **Fishery Independent:** N/A

Figure 67 Framework for multi-jurisdictional collaboration on assessment and management of the Western Victorian Snapper Stock (WVSS).

SAFS- Status of Australia Fish Stock, SETFIA - South East Trawl Fishing Industry Association,
*Formal agreement between AFMA and SETFIA to limit Snapper harvest by Commonwealth licensed operators in Victorian waters, AFMA 2018.



Discussion

For effective management of cross-jurisdictional fish stocks it is important that each jurisdiction that harvests from the stock has fishery management objectives and governance systems in place that are considered satisfactory by the other jurisdiction(s). Each jurisdiction should be comfortable that the other has a transparent and robust assessment and management system, consistent with their level of impact (i.e. harvest) on the stock. Jurisdictions that carry more of the harvest risks should also be expected to contribute more to data collection, monitoring and assessment of the stock (i.e. risk-cost-catch trade-off).

Victoria and South Australia’s high-level management goals and objectives relevant to the WVSS are generally consistent in their intent to deliver sustainable fisheries and prevent overfishing. Victoria, however, lacks a formal management plan that documents how its management and assessment activities will deliver on its goals and objectives, which still need to progress from a draft status. As such there is uncertainty as to how management in Victoria would respond to changes in stock status. South Australia has general management planning documents for commercial, recreational and charters sectors that include proportional harvest allocations and provide a clear and transparent system of management triggers based on key performance indicators. However, there is no detail and how management would react to triggering of management triggers.

In relation to regulation of harvest impacts, South Australia, relies on input mechanisms and does not limit total commercial Snapper harvest (i.e. with TACs, quotas, caps). Victoria, however, has total harvest caps on the main commercial fishery that harvests from the WVSS. South Australia on the other hand has temporal closures during the spawning season that apply to all fishing sectors and these would limit effort and harvest to a certain extent. There are differences in regulations pertaining to gear allowances and size and daily bag limits, with Victorian recreational limits being less restrictive than South Australia. South Australia has a regulated charter fishing industry with mandatory reporting requirements, were as charter boat fishing in Victoria is unregulated with no fishery reporting requirements.

Both States collect commercial harvest and effort data. Victoria invests significantly into monitoring and assessment of the WVSS compared to South Australia, with recreational creel surveys, fishery independent pre-recruit surveys, a diary angler program and routine sampling of age/length compositions. This is consistent with ‘risk-catch-cost’ that Victoria carries most of the burden for stock assessment and data collection. Victorian has also recently developed and integrated stock assessment model, and an MSE model framework (this project). Overall, data availability to assess and track the condition of the WVSS is good, and the onus on data collection is suitably weighted to Victoria. However, in relation to managing the impacts of fishing, the stock assessments are limited by lack of measurement of the direct fishing impacts on the stock, such as total harvest data, effort data or estimation of fishing mortality. Periodic estimation of total recreational harvest or other approaches to estimating fishing mortality are necessary for improving the assessment and management of the WVSS. While an integrated stock assessment model has been developed for the WVSS, increasing confidence in the estimates of biomass trends from this model will depend on recreational harvest data from Victoria. Given there is no commitment for regular recreational Snapper harvest estimates, other forms of monitoring fishing impacts and associated management risk may need to be considered.

While the goals and objectives in relation to fishery and resource sustainability are consistent between Victoria and South Australia, the differences in management, regulatory approaches, and planning documentation underline the value of establishing the MOU between Victoria and South Australia. The MOU obligates VFA and PIRSA/SARDI to routinely collaborate on assessment and fishery management of the WVSS and ensure transparency between jurisdictions around WVSS fishery management. This is the first cross-jurisdictional MOU between Victoria and another State jurisdictional fisheries management agency. While each jurisdiction will continue to manage their jurisdictional fisheries under their Acts/Regulations/Management Plans, the MOU formally recognises the requirement to communicate, jointly assess and consider the interests of other jurisdictions and the agreed overall status of the stock, in any jurisdictional management changes/decisions. The MOU approach does not impinge on each jurisdictions autonomy to use different approaches to manage harvest/fishing impacts within their fisheries but should promote collaborative management and consistency in objectives for managing the stock as a whole.

The modelling tools, in particular, the Management Strategy Evaluation framework, developed in this project can be applied under the MOU to better understand the overall management risks associated with the WVSS fisheries. The framework for the operation of the MOU, also acknowledges the requirement to continue to engage AFMA in the stock assessment and management through provision of annual harvest data and monitoring the continued effectiveness of the AFMA-SETFIA Snapper harvest agreement relevant to Victoria waters. Establishment of the MOU provides reassurance for stakeholders that assessment and management is occurring on a whole of stock basis, including reporting of stock status in publicly available forums, such as ‘Status of Australian Fish Stocks’. The MOU will also simplify the process of routine data sharing, facilitate collaboration of stock assessment expertise, and ultimately lead to a more rigorously reviewed assessment of stock status.

Conclusions

Monitoring of recreational boat fishing effort with ramp cameras can achieve cost-effective unbiased estimates of numbers of fishing trips using time-lapse image capture (images captured every 2 minutes) and image sub-sampling routines. Sub-sampling routines can be selected based on cost/accuracy trade-offs. Total monthly effort estimates obtained from expansion of data from sub-sampling 25-30% of images captured each month achieved coefficients of variation of <10% for high effort months at individual ramps. The time-lapse approach requires images to be viewed and manually classified by a human operator. Time-lapse image capture mode would therefore be most suited to target key ramps and times for targeted studies and time periods. For example, a targeted program for monitoring trends in recreational Snapper fishing effort for the WVSS could involve three months (October-November-December) and four camera systems at the highest usage launch facilities (Clifton Springs, Altona, Patterson River, Hastings). The annual cost associated with this program, including deprecation to replace cameras every 8 years, would be between $AUD 12,600-13,800.

The trial of activity sensor software available with the Mobotix cameras used in this study demonstrated the activity sensing approach, with appropriately positioned cameras and fine-tuning of activity sensor settings, could supersede the requirement for continuous time-lapse image capture for ongoing monitoring programs. While some time-lapse image capture would still be required to periodically re-validate/calibrate relationships between activity triggers and recreational boat launch/retrieval activity, this would incur minimal cost. We estimate that it would cost less than $3,000/year for complete annual coverage of an individual ramp with multiple immediately adjacent lanes, including the depreciation and maintenance cost for the camera. The reduced cost and data processing time lags with activity sensor application will allow greater spatial and temporal coverage of boat fishing effort monitoring with remote IP cameras.

The combination of ramp camera effort data with boat ramp creel survey data on targeted effort, catch rates and composition, can be used to create a recreational 'harvest index' for the WVSS, or estimate harvests from particular locations and times. A 'harvest index' based on the monitoring of a number of key ramp facilities (as indicated above) could be used to track changes in relative harvest and interpolate total annual harvest between periodic total recreational harvest estimates. There is a need to improve the temporal coverage and quantity of recreational Snapper catch rate and composition data, as this was a greater source of uncertainty than the effort estimation. Trial of phone apps/electronic diaries could contribute to this, but would need to be subject to a thorough assessment of any biases in these approaches. In the absence of total recreational harvest estimates, the effort data alone could be used as a direct measure of changes in fishing mortality for management purposes.

The application of the newly developed MSE framework (SnapMSE) utilising SS3 (Stock Synthesis) indicated that constant annual exploitation rates of around 10-15% may be relatively safe considering historic recruitment variation for this fishery. A Tier 1 style harvest control rule (as used for Australia's larger Commonwealth fisheries) with a maximum economic yield target for spawning biomass would also produce similar biomass outcomes as a 10% constant exploitation rate. The MSE study and operational objectives in this project were developed for trial purposes. Further, consideration of objectives and reference points with managers and stakeholders is required to guide further MSE studies that also need to explore implications of other uncertainties in the assessment process and model parameter assumptions.

While the SnapMSE framework can underpin development of fishing mortality reference points and a harvest strategy for the WVSS, the application of the Snapper management advice tool, SnapMAT, indicated that it would be possible to reduce recreational fishing mortality by using various size and bag limit changes, in particular increased LML and slot limit approaches. However, potential changes in angler behaviour and effort in response to size and bag limit changes would need to be carefully considered in relation to how they might negate or enhance the desired impacts of specific regulation changes.

Finally, the risk to Victorian interests in the WVSS from harvest by the South Australian and Commonwealth fisheries have reduced since this project began, reducing the need to consider formal multi-jurisdictional sharing/allocation frameworks. The establishment of an MOU and operational plan between Victoria and South Australian management agencies will drive a collaborative approach to ongoing assessment and management of the WVSS.

Implications

This project has provided a feasible approach for monitoring effort and harvest trends in the WVSS recreational Snapper fishery that builds on the current long-term creel survey program. With implementation of activity sensor technology, the cost of a boat fishing effort monitoring system should not be prohibitive and would contribute important data for sustainable management of the WVSS fishery. Coupling the effort data with targeting data from creel surveys or other approaches such as phone apps/electronic diaries would also allow monitoring of targeted effort on other species with minor additional cost. The outcomes of the boat ramp camera monitoring trial build on other applications of this technology in Australia and overseas to monitor recreational fishing effort.

At the beginning of this project the need to develop a recreational Snapper harvest index was primarily aimed at facilitating a more reliable/robust interpolation of recreational harvest between periodic total recreational Snapper harvest estimates. Having a times series of total harvest data was recognised as a key requirement for application of a recently developed integrated stock assessment to estimate biomass and fishing mortality performance measures. Future total recreational harvest estimates are uncertain in Victoria, however, even without harvest estimates, the implementation of ongoing effort monitoring can provide the core data for development of an effort-based approach for monitoring trends in recreational fishing impact for management purposes. Effort data will also be valuable for socio-economic evaluations.

In relation to identifying risk and preventing overfishing, the MSE framework provides a robust and transparent approach to facilitate the development of informed management planning for the WVSS. The trial management objectives and HCRs used in the MSE study provide managers and stakeholders with a preliminary insight into what might be acceptable exploitation rates for the combined recreational and commercial fisheries. The outcomes of the MSE studies provided an indication that the current level of fishing mortality is probably at an acceptable level, given recruitment uncertainty and the objectives used in this study. However, growing effort does present risks of not achieving performance objectives, particularly under conditions of poor juvenile recruitment. Importantly, further MSE scenarios are required to be tested in collaboration with stakeholders to develop an agreed level of exploitation risk and operational management objectives for the WVSS. Ultimately, the implications of this process will be that managers and stakeholders can make more informed management planning decisions to improve resource security and the associated recreational and commercial fishery benefits.

Improving the understanding of management risk, and developing harvest strategies and appropriate management reference points, is an important step forward, but being able to affect change in fishing mortality rate if required to meet objectives is equally important. The results of exploration of the potential of size and bag limit adjustments to reduce harvest by the recreational sector indicated that catch reductions could be achieved, most notably by use of increases to the LML and a slot limit. The predictions using the SnapMat tool assume no negating effects due the responses of angler effort (i.e. increases) or behaviour to chosen regulation changes, and this requires greater understanding.

Finally, the creation of the MOU between and the Victorian Fisheries Authority and Primary Industries and Regions South Australia will ensure ongoing collaboration on the assessment and management of the WVSS. The operational framework for the MOU includes that Commonwealth harvests are monitored and applied in stock assessment so that the VFA and PIRSA can jointly assess if these are at acceptable levels. The MOU provides assurance to stakeholders in each State that the stock assessment is rigorously reviewed and that their interests are considered when each jurisdiction considers management changes related to the WVSS.

Recommendations

For the MSE framework to be utilised for its intended purpose, operational management objectives need to be developed in collaboration with stakeholders. The objectives applied in this study provide a good starting point but a forum for discussion, such as a formal WVSS stakeholder refence group is recommended. Once objectives are solidified, further exploration of MSE scenarios in a structured/endorsed framework can occur to inform choice of fishing mortality and biomass reference points to apply under an agreed management framework for the WVSS, which could include a harvest or fishery optimisation strategy. Furthermore, implementation such strategies would require methods for monitoring fishing mortality and biomass status. If recreational harvest information is unavailable, application of the integrated assessment model will be compromised, and other methods will need to be developed to estimate these key management parameters. Either way, a desktop exploration of the requirements, cost and feasibility of tagging and catch curves to estimate fishing mortality on the WVSS is recommended. We also suggest that a suitable effort monitoring system using boat ramp cameras, coupled with information on recreational catchability (or effectiveness) from creel surveys and/or phone apps/diaries, has strong potential to provide a measure of variation in fishing mortality rates in the absence of total harvest information, and should be explored further.

In relation to broader and ongoing implementation of the boat ramp camera effort monitoring approach, it is clear that the activity sensor method will be the most cost-effective approach. However, resources to fund and manage an ongoing ramp camera system are not trivial, even with the reduced cost of using activity sensor technology. Expansion of a boat ramp camera system in Victoria will benefit by using them to achieve multiple objectives; including effort monitoring for fisheries management, and provision of real time information to the public on ramp conditions/launch-retrieval wait times and other safety related information through regularly updated images/information via a web portal or phone app. platform. Information on usage patterns and trends for individual ramps can also guide allocation of funds for improvement or expansion works. Multiple objectives would promote sharing of camera infrastructure and operational costs, and collaboration among agencies to improve camera systems, trial new technologies and improve systems for data management, analysis and public display. We recommend that VFA work with other agencies involved in boating to identify multiple objectives for these systems and explore cost-sharing options to expand coverage and ensure resources are sufficient to maintain the systems.

Further development

While this project has provided a number of new analytical tools and approaches for better informing the management of the WVSS and has formalised the collaboration on assessment and management issues between Victoria and South Australia, the value of these outcomes in relation to resource security and optimising socio-economic benefits will not be realised unless there is an agreed management procedure. This requires a formal dialogue between the relevant management agencies (VFA and PIRSA) and stakeholders to initially develop agreed performance measures, operational objectives and assessment procedures. This will ensure that at least the status assessments (i.e. SAFS) are transparent and supported by the State jurisdictions and stakeholders. SnapMSE is the tool to inform this process and provide a common understanding of management risk for this stock and its fisheries.

Developing predictive models of Snapper angling effort and behavioural response to changes in stock abundance and regulations would be valuable to the better understand the capacity for self-regulation of the recreational fishing impact.

Extension and Adoption

The project was initially communicated to recreational and commercial fishery stakeholders in Victoria at a Western Stock Snapper meeting in October 2013. A media release regarding the project was made prior to this meeting (below). Further updates were provided to recreational and commercial fishery stakeholders at Snapper assessment meetings in June 2016.

In September 2014, a workshop was conducted with stakeholders from management agencies and industry representative groups with the objectives to provide updates on research with cross-jurisdictional aspects relevant to the western Victorian Snapper stock and initiate education and discussion of harvest strategy development for this stock (see appendix 6). It was envisaged that this meeting would establish an ongoing ‘Western Victorian Snapper Stock Reference Group’ to support the project. This formal group did not progress, partly owing to uncertainty around resource allocation policy, and the related objectives of this project, when the Victorian Government committed to remove commercial netting and most commercial licenses from the Port Phillip Bay fishery. Now that those commitments have been realised and implemented, it would be appropriate to re-consider the creation of a ‘Western Victorian Snapper Stock Reference Group’. While the establishment of the MOU between the VFA and PIRSA will create a forum for management and science collaboration, a reference group with stakeholders would provide the forum for further extension and adoption of the project outcomes in ongoing management.

The new modelling tools developed in this project can be applied to other species/fisheries and will be published in journals for broader dissemination to the scientific community. We are also open to sharing code with interested parties. A presentation on the ramp camera monitoring sub-sampling approach was given to the 2015 Australian Society for Fish Biology conference in Sydney and further conference presentations are likely. A training workshop for the MSE and bag/size limit models has been provided by the lead modelling scientist to VFA scientists.

VFA have recently installed an additional ramp camera suitable for activity sensor monitoring at a key ramp in Port Phillip Bay (Clifton Springs), and have established an MOU with Transport Safety Victoria to work together on relocating and upgrading current cameras to allow application of the activity sensor approach and expanding coverage of boat ramp cameras for multiple objectives.

Modification and additional questions have been added to the creel survey to improve data on released Snapper numbers and reasons for release, avidity levels and individual trip satisfactions rates. VFA has also embarked on a trial of a phone app./electronic diary. It is hoped this will provide increased data on recreational Snapper catch rates and length compositions, and other information on individual angler characteristics and behaviour that can enhance the current creel survey program and contribute to further research on recreational angler effort responses to stock status.

A project outcomes and next steps/implementation meeting will be held with VFA science management and policy staff when this report is finalised. This meeting will also discuss the options for future stakeholder engagement on management of the WVSS including extension of the project outcomes and further application of MSE to inform management risk. The project outcomes will also be presented to the first meeting of the science and management representatives on the VFA/PIRSA WVSS MOU group in 2019.

Project coverage

Due to the complex nature of the modelling, and the political sensitivities around this work during the Port Phillip Bay commercial netting buy-out, there has been limited media coverage. We expect to get clearer direction on project extension options via popular media at the project outcomes and next steps/implementation meeting.

Media release: October 2013

Department of Environment and Primary Industries

State Government Victoria

Media Release

September 2013 | Media contact:

Ensuring a sustainable and high performing snapper fishery

Fisheries Victoria has begun work on a new project that aims to improve the long-term sustainability and performance of one of the state's most valuable fisheries: the western snapper stock.

Executive Director of Fisheries Victoria Ross McGowan said the western stock snapper fishery extended from Wilsons Promontory to eastern South Australia, including Port Phillip and Western Port, and was the most valuable inshore fin-fish fishery in Victoria.

"The western stock snapper fishery is highly valued by recreational and commercial fishers and consumers alike," Mr McGowan said.

"This new project will explore approaches for managing the snapper harvest by recreational and commercial fishers to ensure long-term sustainability and maximise the performance of the fishery for both sectors."

Mr McGowan said the project recognised the ever increasing popularity of recreational snapper fishing and would also involve developing new approaches for monitoring the recreational catch of the species.

"Managing fishing impacts appropriately is essential to ensure the long-term sustainability and provide secure access to any fishery, and snapper is no exception," he said.

"There are existing management arrangements for state and commonwealth fishers, but this project will involve working with recreational and commercial stakeholders to establish management objectives that will underpin the development of a harvest management framework that could guide future decisions for the fishery."

Fisheries Victoria Senior Research Scientist Dr Paul Hamer said that the western stock snapper fishery was naturally variable due to high variation in spawning success from year to year.

"This variability needs to be accounted for by management approaches that allow for fishers to benefit during productive periods but also recognises that leaving fish 'in the bank' is important during periods of low productivity," Dr Hamer said.

"The challenge is often deciding when and how many fish to leave 'in the bank' and for how long – this project aims in part to tackle this challenge".

"It is risk management in a sense and will require both the commercial and recreational fishing sectors to make informed decisions on acceptable risk levels."

The project is jointly funded by the Fisheries Research and Development Corporation and Victorian Recreational Fishing License fees and is expected to be completed by September 2016.

www.depi.vic.gov.au | Follow us on Twitter: @DEPI_Vic |

Popular media article in Victorian Fishing Monthly: 2016

20th century snapper fishery assessment

GEELONG

Ross Winstanley

Victoria's snapper fishery is at the front of the wave when it comes to the development and application of technology and modelling the way fisheries and fish stocks respond to changing conditions. And yet, with the greater part of the fishery for Victoria's western snapper stock shifting further into the hands of Port Phillip Bay anglers, stock monitoring and fishery management are becoming increasingly dependent on a band of volunteer anglers.

There are several significant implications of the phase-out of commercial netting and the scaling down of longlining in the Bay. From 2022, commercial snapper fishing will be restricted to 88 tonnes shared among up to eight longline anglers.

So, this year marks the start of an 8-year process that will end the 100+ year time series of commercial net fishing records, including the detailed catch and effort statistics collected across a range of commercial fishing methods since 1978. Until recently, this commercial fisheries information has provided the main basis for monitoring and assessing the state of the snapper stocks and the impacts of fishing. After 2022, all that will remain will be a maximum of eight longliners.

This provides one of several good reasons for anglers to get behind the snapper monitoring and assessment program as its importance rises. As the 'major shareholders' in the western Victorian snapper stock and the Port Phillip Bay fishery, anglers have a strong proprietary and emotional interest. Their demands essentially drove the incoming Labor Government's 2014 commitment to phase out commercial netting in Port Phillip Bay. Now that their demands are being met, anglers have more reason than ever to actively engage in stewardship of the Bay fish stocks. Bay anglers along with all other Victorian recreational fishers now bear the costs of the creel survey, Angler Diary and Research Angler programs, met from the Recreational Fishing Licence trust account.

2016 STOCK ASSESSMENT

Early in June, Fisheries Victoria held the first Victorian snapper stock assessment workshop since 2011. In the interim there has been a great deal of research work done, reviewed and reported on snapper. However, this workshop provided the first look at how the future might look as the Port Phillip Bay fishery begins to transition to an even more strongly angler-dominated state. While the workshop's main focus was on the fisheries in the two bays, it examined the current state of knowledge of the western Victorian snapper stock as far as its boundary near Kangaroo Island, SA, and the eastern stock as far as the NSW border (see figure 1).

The workshop covered and updated information on the: year-to-year pattern of recruitment (spawning success), the continuing fish-down of the large year-classes spawned in 2001 and 2004 reflected in the recent decline in catches of big snapper, and a Melbourne University study of the critical Yarra River flows, temperature and nutrient requirements that determine snapper larval survival in the first few days after hatching.

The updated monitoring of annual year class strength at age 0+ years shows that, after average or above average recruitment in 2008, 2009, 2010, 2013 and 2014, we've had two very poor years. The pattern of declining catch rates of pinkies in the January-April period, since 2011, was reflected in Angler Diary and creel survey results for Port Phillip Bay. What matters most is the healthy recruitment in five of the past nine years. As reported in the April issue of VFM, the 2013 and 2014 'recruits' are now entering the legal-sized pinkie fishery and will progress into the adult (ie >40cm) snapper fishery from 2020.

Until now, the separate trends in commercial haul seine and longline catch rates have provided excellent indicators of trends in the abundance of juvenile and adult snapper. Haul seining mainly targets pinkies while longlines mainly target larger adult snapper. Catch rates by the eight longliners who are expected to continue operating beyond 2022 will provide a vital ongoing indicator of the stock of large snapper. With the licence buy-out already leaving just 10 commercial operators in 2016/17, we cannot rely much longer on haul seine catch rates as a fishery 'performance measure'. This means that far greater reliance will now rest on monitoring the recreational fishery through the ongoing creel survey, Angler Diary and Research Angler programs.

Annual commercial catches from Port Phillip Bay varied between 30 and 100 tonnes from 1991/92 until 2011/12 when they rose to a 30-year high of 162 tonnes before falling away over the past four years. The recent pattern of reducing commercial catches was reflected in longline catch rates for large (>8 years) snapper. Length composition data from both creel surveys and Angler Diaries clearly showed the steady depletion of snapper larger than 40 cm between 2011 and 2015.

The only two available estimates of the recreational take from this stock, were approximately 300 tonnes in 2000/01 and 450 tonnes in 2006/07.

The overall assessment of the western snapper stock was that the abundance of legal-sized fish is stable, under-sized snapper numbers are increasing and the stock status is healthy.

It was pointed out that a significant sector of the snapper fishery in both bays – the recreational fishing charter industry – remains unregulated and unmonitored in terms of the impact of their activities on the snapper stock. While recreational fishers continue to bear fishery monitoring costs, the charter industry is exempt from any requirement to contribute catch, effort and size composition information that could be so valuable to stock and fishery assessments.

SA LONGLINE FISHERY

New information presented showed the emergence and impact of a commercial snapper fishery targeting 'Victoria's' western snapper stock in southeastern South Australian waters, beginning in 2005. In both 2009 and 2010, SA longliners took more than the catch by Victoria's commercial Port Phillip Bay and ocean fisheries combined. Catches by the SA fishery dwindled to virtually zero by 2015, apparently as a result of the decline in large snapper numbers as those older year classes were fished down or moved out of the area, making longlining unviable there. Still, this is a legitimate and potentially substantial fishery to keep an eye on in future. Fisheries Victoria and their South Australian counterparts are looking into this cross-jurisdictional aspect of the western stock fishery.

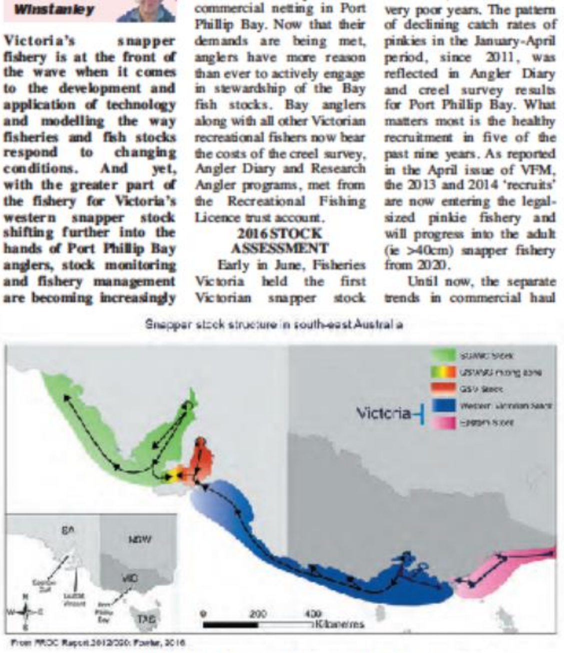
In contrast, off the Victorian coast the reported annual trawl and Danish seine take of snapper, which got anglers irate around 10 years ago, has rarely exceeded 30 tonnes and has decreased to less than 10 tonnes in recent years.

EASTERN VICTORIAN SNAPPER STOCK

Since detailed records began in 1978, the annual Victorian-managed commercial snapper fishery east of Wilsons Promontory rarely exceeded 10 tonnes. The harvest by Commonwealth-managed trawlers rose sharply in 2004/05, peaking at around 25 tonnes in 2011/12 before falling to average less than 10 tonnes in the past three years. The only two estimates of the recreational take from this stock, in 2000/01 and 2006/07, were both around 30 tonnes.

Spawning aggregations are known to occur off the Ninety Mile Beach. At times, along the East Gippsland coast and up into NSW, small juvenile snapper occur in large numbers in coastal inlets before moving out into open coastal waters at 1-3 years of age. Even as juveniles, eastern stock snapper move from eastern Victoria, where the stock is lightly exploited by both commercial and recreational fishers, up into NSW and southern Queensland waters where the stock

Snapper stock structure in south-east Australia



From PIRSA Report 2012/200; Fowler, 2016

Figure 1: Distribution and movement patterns of snapper stocks in Victorian and SA waters.

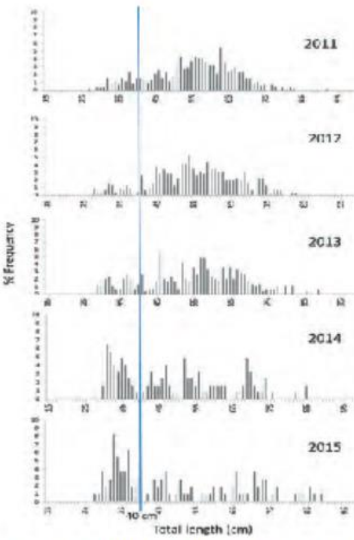


Figure 2: Port Phillip Bay Spring creel surveys show the decline in numbers of adult snapper (>40cm) and the entry of pulses of pinkies in 2014 and 2015 snapper stocks in Victorian and SA waters.

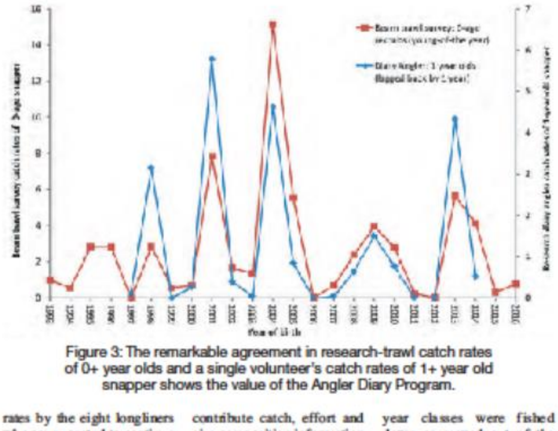


Figure 3: The remarkable agreement in research-trawl catch rates of 0+ year olds and a single volunteer's catch rates of 1+ year old snapper shows the value of the Angler Diary Program.

has been assessed as being over-fished.

The overall assessment of the eastern snapper stock in Victorian waters was limited by a lack of fisheries data but information from fishers in that region suggested that the fishery appears to be in a healthy condition. The workshop heard that a three-state study is being conducted with a view to a consensus approach to assessing this stock, which is exploited to such widely varying degrees from Victoria to Queensland.

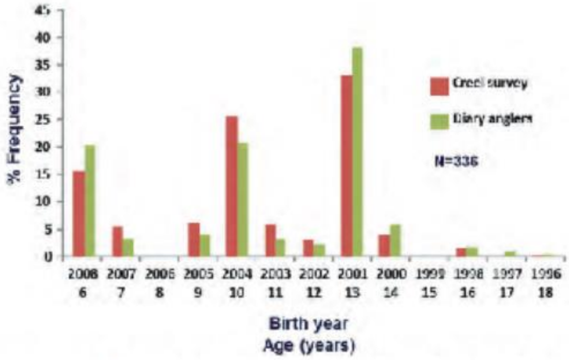


Figure 4: Age composition of snapper taken by Angler Diary and creel survey anglers in spring, 2014.

A growing concern off the Ninety Mile Beach is the increased recreational catch and release fishing targeting spawning aggregations in 35-45m depths. Numbers of distressed 8-9kg fish are being sighted on the surface during the peak November fishery. This indicates the need for a targeted angler education campaign highlighting the fate of these snapper, urging anglers to stop fishing once they achieve their allowable bag limit and advising them on catch and release methods that can maximise the survival of snapper released in these depths.

CREEL SURVEY

Queenscliff's creel survey program has been operating continuously since 1998 in Western Port Bay and since 2002 in Port Phillip Bay. This program provides essential information on angler catch rates and the size composition of the legal sized snapper retained by anglers during the spring 'big snapper' and summer-autumn pinky fishing seasons. The latest results show spring catch rates of large snapper rising steadily from 2002 to 2012 then falling sharply (see figure 2) as overall fishing pressure and natural mortality finally began to exhaust the large pulses of fish spawned back in 2001, 2004 and 2005.

The results for the January to April period showed a generally declining trend in the mainly pinky fishery from 2004 with an up-turn in 2015 as legal-sized pinkies from the successful 2013 spawning began to appear.

Today, catch rate estimates derived from the creel survey program enjoy a high level of confidence. In the near future, the program's detailed continuous data set is about to assume an even greater role in the monitoring of the snapper stock and fishery, including the estimation of the recreational snapper catch. There have only been two recent estimates of the recreational snapper catch – in 2000/01 as part of the National Recreational Fishing Survey and, in 2006/07, as a separate snapper catch survey. Both surveys directly measured the recreational catch using methods that are expensive and time-consuming, hence the lack of more recent and frequent estimates.

To overcome this, Queenscliff researchers are trialling the use of cameras mounted at six boat ramps around Port Phillip Bay and one at Hastings. These 'ramp-cams' record and store boat launch-and-retrieve images every two minutes. An upgrade of this approach, using motion-activated cameras is planned. This approach is a real advance over the traffic counters, which have the inherent inaccuracies resulting from non-fishing vehicle counts and regular vandalism.

The large bulk of the recreational snapper catch in both bays is taken by boat-based fishing. Once the ramp-cams are developed to the point of providing comprehensive estimates of boating trips, it will be possible to estimate the snapper catch from each bay annually, simply by multiplying the catch rate (from creel surveys) by boat trips (from ramp-cams). These estimates are absolutely essential to ensuring that snapper fishing is maintained at sustainable levels and are a key piece remaining in the effort to make this the most well managed and sustainable snapper fishery in Australia.

ANGLER DIARY CONTRIBUTION

This was much more than some earlier workshops which had amounted to little more than plotting the most recent data points onto a few graphs. What particularly impressed the 12 Angler Diary volunteers who participated were the advances being made in the application of technology and modelling and the increasing importance of their contribution to snapper assessments.

Dating back to 1997, the Angler Diary Program has provided a continuous time series of information on catch rates and size composition of snapper and other species targeted by anglers. The key characteristic of these angler volunteers has been their commitment to fish in much the same ways in the same areas, year after year, recording complete details of their fishing activities, gear, bait and catches, including undersized and released fish.

Twice yearly, the volunteers also operate as Research Anglers, fishing to researchers' directions and using standard hooks provided to enable them to catch snapper of all ages from age 1+ year upward. The combination of their fish size and catch rate data has yielded what has proved to be a reliable indication of the relative abundance of juvenile snapper, mainly 1-5 year olds. Until 2011 when the annual Bay trawl surveys ended, Research Angler records provided a third-string indicator of year-to-year recruitment as one-year-old pinkies became vulnerable to hooking at lengths of above 15 cm. As Figure 3 illustrates, this information closely mirrors the annual recruitment trends determined by Queenscliff researchers' fishery-independent sampling.

Port Phillip Bay diary catch rates of mainly spawning snapper during October-December since 2006 varied between 1.0 and 1.5 snapper per angler hour. Size composition records clearly showed the decline in numbers of snapper above 40 cm since 2011. Aging of samples of these larger fish taken from October to December 2014 showed the dominance of year classes spawned in 2001, 2004 and 2008 with only small numbers of fish from spawning in other years as far back as 1997 (See figure 4). The current decline in adult numbers is not expected to stabilise until 2020 when improved numbers of pinkies spawned in 2013 and 2014 reach maturity.

Since 1999, during the pinky season from January to April, the diary catch rates varied between 3-6 snapper per angler hour, with a downward trend from 2011.

RECRUITMENT OF DIARY VOLUNTEERS

The termination of the annual trawl survey in 2011 has left the Angler Diary Program as the only ongoing medium for monitoring snapper year-class strength at ages above one year, increasing researchers' reliance on these angler volunteers. Given the older ages of current participants, there was general agreement at the workshop on the need to recruit younger Angler Diary members.

The results of a review of the Angler Diary Program conducted earlier in the year were not available at this workshop. One of the issues discussed during the review was the desirability of moving from on-board pencil and paper recording of fishing and catch details – later transcribed and submitted in paper logbooks – to immediate electronic data entry and reporting. Anglers at the workshop considered that a shift to on-board electronic data entry will be vital to attracting younger members.

ACOUSTIC TAGGING

The tracking study of snapper movements into, around and out of Port Phillip Bay, using acoustic tags ran from 2011 until 2014. The study followed the movements of 160 tagged snapper, tracked by 47 'listening stations' around the Bay and across Port Phillip Heads. Adult fish were found to move into the Bay, mainly in October, while many left in December immediately after the main spawning period, with a smaller wave of fish exiting in April and May each season.

The Department website shows highlights of the program (see http://agriculture.vic.gov.au/fisheries/science-in-fisheries/fisheries-research-findings) and a final report on the project is being prepared.

WHERE IS THIS ALL HEADING?

Distinct from the long-standing monitoring and assessment of the state of snapper stocks and fisheries, Victoria's snapper research has been advancing in areas of modelling and the development of 'harvest management strategies'. The aim of this is to measure and improve the quality of fisheries management and to make quantitative forecasts based on the array of data now being collected across snapper lengths, ages, growth, recruitment, catches, catch rates and fishing effort.

Harvest strategies provide a structured approach to responding to changes in the snapper stock or fishery in order to keep within boundaries set to ensure that fishing remains sustainable. The modelling tools being developed can compare the risks and benefits of different management options.

All this may seem quite abstract and academic to many anglers, given the 'healthy' status attached to Victoria's snapper stocks and fisheries over the past decade or more. However, as we are already seeing with the Port Phillip Bay sand flathead stock decline, long term environmental changes are occurring and can have significant impacts requiring adjustments to management arrangements. With southeastern Australia seen as a climate change 'hotspot' we need to be preparing to make management adjustments to ensure the best ongoing benefits from snapper, whiting, flathead and other fisheries resources.

Dating back to 1997, the Angler Diary Program has provided a continuous time series of information on catch rates and size composition of snapper and other species targeted by anglers.

Until now we have managed with just two estimates of annual recreational snapper catches, most recently in 2006/07. However regular, reliable and less expensive catch estimates will be critical ingredients to the models and harvest strategies needed to manage our fisheries sustainably in the face of change. That's why the ongoing combination of creel survey, volunteer angler and ramp camera data are so important to the future of our snapper fisheries.

ANGLER DIARY VOLUNTEERS NEEDED:

The contribution by angler diarists in tracking undersize year-classes of snapper fills an important knowledge gap and helps us forecast future snapper catch rates in the fishery. The Angler Diary program is funded by Recreational Fishing Licence fees and is a great example of volunteer anglers giving back to the management of their fishery.

If you're keen to know more, contact Pam Oliveiro on 5258 0233.

Appendices

Appendix 1: List of researchers and project staff

Science and technical:

Paul Hamer (PI): research scientist, Victorian Fisheries Authority

Khageswor Giri: biometrician, Department of Jobs Precincts and Regions, Victoria

Simon Conron: research scientist, Victorian Fisheries Authority

Athol Whitten: lead fisheries modelling collaborator, MEZO Pty Ltd

Michael Smith: data analyst and programming consultant, MEZO Pty Ltd

Rick McGarvey: fisheries modelling expert advisor, South Australian Research and Development Institute (SARDI)

Rich Little: fisheries modelling expert advisor, CSIRO

Management and policy support:

Mark Edwards: Ex. Fisheries Victoria

Dallas D'Silva: Victorian Fisheries Authority

Bill Lussier: Victorian Fisheries Authority

Jonathon McPhail: Primary Industries and Regions South Australia (PIRSA)

Appendix 2: Intellectual Property

NA

Appendix 3: SnapAssess SS3 model

Stock Synthesis Background

Stock Synthesis (SS) provides a statistical framework for calibration of a population dynamics model using a diversity of fishery and survey data. It is designed to accommodate both age and size structure in the population and with multiple stock sub-areas. Selectivity can be cast as age specific only, size-specific in the observations only, or size-specific with the ability to capture the major effect of size-specific survivorship. The overall model contains subcomponents which simulate the population dynamics of the stock and fisheries, derive the expected values for the various observed data, and quantify the magnitude of difference between observed and expected data. Some SS features include ageing error, growth estimation, spawner-recruitment relationship, movement between areas. SS is most flexible in its ability to utilize a wide diversity of age, size, and aggregate data from fisheries and surveys. The ADMB C++ software in which SS is written searches for the set of parameter values that maximize the goodness-of-fit, then calculates the variance of these parameters using inverse Hessian and MCMC methods. A management layer is also included in the model allowing uncertainty in estimated parameters to be propagated to the management quantities, thus facilitating a description of the risk of various possible management scenarios, including forecasts of possible annual catch limits. The structure of Stock Synthesis allows for building of simple to complex models depending upon the data available (see Methot 2013; Methot and Wetzel, 2013).

The SnapAssess model was created using SS3, Version 3.240. The SS3 starter, and control files for SnapAssess 2016 base case model are included below.

```
# SSV3.24O
# Starter File
# Western Victorian Snapper Stock Assessment, 2018
Snapper.dat
Snapper.ctl

0        # 0=use init values in control file; 1=use ss3.par
2        # run display detail (0,1,2)
1        # detailed age-structured reports in REPORT.SSO (0,1)
1        # write detailed checkup.sso file (0,1)
1        # write parm values to ParmTrace.sso (0=no,1=good,active; 2=good,all; 3=every_iter,all_parms; 4=every,active)
2        # write to cumreport.sso (0=no,1=like&timeseries; 2=add survey fits)
0        # Include prior_like for non-estimated parameters (0,1)
1        # Use Soft Boundaries to aid convergence (0,1) (recommended)
0        # Number of bootstrap datafiles to produce
6        # Turn off estimation for parameters entering after this phase
0        # MCMC burn interval
0        # MCMC thin interval
0        # jitter initial parm value by this fraction
-1       # min yr for sdreport outputs (-1 for styr)
-2       # max yr for sdreport outputs (-1 for endyr; -2 for endyr+Nforecastyrs
0        # N individual STD years
0.0001   # final convergence criteria (e.g. 1.0e-04)
0        # retrospective year relative to end year (e.g. -4)
1        # min age for calc of summary biomass
1        # Depletion basis:  denom is: 0=skip; 1=rel X*B0; 2=rel X*Bmsy; 3=rel X*B_styr
1        # Fraction (X) for Depletion denominator (e.g. 0.4)
4        # (1-SPR)_reporting:  0=skip; 1=rel(1-SPR); 2=rel(1-SPR_MSY); 3=rel(1-SPR_Btarget); 4=notrel
1        # F_std reporting: 0=skip; 1=exploit(Bio); 2=exploit(Num); 3=sum(frates)
0        # F_report_basis: 0=raw; 1=rel Fspr; 2=rel Fmsy ; 3=rel Fbtgt
999       # check value for end of file
# SSV3.2O
# Control File
```

C Western Victorian Snapper Stock Assessment, 2018
by Mezo Research, contact mezo@mezo.com.au
C Fleet Information Placeholder

1 #_N_Growth_Patterns
1 #_N_Morphs_Within_GrowthPattern

0 #_Nblock_Patterns
Consider time-blocking as an option if good reason to expect change in gear-selectivity or biology.

Biological specifications
0.5 #_Fracfemale
0 #_NatM_type:_0=1Parm; 1=N_breakpoints;_2=Lorenzen;_3=agespecific;_4=agespec_withseasinterpolate
1 #_GrowthModel: 1=vonBert with L1&L2; 2=Richards with L1&L2; 3=age_speciific_K; 4=not implemented
1 #_Growth_Age_for_L1
999 #_Growth_Age_for_L2 (999 to use as Linf)
0 #_SD_add_to_LAA (set to 0.1 for SS2 V1.x compatibility)
0 #_CV_Growth_Pattern: 0 CV=f(LAA); 1 CV=F(A); 2 SD=F(LAA); 3 SD=F(A); 4 logSD=F(A)
1 #_maturity_option: 1=length logistic; 2=age logistic; 3=read age-maturity matrix by growth_pattern; 4=read age-fecundity; 5=read fec and wt from wtatage.ss
1 #_First_Mature_Age
1 #_Fecundity option:(1)eggs=Wt*(a+b*Wt);(2)eggs=a*L^b;(3)eggs=a*Wt^b; (4)eggs=a+b*L; (5)eggs=a+b*W
0 #_Hermaphroditism option: 0=none; 1=age-specific fxn
3 #_Parameter_offset_approach (1=none, 2= M, G, CV_G as offset from female-GP1, 3= M and CV old offset to young same sex (as per SS2 V1.x)
1 #_Env/block/dev_adjust_method (1=standard; 2=logistic transform keeps in base parm bounds; 3=standard w/ no bound check)

Mortality and growth parameters
#LO HI INIT PRIOR PR_ty SD PHASE env-variable use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn
0.05 0.3 0.20 0.15 -1 0.8 -2 0 0 0 0 0.5 0 0 # M young
10 20 15 12 -1 0.8 -3 0 0 0 0 0.5 0 0 # Lmin
70 100 83 83 -1 0.8 -2 0 0 0 0 0.5 0 0 # Lmax
0.05 0.25 0.10 0.10 -1 0.8 -3 0 0 0 0 0.5 0 0 # VBK
0.01 0.25 0.17 0.1 -1 0.8 3 0 0 0 0 0.5 0 0 # CV young
-3 3 1 0 -1 0.8 -3 0 0 0 0 0.5 0 0 # CV old: exp offset to CV young

```
# Males (Offset to Females)
-3   3   0   0   -1  0.8   -3   0  0  0  0  0.5   0  0  # M young: exp offset to morph 1
-3   3   0   0   -1  0.8   -3   0  0  0  0  0.5   0  0  # Lmin: exp offset to morph 1
-3   3   0   0   -1  0.8   -2   0  0  0  0  0.5   0  0  # Lmax: exp offset to morph 1
-3   3   0   0   -1  0.8   -3   0  0  0  0  0.5   0  0  # VBK: exp offset to morph 1
-3   3   0   0   -1  0.8   -4   0  0  0  0  0.5   0  0  # CV young: exp offset to morph 1
-3   3   0   0   -1  0.8   -4   0  0  0  0  0.5   0  0  # CV old: exp offset to CV young (male)

# Weight-length and maturity parameters (L in cm, W in kg)
# Females
# Lo    Hi     Init    Prior Prior    Prior   Param   Env Use Dev     Dev     Dev Block   block
# bnd   bnd    value   mean  type     SD      phase   var dev minyr   maxyr   SD  design  switch
-3   3    0.000045   0  -1   0.8   -3   0  0  0  0  0.5   0  0  # W-L scale (Female) (Parameter A in W=A*L^B, Weight in kg)
 1   4    2.795      0  -1   0.8   -3   0  0  0  0  0.5   0  0  # W-L power (Female) (Parameter B in W=A*L^B, Weight in kg)
 25  50   36.3       0  -1   0.8   -3   0  0  0  0  0.5   0  0  # Len at 50% maturity (Logistic curve inflection point (size at 50% Maturity), in cm)
-6   3    -0.25      0  -1   0.8   -3   0  0  0  0  0.5   0  0  # Maturity slope (Logistic curve slope, must have a negative value)
-3   3    1          0  -1   0.8   -3   0  0  0  0  0.5   0  0  # Intercept eggs/gm
-3   3    0          0  -1   0.8   -3   0  0  0  0  0.5   0  0  # Slope eggs/gm

-3   3    0.000047   0  -1   0.8   -3   0  0  0  0  0.5   0  0  # W-L scale (Male) (Parameter A in W=A*L^B, Weight in kg)
 1   4    2.780      0  -1   0.8   -3   0  0  0  0  0.5   0  0  # W-L power (Male) (Parameter B in W=A*L^B, Weight in kg)
```

Distribute recruitment among growth pattern x area x season
-4 4 0 0 -1 99 -3 0 0 0 0 0.5 0 0 # RecrDist_GP_1
-4 4 0 0 -1 99 -3 0 0 0 0 0.5 0 0 # RecrDist_Area_1
-4 4 0 0 -1 99 -3 0 0 0 0 0.5 0 0 # RecrDist_Seas_1

Cohort growth (K) deviation parameter
0.5 1.5 1 1 -1 99 -5 0 0 0 0 0.5 0 0 # CohortGrowDev

Ageing error matrix parameters
0 2 1 3 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_1_Start_Age
-2 5 0.25 1 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_2_Bias_Start_Age
-3 5 1.25 1 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_3_Bias_Max_Age
0.01 5 1 1 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_4_Power_Fxn_Coef_Btwn_P1_P2 (0 = Linear)
0.01 5 2 1 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_5_Stdv_Start_Age
0.01 5 4 1 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_6_Stdv_Max_Age
0.01 5 1 1 -1 99 -4 0 0 0 0 0 0 0 # Age_Key_Parm_7_Power_Fxn_Coef_Btwn_P5_P6 (0 = Linear)

Seasonal_effects_on_biology_parms
0 0 0 0 0 0 0 0 0 0 #_femwtlen1,femwtlen2,mat1,mat2,fec1,fec2,Malewtlen1,malewtlen2,L1,K

MG_Deviations Parm Phase (CONDITIONAL, if any MG parameters use annual-devs, then estimation for the deviations will begin in this phase)
#4

Spawner-recruit parameters
3 #_SR_function: 2=Ricker; 3=std_B-H; 4=SCAA; 5=Hockey; 6=B-H_flattop; 7=survival_3Parm
Lo Hi Init Prior Prior Prior Param
bnd bnd value mean type SD phase
4 12 6.85 0 -1 10 1 # Ln(R0) # SR_R0
0.2 1 0.9 0 -1 0.8 -2 # Steepness # SR_steep
0 2 0.8 0 -1 0.8 -3 # Sigma R # SR_sigmaR
-5 5 0 0 -1 1 -3 # Environmental link coefficient # SR_envlink
-5 5 0 0 -1 1 -4 # Initial equilibrium offset to virgin # SR_R1_offset
0.0 0.5 0.0 0 -1 99 -2 #_Reserve for future autocorrelation # SR_autocorr

Spawner-recruit set-up
0 #_SR_env_link
0 #_SR_env_target_0=none;1=devs;_2=R0;_3=steepness

1 # do_recr_dev: 0=none; 1=devvector; 2=simple deviations
1990 # first year of main recr_devs; early devs can preceed this era
2016 # last year of main recr_devs; forecast devs start in following year
3 #_recdev phase
1 # (0/1) to read 13 advanced options
-10 #_recdev_early_start (0=none; neg value makes relative to recdev_start)
4 #_recdev_early_phase
0 #_forecast_recruitment phase (incl. late recr) (0 value resets to maxphase+1)
1000 #_lambda for prior_fore_recr occurring before endyr+1
1966 #_last_early_yr_nobias_adj_in_MPD
1996 #_first_yr_fullbias_adj_in_MPD
2016 #_last_yr_fullbias_adj_in_MPD
2024 #_first_recent_yr_nobias_adj_in_MPD
0.98 #_max_bias_adj_in_MPD
0.0 # period for recruitment cycles - use only if modelling seasons as years
-15 #min rec_dev
15 #max rec_dev
0 #_read_recdevs
End of advanced SR options

#Fishing Mortality info
0.1 # F ballpark for tuning early phases
2000 # F ballpark year (neg value to disable)
3 # F_Method: 1=Pope; 2=instan. F; 3=hybrid (hybrid is recommended)
4 # max F or harvest rate, depends on F_Method
5 #N iterations for tuning F in hybrid method (recommend 3 to 7)

Initial_F_parms
#LO HI INIT PRIOR PR_type SD PHASE
0.00 0.1 0.07 0 -1 99 1 # Long_Line
0.00 0.1 0.02 0 -1 99 1 # Haul_Seine

```
0.00    0.1 0.02    0       -1      99      1       # Comm_Other
0.00    0.1 0.04    0       -1      99      1       # RR_Pink
0.00    0.1 0.03    0       -1      99      1       # RR_Adult
0.00    0.1 0.01    0       -1      99      1       # Rec_Other

# 0     1   0.0     0       -1      99      -1      # Long_Line
# 0     1   0.0     0       -1      99      -1      # Haul_Seine
# 0     1   0.0     0       -1      99      -1      # Comm_Other
# 0     1   0.0     0       -1      99      -1      # RR_Pink
# 0     1   0.0     0       -1      99      -1      # RR_Adult
# 0     1   0.0     0       -1      99      -1      # Rec_Other

# Q_setup
# Q_type options:  <0=mirror, 0=float_nobiasadj, 1=float_biasadj, 2=parm_nobiasadj, 3=parm_w_random_dev, 4=parm_w_randwalk, 5=mean_unbiased_float_assign_to_parm
0 0 0 0 # 1 Long_Line
0 0 0 0 # 2 Haul_Seine
0 0 0 0 # 3 Comm_Other
0 0 0 0 # 4 RR_Pinky
0 0 0 0 # 5 RR_Adult
0 0 0 0 # 6 Rec_Other
0 0 0 0 # 7 Zero_Survey
```

```
# Size_selex_types
# Discard_options:_0=none;_1=define_retention;_2=retention&mortality;_3=all_discarded_dead
# Pattern Discard Male Special
1    0   0   0   # 1 Long_Line
24  0   0   0   # 2 Haul_Seine
5    0   0   2   # 3 Comm_Other
24  0   0   0   # 4 RR_Pinky
1    0   0   0   # 5 RR_Adult
5    0   0   5   # 6 Rec_Other
33  0   0   0   # 7 Zero_Survey

# Age_selex_types
# Pattern :: Male Special
10 0 0 0 # 1 Long_Line
10 0 0 0 # 2 Haul_Seine
10 0 0 0 # 3 Comm_Other
10 0 0 0 # 4 RR_Pinky
10 0 0 0 # 5 RR_Adult
10 0 0 0 # 6 Rec_Other
10 0 0 0 # 7 Zero_Survey

# Size_selex_parms
# LO    HI      INIT    PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn

# Size_Selex_Parms 1: Long_Line (Logistic)
30      60      48      0       -1      99      2   0   0   0   0   0.5     0   0   # 1 Inflection point
6       18      12      0       -1      99      3   0   0   0   0   0.5     0   0   # 2 Width

# Size_Selex_Parms 2: Haul_Seine (Double Normal)
 18     30       23     0       -1      99      2   0   0   0   0   0.5     0   0   # 1 Peak
-10      0       -4     0       -1      99      3   0   0   0   0   0.5     0   0   # 2 Top
-3       1       -1     0       -1      99      4   0   0   0   0   0.5     0   0   # 3 Asc - width
 0       5       2.5    0       -1      99      3   0   0   0   0   0.5     0   0   # 4 Desc - width
-25     -10     -15     0       -1      99      5   0   0   0   0   0.5     0   0   # 5 Init
-5       5        0     0       -1      99      5   0   0   0   0   0.5     0   0   # 6 Final
```

Size_Selex_Parms 3: Comm_Other (Mirror 2: Haul_Seine)
0 0 0 0 -1 99 -1 0 0 0 0 0.5 0 0 # 1 Inflection point
0 0 0 0 -1 99 -1 0 0 0 0 0.5 0 0 # 2 Width

Size_Selex_Parms 4: RR_Pinky (Double Normal)
15 35 25 0 -1 99 2 0 0 0 0 0.5 0 0 # 1 Peak
-20 10 -15 0 -1 99 3 0 0 0 0 0.5 0 0 # 2 Top
-1 5 2 0 -1 99 4 0 0 0 0 0.5 0 0 # 3 Asc - width
-1 7 3 0 -1 99 3 0 0 0 0 0.5 0 0 # 4 Desc - width
-10 0 -5 0 -1 99 5 0 0 0 0 0.5 0 0 # 5 Init
-5 1 -2 0 -1 99 5 0 0 0 0 0.5 0 0 # 6 Final

Size_Selex_Parms 5: RR_Adult (Logistic)
30 46 38 0 -1 99 2 0 0 0 0 0.5 0 0 # 1 Inflection point
15 25 20 0 -1 99 3 0 0 0 0 0.5 0 0 # 2 Width

Size_Selex_Parms 6: Rec_Other (Mirror 5: RR_Adult)
0 0 0 0 -1 99 -1 0 0 0 0 0.5 0 0 # 1
0 0 0 0 -1 99 -1 0 0 0 0 0.5 0 0 # 2

Size_Selex_Parms 7: Otter_Survey (Double Normal)
No parms required here: set as Special Selectivity Pattern 33; Expecting only 0+ fish.

Cond: Custom_sel-env_setup
Cond: 2 2 0 0 -1 99 -2 #_placeholder when no enviro fxns

Cond: Selex time-block setup:
#1 #(0=Read one line apply all, 1=read one line each parameter)

Tag loss and tag reporting
0 # 0=no read; 1=read if tags exist

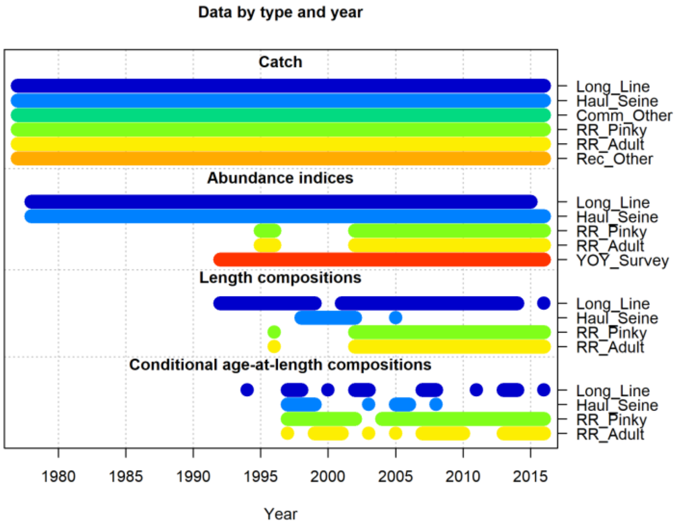
Likelihood related quantities
Variance adjustments to input values

```
1 #_Variance_adjustments_to_input_values
# Fleets 1, 2, 3, 4, 5, 6, and Survey 7
0.000 0.000 0.000 0.000 0.000 0.000 0.000   # constant added to survey CV
0.000 0.000 0.000 0.000 0.000 0.000 0.000   # constant added to discard SD
0.000 0.000 0.000 0.000 0.000 0.000 0.000   # constant added to body weight SD
1.000 1.000 1.000 1.000 1.000 1.000 1.000   # multiplicative scalar for length comps
1.000 1.000 1.000 1.000 1.000 1.000 1.000   # multiplicative scalar for agecomps
1.000 1.000 1.000 1.000 1.000 1.000 1.000   # multiplicative scalar for length at age obs

2   # Max number of lambda phases: read this number of values for each component below
1   # SD offset (CPUE, discard, mean body weight, recruitment devs): 0=omit log(s) term, 1=include

13 # number of changes to make to default Lambdas (default value is 1.0)
# Like_comp codes:  1=surv; 2=disc; 3=mnwt; 4=length; 5=age; 6=SizeFreq; 7=sizeage; 8=catch;
# 9=init_equ_catch; 10=recrdev; 11=parm_prior; 12=parm_dev; 13=CrashPen; 14=Morphcomp; 15=Tag-comp; 16=Tag-negbin
#like_comp fleet/survey  phase  value  sizefreq_method

# Lambda values for length data
4   1   1   0.50    1
4   2   1   0.50    1
4   4   1   0.50    1
4   5   1   0.50    1
```

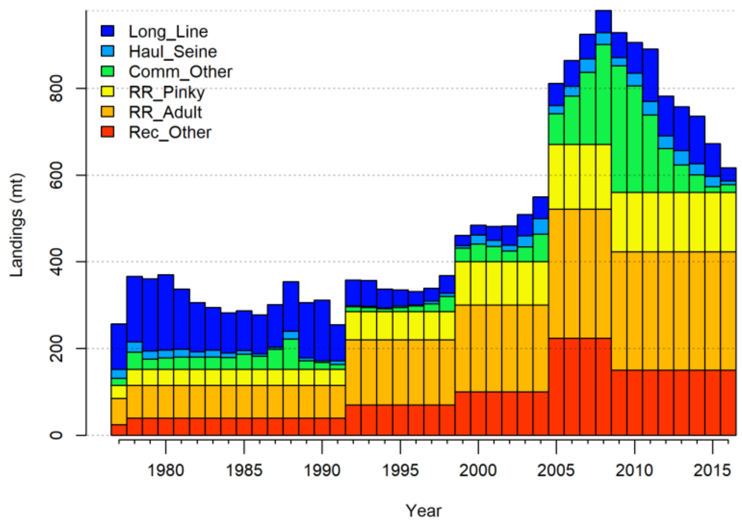
Lambda values for age data
5 1 1 0.50 1
5 2 1 0.50 1
5 4 1 0.50 1
5 5 1 0.50 1
Lambda values for indices (surveys)
1 1 1 1.0 1
1 2 1 1.0 1
1 4 1 1.0 1
1 5 1 1.0 1
1 7 1 2.0 1

0 # (0/1) read specs for more stddev reporting
999 # EOF

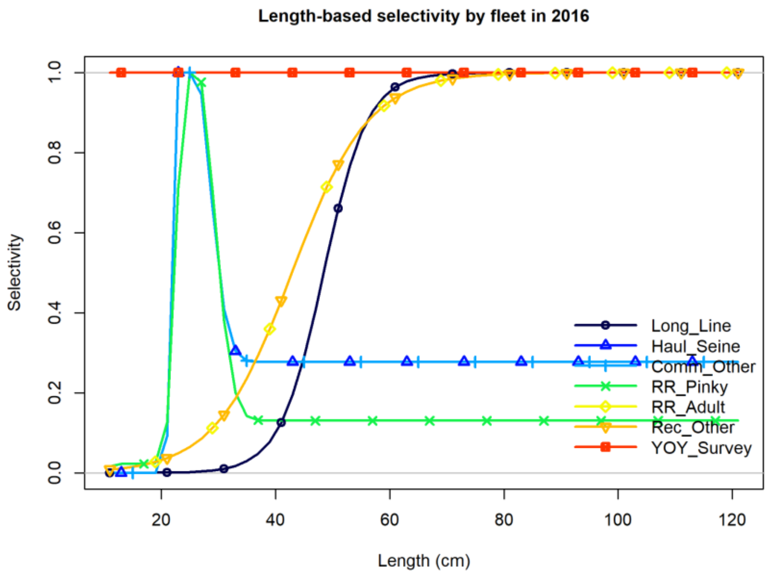
Figures summarising data inputs, model fits, and biomass estimates from SnapAssess.



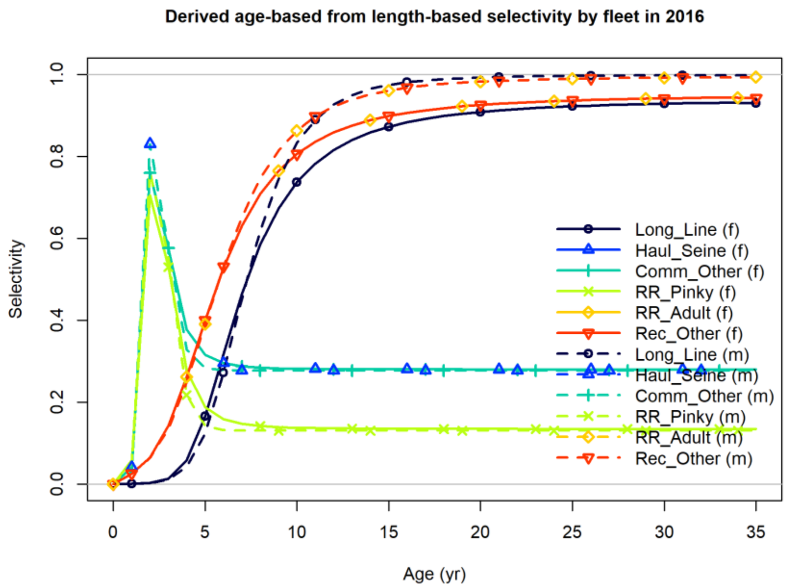
Appendix 3, Figure 1. Summary of data used for the SnapAssess 2016 base case model used to condition the OM in the MSE experiments.



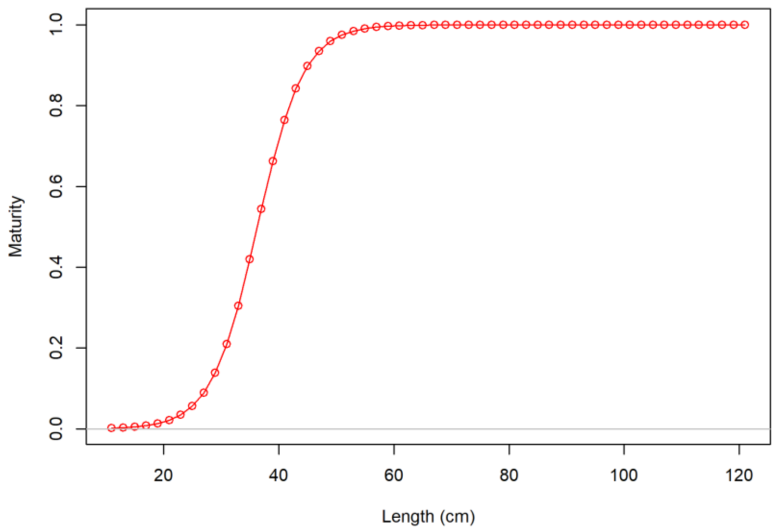
Appendix 3, Figure 3. Summary of catch history used for the SnapAssess 2016 base case model used to condition the OM in the MSE experiments.



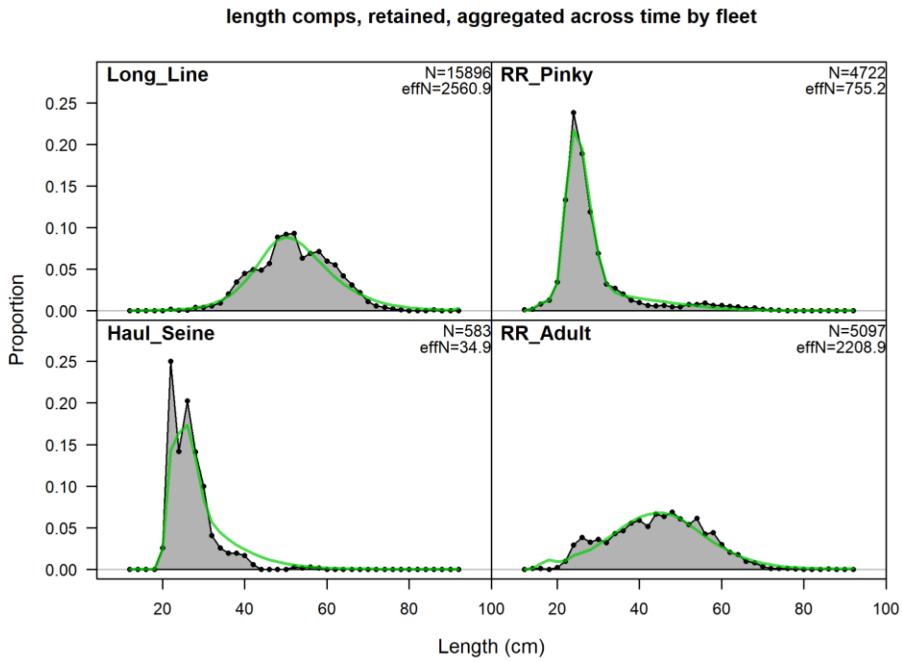
Appendix 3, Figure 4. Fleet selectivity patterns by length (fork length, FL) used for the SnapAssess 2016 base case model that was used for condition the OM in the MSE experiments.



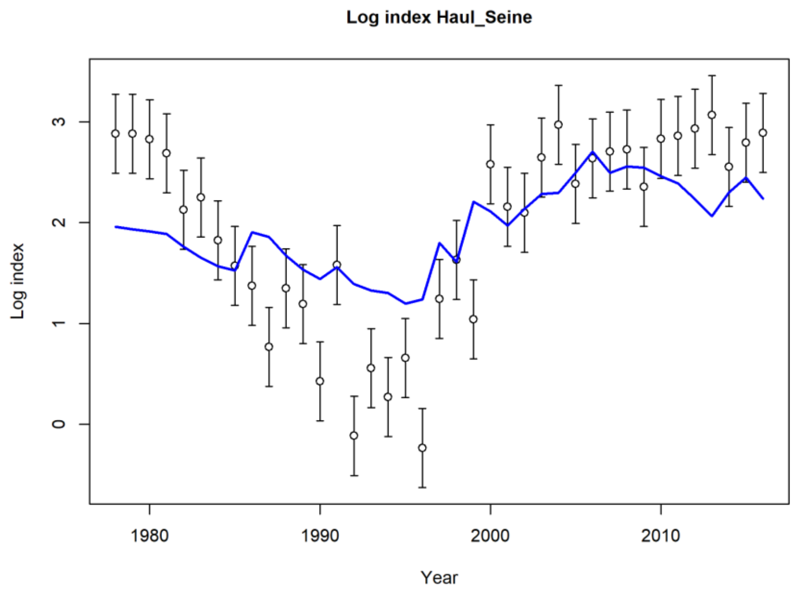
Appendix 3, Figure 5. Derived fleet selectivity patterns by age from the SnapAssess 2016 base case model used to condition the OM in the MSE experiments.



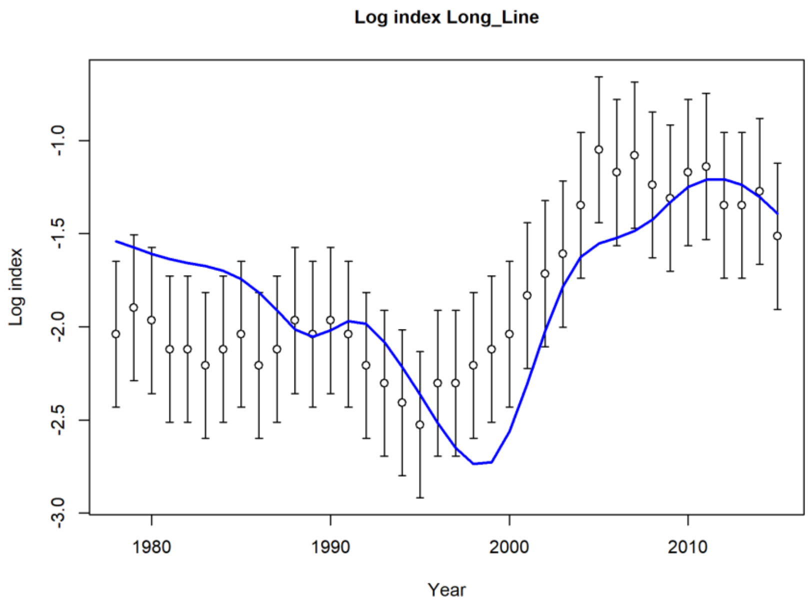
Appendix 3, Figure 6. Length at maturity ogive for Snapper applied in the SnapAssess 2016 base case model used to condition the OM in the MSE experiments.



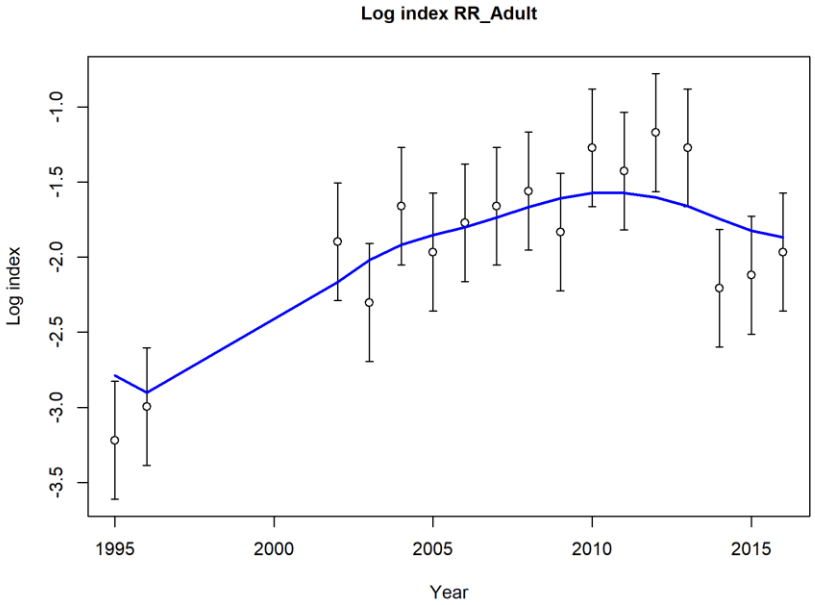
Appendix 3: Figure 7. SnapAssess base case model fits (green lines) to aggregated length composition data (grey).



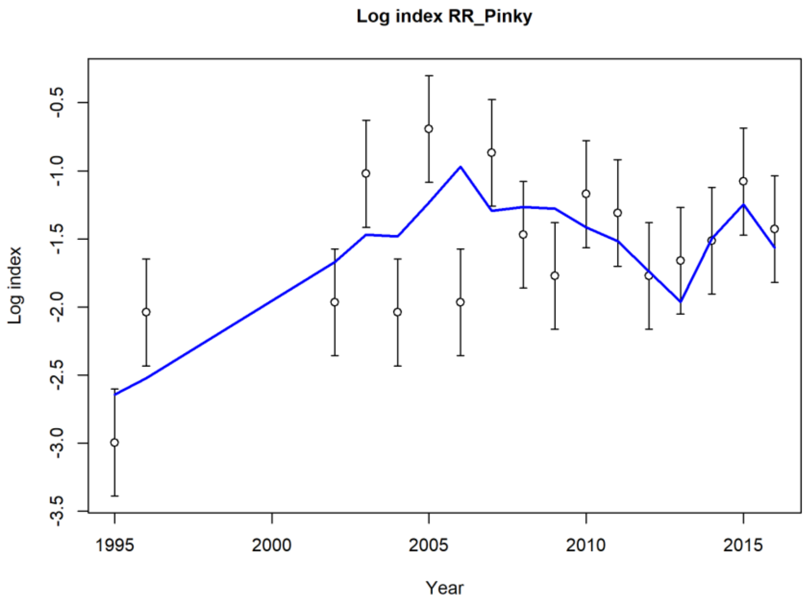
Appendix 3: Figure 8. SnapAssess base case model fits (blue line) to Port Phillip Bay commercial haul seine CPUE index.



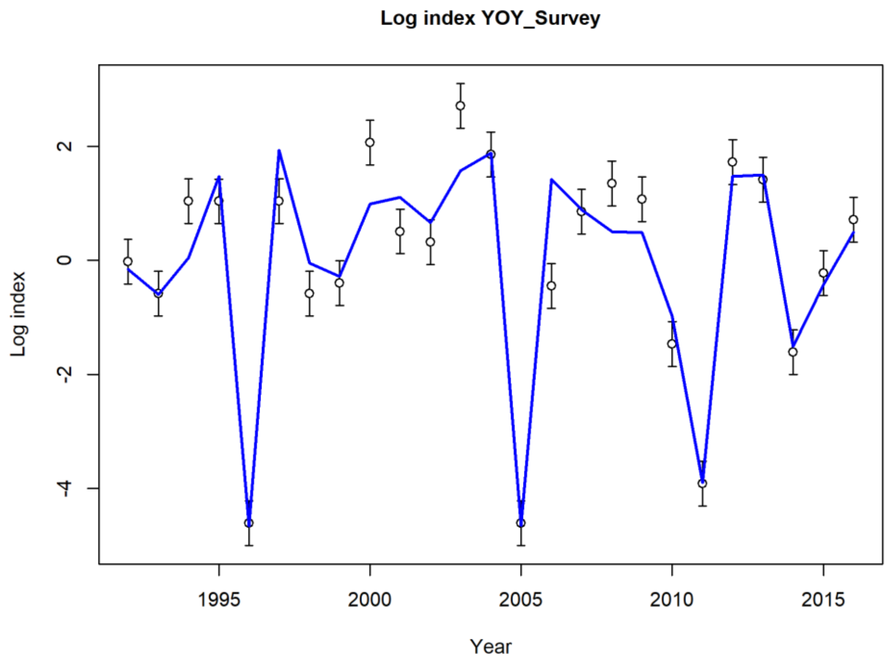
Appendix 3: Figure 8. SnapAssess base case model fits (blue line) to Port Phillip Bay commercial long-line standardised CPUE index.



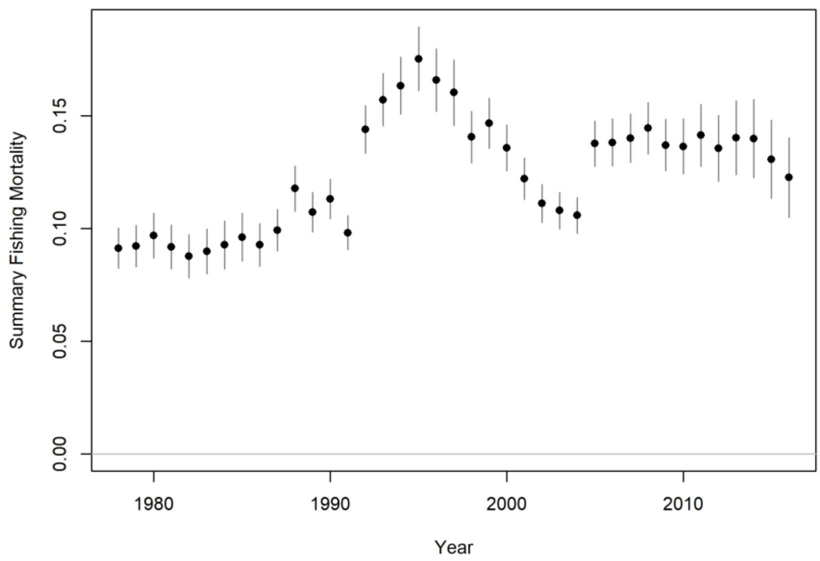
Appendix 3: Figure 9. SnapAssess base case model fits (blue line) to Port Phillip Bay recreational "adult" fishery CPUE index.



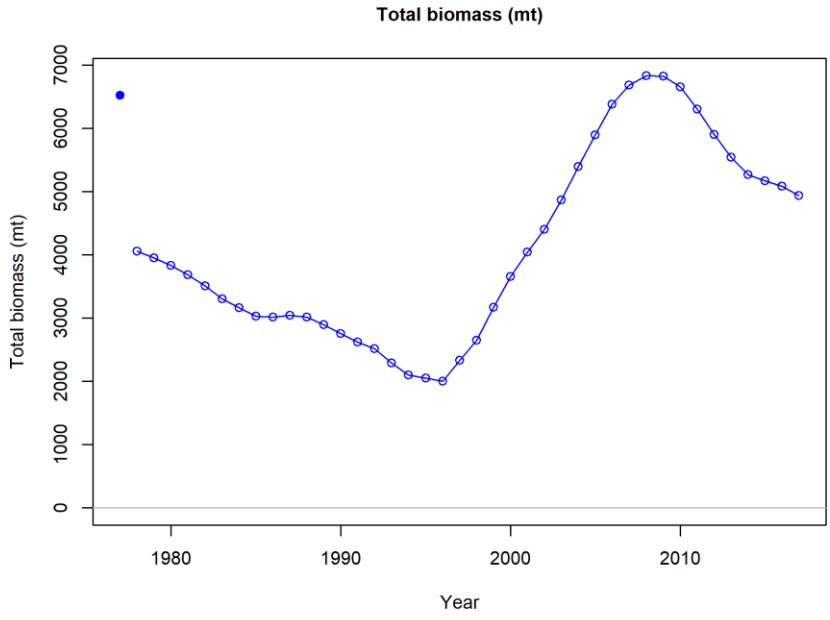
Appendix 3: Figure 10. SnapAssess base case model fits (blue line) to Port Phillip Bay recreational 'Pinky' fishery CPUE index.



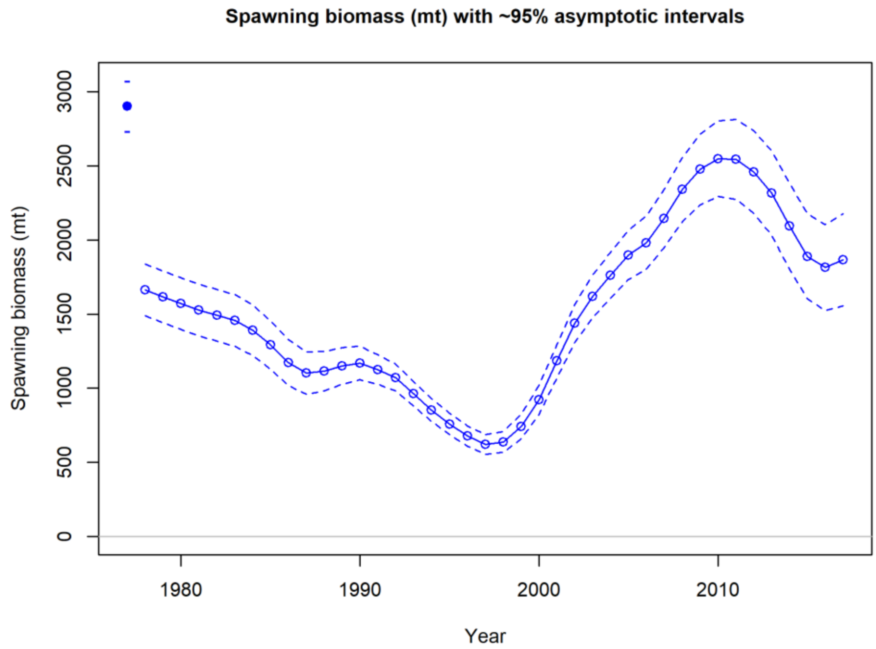
Appendix 3: Figure 11. SnapAssess base case model fits (blue line) to YOY (0+ age) fishery independent trawl survey CPUE index.



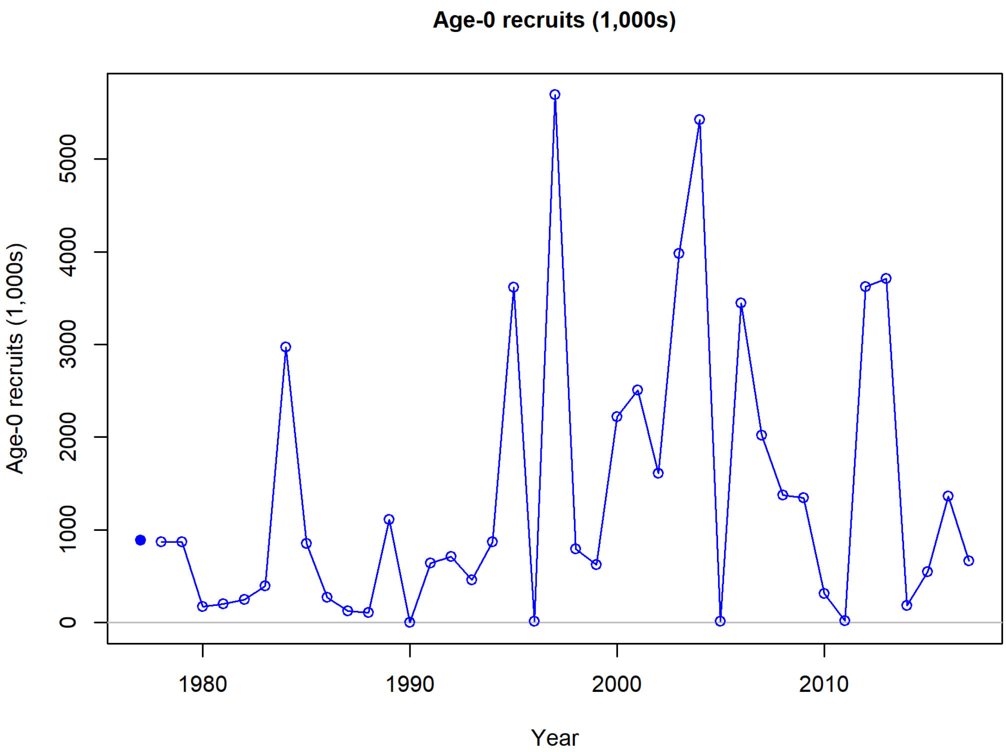
Appendix 3: Figure 12. SnapAssess base case model predictions of fishing mortality.



Appendix 3: Figure 13. SnapAssess base case model predictions of total biomass.



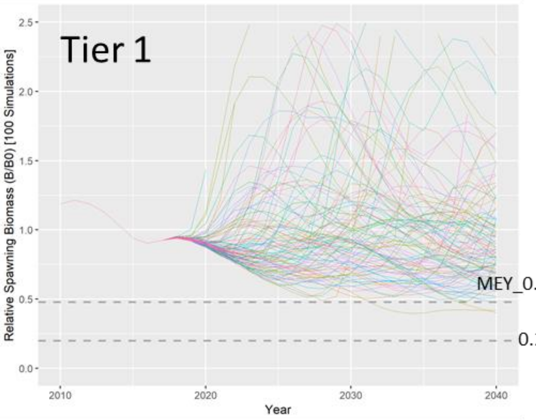
Appendix 3: Figure 14. SnapAssess base case model predictions of **female** spawning biomass.

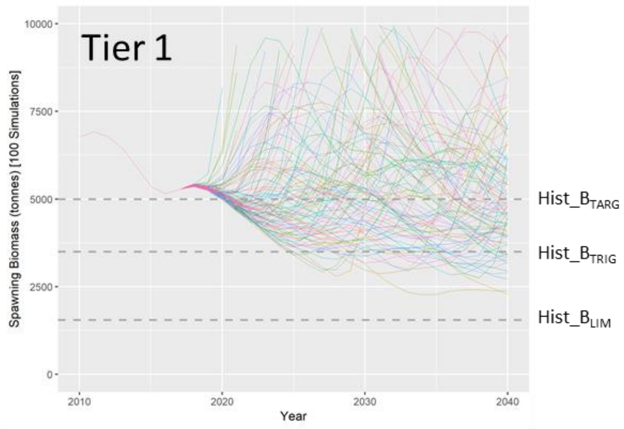


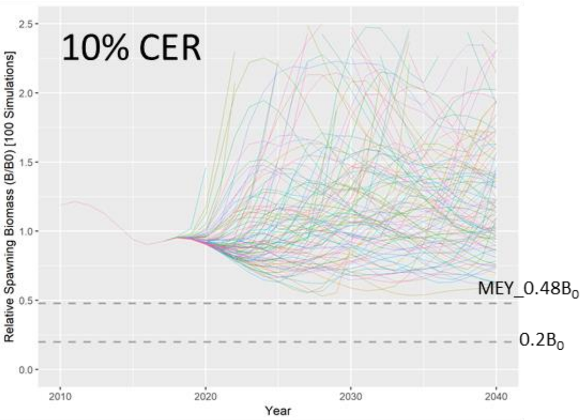
Appendix 3: Figure 15. SnapAssess base case model predictions of **0**+ age recruitment.

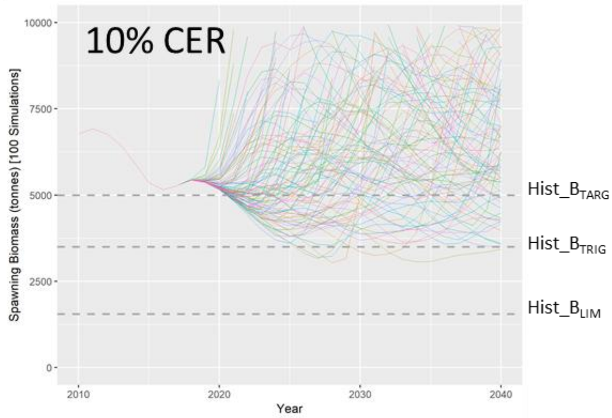
Appendix 4: MSE spawning biomass trajectories for all simulation runs

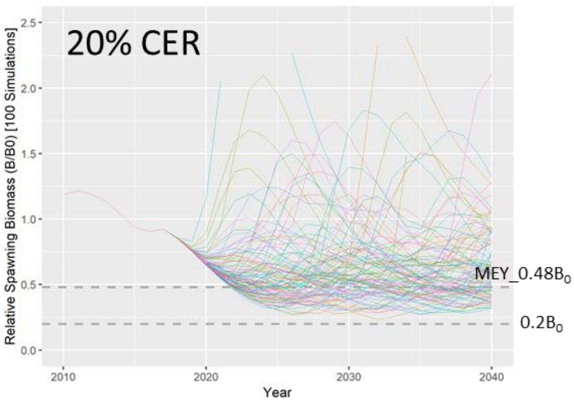
a) MSE spawning biomass trajectories for all 100 simulations: **Recruitment Scenario A - High**

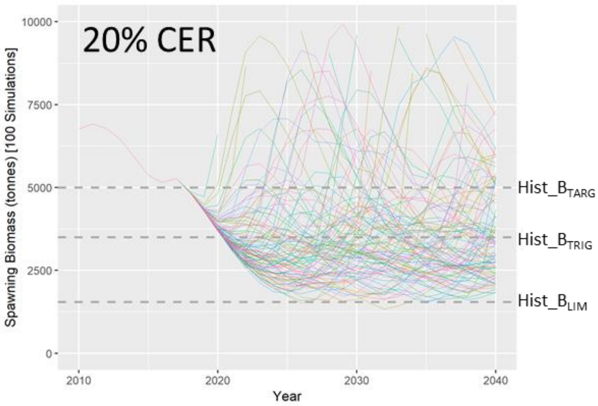


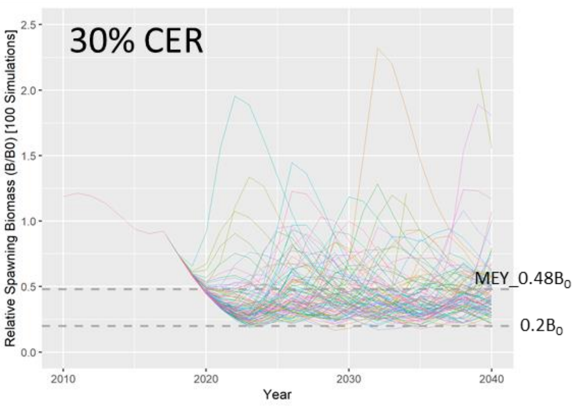


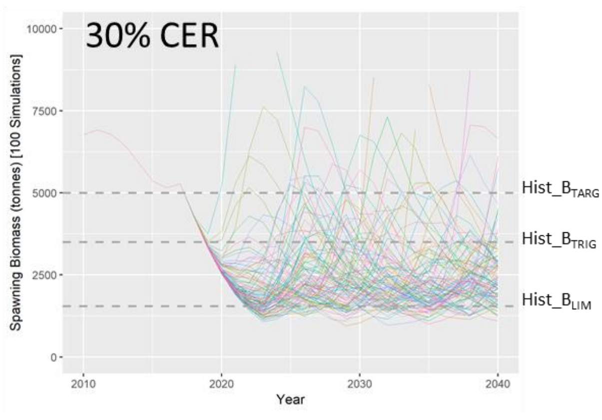




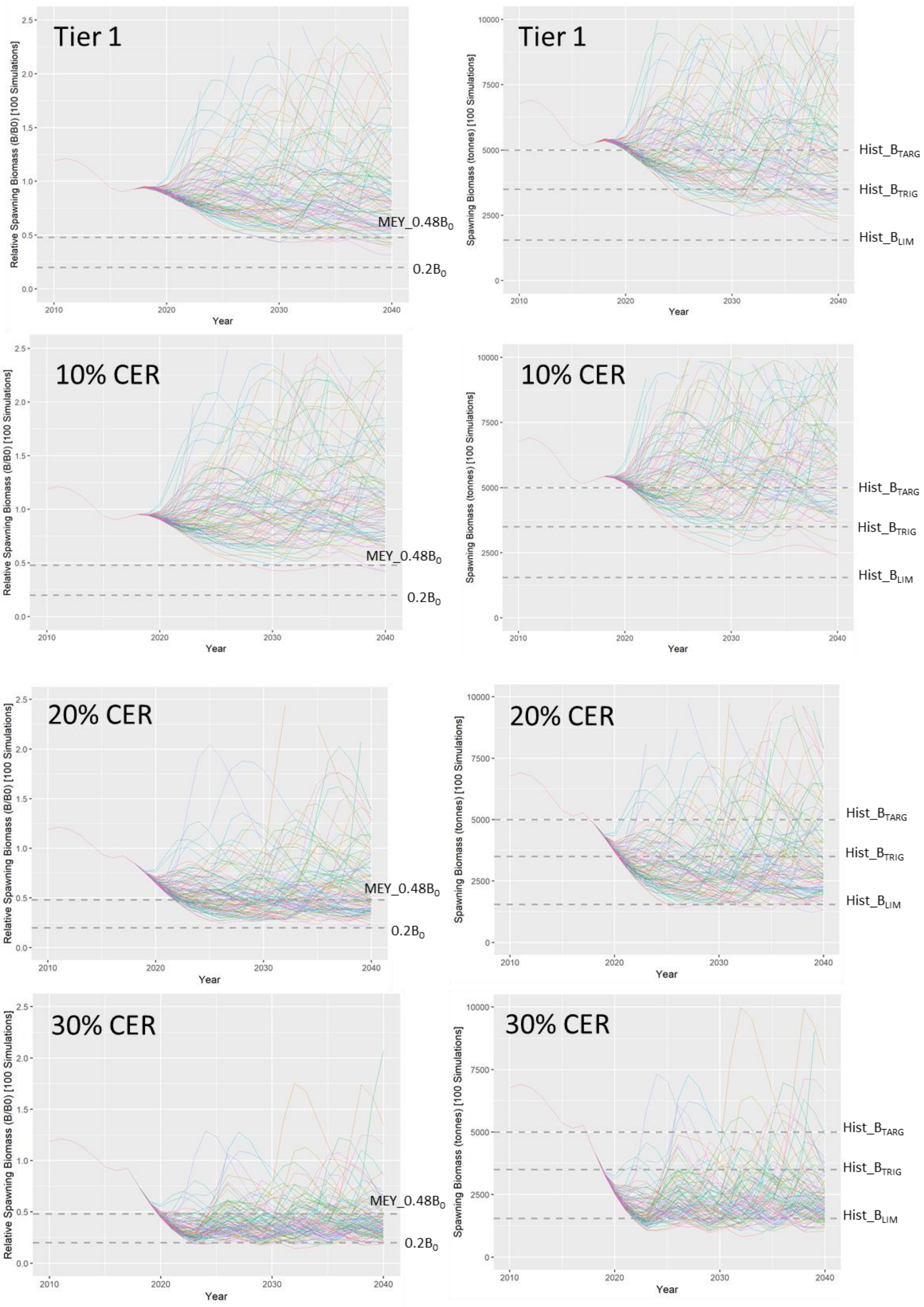




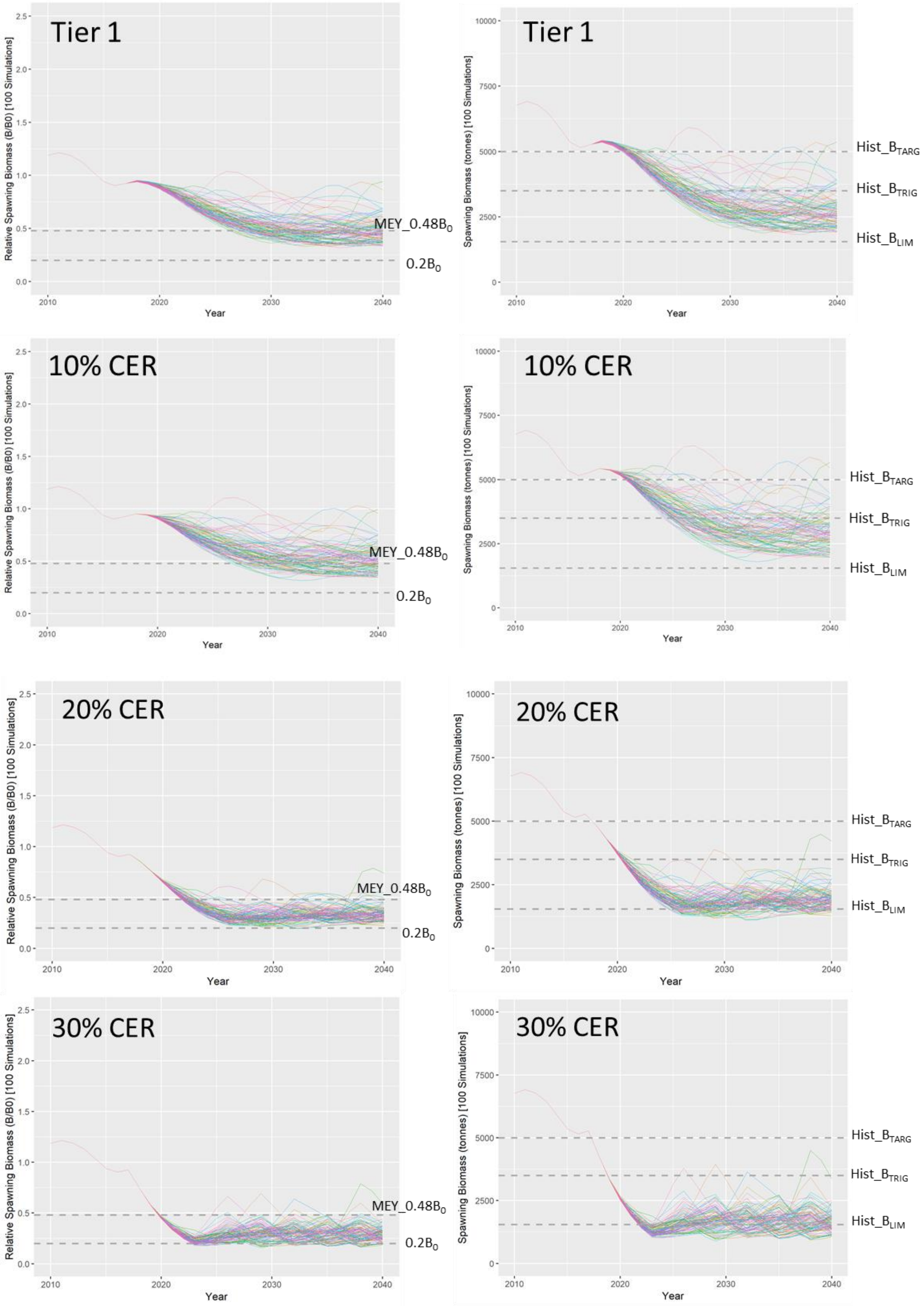




b) MSE spawning biomass trajectories for all 100 simulations: **Recruitment Scenario B - Average**



c) MSE spawning biomass trajectories for all 100 simulations**: Recruitment Scenario C - Low**



Appendix 5: SnapMat R Script

```
################################################################################
# Snap-MAT: Snapper Management Advice Tool
# developed for Fisheries Victoria [Snapper MSE FRDC Project 2018]
# by Athol Whitten, Mezo Research
# contact mezo@mezo.com.au
################################################################################

#------------------------
# Load Packages and Data
#------------------------

# Load required packages:
library(tidyr)
library(ggplot2)
library(splitstackshape)
library(lubridate)
library(dplyr)
library(reshape2)

# Read raw data from file:
creel_raw <- read.csv("./data/ppb-wpb-creel.csv", header = TRUE)
lf_raw <- read.csv("./data/ppb-wpb-lf-rec.csv", header = TRUE)

# Specify whether to show plots on screen (TRUE) or just record for reporting (FALSE):
show_plots <- FALSE


#--------------------
# Snap-MAT Controls
#--------------------

# Set species, target species, zone, season (fishery), and years:
species       <- "Snapper"
targetspecies <- "All"        # Targetspecies can be "All" or some nominated species (e.g. Snapper)
zone          <- "PPB"        # Zone can be PPB, WPB, or both c("PPB", "WPB")
subzone       <- "NE"         # Zone can be NE, SE, SW (for PPB) or WP (for WPB), or "All"
season        <- "Adult"      # Fishery is represented by season, can be "Pinky" or "Adult" or both
c("Adult", "Pinky")
finyears      <- 2014:2017    # Years are Financial Years, where FY2017 begins July 2017 (i.e.
17/18)

# Set management controls (numbers and total length):
bag_size_a <- 8  # Total allowable bag size [RULE = 10]
bag_size_b <- 2   # Total allowable sub-bag size [RULE = 3]
size_lim_a <- 36  # Legal minimum length (LML, total-length) [RULE = 28]
size_lim_b <- 38  # Can have bag_size_b equal to or greater than this length [RULE = 40]

# Set current size limit (as per data supplied):
lml <- 28

# Set post release mortality values:
prm_val_a <- 0.1  # This value for all fish less than prm_size
prm_val_b <- 0.2  # This value for all fish greater than or equal to prm_size
prm_size  <- 40   # This size in cm, total length of prm split point

# Weight at length parameters (for total length):
wa <- 0.000023
wb <- 2.8625

#------------------------------------
# Data Wrangling and Plotting (CREEL)
#------------------------------------

# Filter raw creel data, select only required columns:
creel <- select(
  creel_raw,
  one_of(c("Interviewdate", "Interviewer", "year", "month")),
  starts_with("Targetsp"),
  one_of(c(species, "Location", "Snap_MAT_area", "season", "Nofishermen", "Hourfished", "Recordno"))
)

# Rename variables as required:
creel <- rename(creel, Year = year) %>%
        rename(Month = month) %>%
        rename(Zone = Location) %>%
        rename(Subzone = Snap_MAT_area) %>%
        rename(Season = season) %>%
        rename(N_Anglers = Nofishermen)

# Create financial year column from Year and Month:
creel <- mutate(creel, Finyear = creel$Year - as.numeric(creel$Month <= 6))

# Change variable class to factor as required:
creel$Year <- as.factor(creel$Year)
creel$Finyear <- as.factor(creel$Finyear)

# Replace season variable with names:
creel$Season[creel$Season == 1] <- "Adult"
creel$Season[creel$Season == 2] <- "Pinky"
creel$Season[creel$Season == 3] <- "Winter"

# NOTE: CREEL & LF DATA HAS THREE SEASONS
# 1 (Adult) is Oct thru Dec
# 2 (Pinky) is Jan thru May
# 3 (Winter) is Jun thru Sept, winter sampling only done between 2006 and 2011

# Filter creel data by options set above:
creel <- filter(creel, Finyear %in% finyears) %>%
        filter(Zone %in% zone) %>%
        filter(Season %in% season) %>%
        filter(N_Anglers > 0) %>%
        filter(Recordno == 1)

if (targetspecies != "All"){
        creel <- filter(creel, Targetspecies %in% targetspecies)
}

if (subzone != "All"){
        creel <- filter(creel, Subzone %in% subzone)
}

# Create a histogram of the number of Snapper kept (per boat interview):
plot_nkept <- ggplot(creel, aes(Snapper)) +
  geom_histogram(binwidth = 1, fill = "darkorange", colour = "white") +
  xlab("No. Snapper Kept Per Boat Interview") + ylab("Count") + xlim(-1, 15)

if (show_plots) show(plot_nkept)


#---------------------------------
# Data Wrangling and Plotting (LF)
```

```r
#-----------------------------------

# Remove NA values (if any) from length frequency data:
lf <- filter(lf_raw,
             !is.na(Snap_Total_length))

# Create financial year column from Year and Month:
lf <- mutate(lf, Finyear = lf$year - as.numeric(lf$month <= 6))

# Rename and modify variables and add new columns:
lf <- mutate(lf, Finyear = factor(Finyear)) %>%
        rename(Zone = Location) %>%
        mutate(Zone = factor(Zone)) %>%
        rename(Subzone = Snapmat_subarea) %>%
        mutate(Subzone = factor(Subzone)) %>%
        rename(Season = season.CDP) %>%
        mutate(Snap_Total_length = floor(Snap_Total_length)) %>%
        rename(Total_Length = Snap_Total_length)

# Replace season variable with names:
lf$Season[lf$Season == 1] <- "Adult"
lf$Season[lf$Season == 2] <- "Pinky"
lf$Season[lf$Season == 3] <- "Winter"

# NOTE: CREEL & LF DATA HAS THREE SEASONS
# 1 (Adult) is Oct thru Dec
# 2 (Pinky) is Jan thru May
# 3 (Winter) is Jun thru Sept, winter sampling only done between 2006 and 2011

# Filter data by options set above:
lf <- filter(lf, Finyear %in% finyears) %>%
        filter(Zone %in% zone) %>%
        filter(Season %in% season)

if (targetspecies != "All"){
        lf <- filter(lf, Targetspecies %in% targetspecies)
}

if (subzone != "All"){
        lf <- filter(lf, Subzone %in% subzone)
}

# Create faceted histogram of length composition by year, for each season:
plot_lf_byrf <- ggplot(lf, aes(x = Total_Length, y = ..density.., fill = Season)) +
  geom_histogram(binwidth = 1.0, colour = "white") +
  facet_grid(Finyear ~ Season) +
  labs(x = "Total Length", y = "Proportion") +
  theme(panel.grid.minor = element_blank())

if (show_plots) show(plot_lf_byrf)

# Get and plot LF comp for aggregated years per fishery and by zone
plot_lf_comp_ag <- ggplot(lf, aes(x = Total_Length, y = ..density.., fill = Season)) +
  geom_histogram(binwidth = 1.0, colour = "white") +
  facet_wrap(~Season) +
  labs(x = "Total Length", y = "Proportion") +
  theme(panel.grid.minor = element_blank())

if (show_plots) show(plot_lf_comp_ag)



#-----------------------------------------------------
# Length Frequency Proportions for Size Limit Changes
#-----------------------------------------------------

# Calculate proportions required for application of size limit changes:
count_lf <- count(lf, Total_Length)
count_lf_n <- summarise(count_lf, Total = sum(n))
count_n_sum <- as.numeric(count_lf_n)
```

```r
# Add column for proportions by zone:
count_lf <- mutate(count_lf, Prop = (n / count_n_sum))

# Check proportions add to one:
sum(count_lf$Prop) == 1

# Get vectors to apply across bins for proportion removed:
prop_lf <- as.data.frame(as.vector(count_lf[, c("Total_Length", "Prop")]))


#-----------------------------------------------------
# With Creel Data: Get Allocated Bag Size per Angler
#-----------------------------------------------------

# Create function to allocate bag to each individual angler:
get_bag <- function(nkept, nanglers) {
  quo <- nkept %/% nanglers
  bag <- rep(quo, nanglers)
  mod <- nkept %% nanglers
  if (mod > 0) bag[1:mod] <- bag[1:mod] + 1
  return(bag)
}

# Apply function to each row of creel data_frame (with n_fish_kept, and n_anglers):
bags_list <- apply(creel[, c(species, "N_Anglers")], 1,
                   function(x) get_bag(x[species], x["N_Anglers"]))

# Create vector of allocated bags, and add to expanded creel data_frame:
bags <- as.numeric(unlist(bags_list))
creel_exp <- expandRows(creel, "N_Anglers", drop = FALSE)
creel_bags <- cbind(creel_exp, Bag = bags)

# Create a histogram of the number of Snapper kept (per angler, bag sizes):
plot_nkept_angler <- ggplot(creel_bags, aes(Snapper)) +
        geom_histogram(binwidth = 1, fill = "darkorange", colour = "white") +
        xlab("No. Snapper Kept Per Angler") + ylab("Count") + xlim(-1, 7.5)

if (show_plots) show(plot_nkept_angler)

#-------------------------------------------------
# Calculate Numbers and Proportions per Bag Size
#-------------------------------------------------

# Count number of angler trips for each bag size:
count_bags <- as.data.frame(count(creel_bags, Bag))
count_bags <- rename(count_bags, N_Bags = n)

# Get number of fish per bag size:
count_bags <- mutate(count_bags, N_Fish = Bag * N_Bags)

# Get numbers at length for each bag size:
nlf <- prop_lf
for (i in 1:length(count_bags$N_Fish)) {
  n_bag <- nlf$Prop * count_bags$N_Fish[i]
  nlf <- cbind(nlf, n_bag)
  names(nlf)[i + 2] <- paste0("N_Bag_Size_", i - 1)
}


#----------------------------------
# Calculate Total Biomass Sampled
#----------------------------------

# Get numbers, weight, and then biomass (nwb) at each length:
nlf_nwb <- mutate(nlf, N = rowSums(nlf[,-(1:2)])) %>%
        mutate(Weight = wa * (nlf$Total_Length ^ wb)) %>%
        mutate(Biomass = N * Weight)

sample_biomass = sum(nlf_nwb$Biomass)

#-----------------------------------------
# Bag and Size Limit Change Calculations
#-----------------------------------------
```

```
# Begin with size check, if new size limit greater than LML, run size limit change calcs:
if(size_lim_a > lml){

        # Modify numbers at length, by bag size, by applying new size limit (record new nlf, and
returned nlf):
        new_nlf <- nlf[which(nlf["Total_Length"] >= size_lim_a), ]
        ret_nlf <- nlf[which(nlf["Total_Length"] < size_lim_a), ]

        # Get number dead from post release mortality due to size limit change (by length bin and bag
size):
        ret_nlf_prm <- ret_nlf

        # Adjust length classes below, and then above, PRM split point:
        ret_nlf_prm[which(ret_nlf_prm["Total_Length"] < prm_size), -c(1,2)] <-
                ret_nlf_prm[which(ret_nlf_prm["Total_Length"] < prm_size), -c(1,2)] * prm_val_a

        ret_nlf_prm[which(ret_nlf_prm["Total_Length"] >= prm_size), -c(1,2)] <-
                ret_nlf_prm[which(ret_nlf_prm["Total_Length"] >= prm_size), -c(1,2)] * prm_val_b


        # Get numbers, weight, and then biomass (nwb) at each length for returned fish subject to
PRM:
        ret_nlf_prm_nwb <- mutate(ret_nlf_prm, N = rowSums(ret_nlf_prm[,-(1:2)])) %>%
                mutate(Weight = wa * (ret_nlf_prm$Total_Length ^ wb)) %>%
                mutate(Biomass = N * Weight)

        prm_biomass <- sum(ret_nlf_prm_nwb$Biomass)

} else {

        # If new size limit is not greater than LML, new NLF is unmodified, and inherits NLF:
        new_nlf <- nlf

        # Post-release biomass is therefore zero:
        prm_biomass <- 0
}


# Get column sums (total number of fish) for new numbers at length (by bag size, retained):
new_nlf_sums <- as.numeric(round(colSums(new_nlf)[-(1:2)]))

# Distribute new numbers of fish back into bag sizes (size limit applied):
n_bags_sla <- new_nlf_sums %/% count_bags$Bag
n_bags_sla[1] <- 0

# Get extra fish that do not re-distribute evenly back to bags:
ex_bags_sla <- new_nlf_sums %% count_bags$Bag
ex_bags_sla[1] <- 0

# Allocate extra fish as new bags, count number of each extra bag by size:
ex_bags_add <- hist(ex_bags_sla, breaks = c(-1, count_bags$Bag), plot = FALSE)$counts
ex_bags_add[1] <- 0

# Add new columns with size limit applied (SLA):
count_bags_sla <- mutate(count_bags,
        N_Fish_SLA = new_nlf_sums,
        N_Bags_SLA = n_bags_sla + ex_bags_add)

# Get change in total catch from reduction in bag size:
count_bags_new <- count_bags_sla[which(count_bags_sla["Bag"] <= bag_size_a), ]
add_bags <- sum(count_bags_sla$N_Bags_SLA[which(count_bags_sla["Bag"] > bag_size_a)])
bag_row <- nrow(count_bags_new)

# Update new bags data_frame with adjusted numbers:
count_bags_new <- mutate(count_bags_new, N_Bags_BSA = N_Bags_SLA)
count_bags_new["N_Bags_BSA"][bag_row, ] <- count_bags_new["N_Bags_BSA"][bag_row, ] + add_bags

# Get new equivalent number of fish given adjusted bags:
count_bags_new <- mutate(count_bags_new, N_Fish_BSA = Bag * N_Bags_BSA)

# Get number of fish 'not caught' after total bag size adjustment:
n_fish_bsa_not_caught <- sum(count_bags_sla$N_Fish_SLA) - sum(count_bags_new$N_Fish_BSA)
```

```
# NOTE: BAG SIZE CHANGES SHOULD NOT LEAD TO FISH RETURNS, ONLY TO FEWER FISH BEING CAUGHT!
# Thus this section not subject to PRM calculations.


# Sub-Bag and Max-Size Limit Change Calculations:
# ================================================

# Get updated proportions at length, calculated from 'new numbers at length' array:
prop_lf_mod_prop <- new_nlf$N_Bag_Size_1 / sum(new_nlf$N_Bag_Size_1)
prop_lf_mod <- data.frame(Total_Length = new_nlf$Total_Length, Prop = prop_lf_mod_prop)

# Check proportions add to one:
sum(prop_lf_mod$Prop) == 1.00

# Get numbers at length for each bag size (for modified count of bags):
nlf_mod <- prop_lf_mod
for (i in 1:length(count_bags_new$N_Fish_BSA)) {
        n_bag <- nlf_mod$Prop * count_bags_new$N_Fish_BSA[i]
        nlf_mod <- cbind(nlf_mod, n_bag)
        names(nlf_mod)[i + 2] <- paste0("N_Bag_Size_", i - 1)
}

# Devide numbers of fish into large and small bag groups (with upper sub-bag size):
nlf_mod_large <- nlf_mod[which(nlf_mod["Total_Length"] >= size_lim_b), ]
nlf_mod_small <- nlf_mod[which(nlf_mod["Total_Length"] < size_lim_b), ]

# Get column sums (total number of fish) for new groups of numbers at length (apply upper bag size):
nlf_mod_large_sums <- as.numeric(round(colSums(nlf_mod_large)[-(1:2)]))
nlf_mod_small_sums <- as.numeric(round(colSums(nlf_mod_small)[-(1:2)]))

# Modify updated bag count dataframe with large and small group numbers:
count_bags_new <- mutate(count_bags_new, N_Fish_Small = nlf_mod_small_sums, N_Fish_Large =
nlf_mod_large_sums)

# Get number of large fish 'not caught' under this scenario (by bag size):
large_fish_not_caught <- count_bags_new$N_Fish_Large - (count_bags_new$N_Bags_BSA * bag_size_b)
large_fish_not_caught[which(large_fish_not_caught < 0)] <- 0

# Get total number of large fish 'not caught' under this scenario:
large_fish_not_caught_total <- sum(large_fish_not_caught)

# Apply upper bag size limit (harvest limit):
count_bags_new <- mutate(count_bags_new, N_Fish_Large_UBSA = N_Fish_Large - large_fish_not_caught)
%>%
                   mutate(N_Fish_UBSA = N_Fish_Small + N_Fish_Large_UBSA)


# NOTE: Excess large fish are removed from the count of fish in the upper bag group.
# These don't get 'returned'; they would not have been caught owing to the new harvest limit.

# Get and plot numbers-at-length (NLF) compared between modified and existing LF:
nlf_compare_a <- nlf[, c(1,2)]
nlf_compare_a <- mutate(nlf_compare_a, Name = 'NLF')

nlf_compare_b <- nlf_mod[, c(1,2)]
nlf_compare_b <- mutate(nlf_compare_b, Name = 'NLF (SLA)')

nlf_compare <- rbind(nlf_compare_a, nlf_compare_b)

plot_nlf_compare <- ggplot(nlf_compare, aes(x = Total_Length, y = Prop, fill = Name)) +
        geom_col(colour = "white") +
        facet_wrap(~Name) +
        labs(x = "Total Length", y = "Proportion") +
        theme(panel.grid.minor = element_blank())

if (show_plots) show(plot_nlf_compare)

#-------------------------------------------------------------
# Calculate Total Retained Biomass Expected after Rule Changes
#-------------------------------------------------------------

# Get numbers, weight, and then biomass (nwb) at each length for small group:
```

```
nlf_mod_small_nwb <- mutate(nlf_mod_small, N = rowSums(nlf_mod_small[, -(1:2)])) %>%
        mutate(Weight = wa * (nlf_mod_small$Total_Length ^ wb)) %>%
        mutate(Biomass = N * Weight)

# Get biomass total of small fish retained:
mod_biomass_small <- sum(nlf_mod_small_nwb$Biomass)

# Get updated proportions at length for large group, calculated from 'new numbers at length' array:
prop_lf_mod_large_prop <- nlf_mod_large$N_Bag_Size_1 / sum(nlf_mod_large$N_Bag_Size_1)
prop_lf_mod_large <- data.frame(Total_Length = nlf_mod_large$Total_Length, Prop =
prop_lf_mod_large_prop)

# Get numbers at length for each bag size (for modified count of bags for large group):
nlf_mod_large_b <- prop_lf_mod_large
for (i in 1:length(count_bags_new$N_Fish_Large_UBSA)) {
        n_bag <- nlf_mod_large_b$Prop * count_bags_new$N_Fish_Large_UBSA[i]
        nlf_mod_large_b <- cbind(nlf_mod_large_b, n_bag)
        names(nlf_mod_large_b)[i + 2] <- paste0("N_Bag_Size_", i - 1)
}

# Get numbers, weight, and then biomass (nwb) at each length for large group:
nlf_mod_large_nwb <- mutate(nlf_mod_large_b, N = rowSums(nlf_mod_large_b[, -(1:2)])) %>%
        mutate(Weight = wa * (nlf_mod_large_b$Total_Length ^ wb)) %>%
        mutate(Biomass = N * Weight)

# Get biomass total of large fish retained:
mod_biomass_large <- sum(nlf_mod_large_nwb$Biomass)

# Get biomass total of small and large fish retained:
mod_biomass_total <- mod_biomass_small + mod_biomass_large

# Add PRM biomass to total biomass retained:
mod_biomass_total <- mod_biomass_total + prm_biomass

#----------------------------------------------------------------------
# Calculate Expected Total Returned or 'Not Caught' Biomass Components
#----------------------------------------------------------------------

# If requiredm, get numbers, weight, and biomass (nwb) of fish 'returned' after size level (LML)
adjustment:
if(size_lim_a > lml){

        ret_nlf_nwb <- mutate(ret_nlf, N = rowSums(ret_nlf[, -(1:2)])) %>%
                mutate(Weight = wa * (ret_nlf$Total_Length ^ wb)) %>%
                mutate(Biomass = N * Weight)

        ret_fish <- sum(ret_nlf_nwb$N)

        ret_biomass <- sum(ret_nlf_nwb$Biomass)

} else {

        ret_biomass <- 0
}

# Get total number of fish 'not caught' after bag size adjustments:
fish_not_caught <- n_fish_bsa_not_caught + large_fish_not_caught_total

# Get numbers, weight, and biomass of fish 'not caught', by length class (after total bag size
adjustment):
nlf_fish_bsa_not_caught <- prop_lf_mod
nlf_fish_bsa_not_caught <- mutate(nlf_fish_bsa_not_caught,
                                    N = n_fish_bsa_not_caught * nlf_fish_bsa_not_caught$Prop) %>%
        mutate(Weight = wa * (nlf_fish_bsa_not_caught$Total_Length ^ wb)) %>%
        mutate(Biomass = N * Weight)

# Get total biomass of large fish 'not caught' after bag size adjustment:
fish_bsa_not_caught_biomass <- sum(nlf_fish_bsa_not_caught$Biomass)


# Get numbers, weight, and biomass of large fish 'not caught', by length class (after upper bag size
adjustment):
nlf_large_fish_not_caught <- prop_lf_mod_large
```

```
nlf_large_fish_not_caught <- mutate(nlf_large_fish_not_caught,
                                N = large_fish_not_caught_total * nlf_large_fish_not_caught$Prop) %>%
                                mutate(Weight = wa * (nlf_large_fish_not_caught$Total_Length ^ wb))
%>%
                                mutate(Biomass = N * Weight)

# Get total biomass of large fish 'not caught' after bag size adjustment:
large_fish_not_caught_biomass <- sum(nlf_large_fish_not_caught$Biomass)

# Get total biomass of fish 'not caught' after size limit changes and both bag size adjustments:
biomass_not_caught <- sum(ret_biomass, fish_bsa_not_caught_biomass, large_fish_not_caught_biomass)


#------------------------------
# Change in Biomass Analysis
#------------------------------

# Get proportional change in catch (numbers):
n_catch_prop <- round(100 - (100 * (sum(count_bags_new$N_Fish_UBSA) / sum(count_bags$N_Fish))), 1)
# NOTE: These numbers don't include the number dead from PRM.

# Get proportional change in catch (biomass):
bio_catch_prop <- round(100 - 100 * (mod_biomass_total / sample_biomass), 1)

# Print messages related to catch numbers to console:
message("Number of fish recorded before changes: ", sum(count_bags$N_Fish))
message("Number of fish estimated to be caught after changes: ", sum(count_bags_new$N_Fish_UBSA))

message("Adjustments to size limits and/or bag sizes would have
resulted in an estimated ", n_catch_prop, " percent reduction in catch (by numbers).")

# Print messages related to catch biomass to console:
message("Biomass of fish recorded before changes: ", sample_biomass)
message("Biomass of fish estimated to be caught after changes: ", mod_biomass_total)

message("Adjustments to size limits and/or bag sizes would have
        resulted in an estimated ", bio_catch_prop, " percent reduction in catch (biomass).")

#-------------------
# End of Snapmat.R
#-------------------
```

Appendix 6: Initial Reference Group Meeting

WESTERN STOCK SNAPPER REFERENCE GROUP

LOCATION: PARK ROYAL HOTEL – MELBOURNE AIRPORT

DATE: FRIDAY 12TH SEPTEMBER: 10 AM – 4 PM

INVITEES: FISHERIES SCIENTISTS, MANAGERS AND STAKEHOLDER REPRESENTATIVES, VIC, SA AND COMMONWEALTH

CHAIR: MARK EDWARDS (DEPI)

OBJECTIVES:

- Provide updates on research with cross-jurisdictional aspects relevant to the western snapper stock
- Initiate education and discussion of harvest strategy development for the western snapper stock.

AGENDA:

10:00 Coffee and pre-meeting discussion

10:15 Introduction to morning session (Edwards)

10:30 Western stock snapper update – a Victorian perspective (Hamer, FRDC)

10:45 Project update: "The influence of fish movement on regional fishery production and stock structure for SA's snapper fishery" with implications for assessment and management of the western stock (Fowler, FRDC)

11:15 Considerations for multi-jurisdiction management and assessment of the western stock (Group discussion)

11:30 Project update: "Development of a harvest management, governance and resource sharing framework for a complex multi-sector, multi-jurisdiction fishery: the SE Aust. 'western' snapper stock" (Hamer, FRDC)

12:00 Project update: "Developing a fishery independent estimate of biomass for snapper" (Steer, FRDC)

12.30 LUNCH

13:15 Introduction to afternoon session (Edwards)

13:25 Introduction to harvest strategies and management strategy evaluation (Hamer)

13:45 Case example(s) – Garfish (Steer), Blue grenadier and SA pipi (Hamer)

14:15 AFTERNOON TEA

14:30 Towards a western stock harvest strategy framework (Group)

16:00 CLOSE

<u>Summary of the workshop</u>

Workshop got underway at 10.15

Present were:
Vic: *Stakeholders:* Johnathon Davey (SIV), Franz Grasser (VRFish), David Kramer (Future Fish)
Gov: Paul Hamer (Science-FV), Mark Edwards (Policy-FV), Megan Higson (Policy-FV), Bill Lussier (Management-FV)

SA: *Stakeholders:* Nathan Bicknell (Marine Fishers Association - Commercial), Neil MacDonald (Consultant to SA Commercial fishing industry).
Gov: Tony Fowler (Science-SARDI), Mike Steer (Science-SARDI), Tim Ward (Science-SARDI), Michelle Besley (Management-PIRSA)

Commonwealth: George Day (Management-AFMA)
Stakeholder rep.– Simon Boag (SETFIA)

FRDC: Crispian Ashby (funding agency)

Other: WA Fisheries: Garry Jackson (Science-WA fisheries)

Apologies: Steve Javni (PPB commercial fisher), Brenton Schahinger (RecFishing SA), Simon Conron (science-FV), Ross Winstanley (VR Fish research committee), Simon Branigan (VNPA).

- Workshop was introduced by Mark Edwards from Fisheries Victoria – outlined the common interest of the group in the western Snapper stock and that this was an opportunity to provide the latest research and status information on this stock (morning) and start the discussion around development of technical tools and frameworks to guide better cross-jurisdictional management to both maximize benefits and ensure biological sustainability (afternoon).
- Round the table introductions.

Mark described the context and goals for the day and emphasized that the new **co-funded FRDC/RFL project on western stock Snapper** is designed to develop and deliver the key technical tools and management frameworks required to better inform and manage of the western stock fisheries – both recreational and commercial. The new project is not about implementation of new management (this is up to the management agencies to determine beyond the project) but is about research and development to improve the long-term capacity to effectively manage the stock and its associated fisheries.

Presentation 1 – **Western stock Snapper update – a Victorian perspective**

Paul Hamer gave an overview of the western Snapper stock from a Victorian perspective, defining the fisheries, current management, catches, recruitment process (i.e. Port Phillip Bay being the main spawning and nursery area), and a range of empirical stock assessment data from both fishery dependent (commercial long-line (adult fish) and haul seine (sub-adults) catch and effort), recreational catch rates, and fishery independent (Port Phillip Bay pre-recruit index – annual surveys of 0+ age fish with a small beam trawl) sources. Also mentioned that an integrated assessment model has been developed. He showed how the pre-recruit index is a reliable indicator of future catch rates and explained a conceptual model of what influence recruitment variation and how this variation originates in the larval stages. The point was made that the high interannual variation was driven by a variable interaction of the timing of the optimal temperature window for egg and larval survival (18-22°C, determined by the FRDC project 2011/039) and the summer peak in availability of copepod zooplankton (the food of the larvae). The point was also made that to maximize the benefit/return from the rare years when the above processes line up and the larval feeding conditions are exceptional, the more eggs that hatch out the better the return in terms of juvenile recruitment. Therefore, maintaining a certain level of egg production is critical to ensure that these periodic super-strong year classes that drive fishery production for significant periods of time can continue to occur in the long-term.

The empirical indicators all suggested that the stock was currently in a very good shape but declines in catch rates were expected over the coming years, due to a reduction in cumulative recruitment over the last 7 years. Although catch rates in the immediate future are still expected to be well above the long-term average.

Key comments: were on the wealth of biological knowledge that had been developed on the western stock, how well we measure and understand its dynamics, but that there was no clear route for this information into management processes and therefore the potential for management "paralysis" if the stock declined due to either excessive fishing pressure and/or longer-term recruitment failure.

Presentation 2: **"The influence of fish movement on regional fishery production and stock structure for SA's Snapper fishery" with implications for assessment and management of the western stock.**

Tony Fowler gave a presentation on the results of the FRDC project: "The influence of fish movement on regional fishery production and stock structure for SA's Snapper fishery" with a western stock focus. The project is a collaboration between SARDI scientists and Fisheries Victoria (Paul Hamer). The presentation provided background on the spatial changes in the SA Snapper fishery over the last decade, in particular the growth of catches in the SE (south east – coastal waters) and NGSV (Northern Gulf St Vincent) regions and the drop in catches from the Spencer Gulf. There were strong size and age composition differences between the NGSV and SGSV (Southern Gulf St Vincent) and SE region catches, also the cohorts that dominated commercial catches varied. There as a broader mix of contributing cohorts in NGSV, compared to just a few in SE (dominated by the 2001 and 2004 birth years).

The project applied otolith-based methods (chemistry, increment widths, otolith growth axes measures) with the inclusion of samples from Port Phillip Bay to provide very strong evidence that the recent spike in SE catches were based on fish of the same origins as those in Port Phillip Bay. Based on other evidence it was concluded the SE region fishery grew based on the expansion/spread/spill-over of the super-strong 2001 and 2004 cohorts originating in PPB. There was also evidence that these cohorts from Port Phillip Bay also contributed to the fishery in SGSV, but this fishery was supported by fish originating both from PPB and NGSV depending on the cohort – thus the SGSV represents the western boundary region of the western stock.

Considerations for multi-jurisdiction management and assessment of the western stock: There was discussion on the implications of these results for management and assessment. It was generally agreed to look at working together on management and assessment of the western stock across SA and Vic. There was discussion about whether or not the fish caught in the SE fishery may have potentially contributed to spawning by migrating back to PPB. Acoustic tags and traditional tag recapture approaches were both viable options to look at this question. However, in the meantime the conservative approach is to assume those catches from the SE are included in the assessment as part of the overall impact on the western stock spawning biomass, as opposed to spill-over with no contribution to spawning. Data to be supplied from SARDI to FV to incorporate into assessments.

Presentation 3: **Project update: "Development of a harvest management, governance and resource sharing framework for a complex multi-sector, multi-jurisdiction fishery: the SE Aust. 'western' Snapper stock"**

Paul Hamer provided an overview of the recently started project on the western stock "Development of a harvest management, governance and resource sharing framework for a complex multi-sector, multi-jurisdiction fishery: the SE Aust. 'western' Snapper stock". This project involves investigators from science and policy areas from SARDI/PIRSA, Fisheries Victoria, CSIRO and AFMA. The project is joint funded by FRDC and the Victorian Recreational Fishing License Trust, starting in late

2013 and scheduled to finish in late 2016. Paul pointed out that the project had gotten off to a slow start due to staffing issues but was getting back on track. The project has three main objectives;

1. To provide managers and stakeholders with a robust and transparent approach to harvest management decisions that provides for both biological sustainability and certainty of access
2. To provide managers with cost effective options for ongoing monitoring of recreational catch and a tool to assist in deciding among different regulatory approaches for managing catches by the recreational sector
3. To develop a multi-sector, multi-jurisdiction sharing and governance framework, and an associated implementation plan for the western stock Snapper fishery.

It was pointed out that the fisheries that accessed his stock were diverse both in relation to jurisdictions (Victoria, SA and commonwealth), fishing methods and licensing arrangements and that this complicated overall management effectiveness and assessment. The largest catch component was attributed to the Victorian recreational sector, although it was pointed out that the last estimate of the recreational was made in 2006/07 and that catches may fluctuate from year to year due to weather patterns that affects the ability of people to access the fishing grounds.

As mentioned earlier in the day there is lots of information and good monitoring on this stock but that the information does not feed into tools and frameworks designed to guide management, particularly in relation to harvest. It was difficult to know if the current arrangements were striking the right balance between risk and benefit. A key part of this project therefore involves the development of quantitative tools (i.e. and MSE (management strategy evaluation) model and a harvest strategy framework to help guide harvest regulation decisions. Importantly the project will need to consult with stakeholder groups to develop objectives that guide the choice and application (i.e. limit and target reference points) of performance indicators within a harvest strategy framework. There has been progress in this area of the project with the modelling scientist having now created the assessment model that will be the basis for the operating and estimation models for the MSE.

The other key part of the project which has progressed is the development of cost effective options for ongoing monitoring of recreational catch. Cameras have now been set up at 4 key boat ramps around the bay, with the 5th and 6th installations imminent. Traffic counters are in the process of also being installed, with one installation complete. Paul explained how the cameras are programmed to take images every 2 minutes to capture boat launches/retrievals. These data are then sub-sampled to provide an index of fishing effort that when combined with data from Fish Vic's. ongoing creel surveys provide and index of total catch variation. This can then be used to interpolate total catches between period large-scale phone diary survey estimates of total catch to provide an annual time series of recreational catches that accounts for variable effort, catch rates and size composition of the catch across years.

Presentation 4: **Project update "FRDC project -Developing a fishery independent estimate of biomass for Snapper"**

Mike Steer gave an update on progress with development of the daily egg production method (DEPM) for estimating spawning biomass of Snapper in SA Gulfs. His presentation went into the issues that have resulted in changes to consistency of the performance measures used to inform model-based biomass assessments. The DEPM method is seen as a very promising fishery independent approach to estimate biomass so that harvest strategies decisions based on the typical assessment method can be validated against an independent measure of biomass. The presentation made clear how this approach could be highly suited to Port Phillip Bay, the main spawning area for the western stock. The stakeholders benefited from understanding the applicability of this approach as a validation of model estimates and further informing harvest management decision processes.

Presentation 5: **"Introduction to harvest strategies and management strategy evaluation"**

Paul Hamer gave an introduction to 'harvest strategies" and management strategy evaluation (MSE). In particular how these approaches where important to apply to the western stock fishery and how this project if going about their development. For several of the stakeholder representatives these concepts were new and there was a clear educational benefit. An important aspect of the presentation related to setting objectives and distinguishing between high level management objectives and 'operational objectives'. The presentation was largely based around the National Guidelines (FRDC project 2010/061). Examples of harvest strategies were present for Blue Grenadier (high level tier 1 type) and SA pipis (lower level, empirical data driven etc.)

Presentation 6: **Case example(s) – Garfish (Steer)**

Mike Steer gave a presentation on the SA garfish fishery that faced a situation where the harvest strategies fishing mortality limit point had been breached and a management response was required to reduce to fishing mortality to a target level over a certain time period. It demonstrated how stakeholders can drive a management strategy evaluation process by making choices and trade-offs among different management responses. The key point of this case study was to show the stakeholders how the implementation and operation of a harvest strategy requires stakeholder involvement and how they can play a key role in driving the management response in a timely manner.

Group Exercise – "Developing candidate operation objectives"

The final activity of the day was to break into groups (recreational representatives, commercial representatives, and policy/management representatives, with scientists on each group) and begin to think about 'operational objectives'. This exercise was partly aimed at getting people to start thinking harvest strategies and about operational objectives and how they might describe them, and also to identify a few relevant operational objectives that can be used in the MSE development and simulation exercises.

Key points made by the commercial group:

- Issues of allocation required before any strong consideration can be made in developing clear reference points.
    - Harvest strategies. can be applied at the scale of allocation % and remain sector specific, avoiding wholesale strategies.
    - Must be stock specific – potential to account for SA component of Western Stock
    - Market demand or estimate of recreational surveys can be used to ascribe allocation.
- What reference points to use?
    - Suggested that market value be used as a proxy – but be converted to a catch rate ... eg... LRP may be 20% return on catch, TRP may be 40% return.
- Cost of Management...
    - Equitable to allocated share.

Key point from the management group:

The management group focused more on the development of the operational objectives than on harvest strategy requirements:

Conceptual objectives:

Maximize recreational utility and economic yield while ensuring sustainability.

Operational objectives:

Limits: avoid growth and recruitment overfishing

Targets: Biological – maintain or move spawning biomass to X% above BMSY.

Recreational – maximize recreational utility, survey to establish info. on views about optimal balance between catch rate/no. of fish per trip/size of fish

Commercial: maximize profit (yield v costs)

Social: be predictive, minimize frequency/rate of changes in management controls (stability objective)

Key point from the recreational group:

The recreational group also focused more on the development of the operational objectives than on harvest strategy requirements:

A key point was made that the recreational Snapper fishery is diverse: boat based, shore/pier based, large fish small fish etc. Different sub-groups within the recreational fishery will have different aspirations, expectations and values, which could lead to conflicting operational objectives.

Performance “values”:

Maximize success of a trip – success could be “a feed”, “a large fish” etc. (catch rate related),

Mixed fishery – want access to both smaller and large fish is important (composition and catch rate related),

Maintaining strong social license,

Spatial access, no erosion of access.

Limits: based on biological sustainability, or above to ensure that the performance values can be met consistently, lower risk approach.

It was clear that a strategy for engaging more broadly across the recreational Snapper fishery participants was important, and a first step to this was to better define the fishery.

Appendix 7: Western stock Snapper multi-jurisdiction MOU meeting

SARDI, Adelaide, 22 November 2017

Attendees: Bill Lussier (Senior Manager, Victorian Fisheries Authority (VFA)), Paul Hamer (Senior Research Scientist, VFA), Jon Presser (General Manager Fisheries Policy and Management Unit, Primary Industries & Regions South Australia (PIRSA)), Jonathan McPhail (Fishery Manager –

Marine Scalefish Fishery (PIRSA), Anthony Fowler (Senior Research Scientist, South Australian Research and Development Institute (SARDI), Rick McGarvey (Sub-program Leader Fisheries Modelling, SARDI), Mike Steer (Leader Finfish Fisheries Sub-program, SARDI), George Day (Senior Manager Demersal & Midwater, Australian Fisheries Management Authority (AFMA))

Agenda

10.00 am – Background, links to FRDC projects

10.20 am **-** Western stock status updates/discussion

11.00 am – Management fishery/status updates for Vic and SA

11.30 am **-** Purpose and scope of MOU

11.50 am – MOU process (SA and VIC – what's required for an MOU in each State)

12.00 pm **-** MOU content **-** identify the main topics to be covered in the MOU

12.30 pm – Lunch

1 pm – Drafting MOU content

3.00 – Next steps

3.30 pm – Close

Appendix 8: MOU

Memorandum of Understanding between Primary Industries and Regions South Australia and the Victorian Fisheries Authority regarding management of the western Victorian snapper stock

October 2018

Victorian Fisheries AUTHORITY

Government of South Australia

Primary Industries and Regions SA

1

1. **Purpose**

   1.1. Primary Industries and Regions South Australia (PIRSA) and the Victorian Fisheries Authority (VFA) have agreed to collaborate on the management and stock assessment of the western Victorian snapper stock.

   1.2. This Memorandum of Understanding (MOU) sets out the terms and understanding between PIRSA and the VFA with regards to this collaboration.

2. **Background**

   2.1. Snapper are highly valued by recreational and commercial fishers in Victoria and South Australia.

   2.2. In recognition of this, both the VFA and PIRSA devote significant management, compliance and scientific resources towards these fisheries.

3. **Definitions**

   3.1. *Snapper: Chrysophrys auratus*

   3.2. *Western Victorian snapper stock*: the snapper stock that inhabits the region from the west side of Wilsons Promontory in Victoria to Kangaroo Island in South Australia (Appendix 1).

   3.3. *Parties:* Primary Industries and Regions South Australia (PIRSA) and the Victorian Fisheries Authority (VFA).

   3.4. *SAFS:* Status of Australian Fish Stocks - A national reporting framework collaboratively developed by Australian fisheries scientists that uses standardised terminology and reference points for stock status classifications.

   3.5. *Data*: Biological and fisheries data that are collected and interpreted in a stock assessment

4. **Background and objectives of this MOU**

   4.1. The western Victorian snapper stock extends from the west side of Wilsons Promontory in Victoria to Kangaroo Island in South Australia. It is an important stock for recreational and commercial fisheries in Victoria and South Australia (Appendix 1).

   4.2. As a cross-jurisdictional stock, sustainable management of the western Victorian snapper stock is a shared responsibility of PIRSA and the VFA and is affected by each jurisdiction's management objectives and regulatory arrangements.

   4.3. This MOU recognises this shared responsibility and establishes the principles under which both parties will approach management, information sharing and stock assessment of the western Victorian snapper stock.

   4.4. This MOU does not commit either jurisdiction to altering their management arrangements or stock assessments/science for snapper, or in any way impinge on each jurisdiction's autonomy for managing the fisheries within their state waters.

4.5. This MOU may be modified at any time with the agreement of both parties.

5. Scope

This MOU:

5.1. Relates to snapper that are part of the western Victorian snapper stock.

5.2. Establishes a commitment between PIRSA and the VFA to communicate and collaborate on stock assessment and management issues.

5.3. Outlines roles and responsibilities for operation of the MOU.

5.4. Identifies key contacts for stock assessment and management of the western Victorian snapper stock within PIRSA and VFA.

6. Roles and Responsibilities

The VFA and PIRSA commit under this MOU to:

6.1. Collaborate on stock assessment data analysis and interpretation for the western Victorian snapper stock, and representation of both parties at formal stock assessment meetings.

6.2. Share relevant data that are required to assess the biological and fishery status of the western Victorian snapper stock, subject to jurisdictional legislative, privacy and confidential requirements.

6.3. Work together to develop efficient processes for sharing data.

6.4. Collaborate on SAFS stock status reviews with the objective of developing an agreed SAFS classification for the western Victorian snapper stock.

6.5. Engage and consult with the other party regarding state issues or potential management arrangements that relate to the shared western Victorian snapper stock.

6.6. Consult and collaborate on research proposals and projects related to the western Victorian snapper stock, wherever possible.

6.7. Consult on external communications and stakeholder engagement arising from management reviews and/or stock and fishery status related to the western Victorian snapper stock.

6.8. Act in the spirit of cooperation and good faith in the performance of this MOU.

6.9. Agree on the extent of use of data provided by the other party, where it may be sensitive in nature.

7. Operation of this MOU

7.1. PIRSA and VFA fisheries managers and/or scientists will meet annually or as required to discuss and share information on the western Victorian snapper stock.

7.2. Meeting locations will be by mutual agreement with both parties participating at their own cost.

7.3. Outcomes of the meetings will be recorded, mutually agreed and shared across both parties.

7.4. Agenda items for these meetings will include but not be limited to:

- Status of the stock;
- Management status;
- Fishery status and stakeholder perspectives;
- Operation of this MOU;
- Research and development opportunities/updates; and
- Immediate and future expectations with regard to stock biomass trends/fishery productivity and management of the western Victorian snapper stock.

7.5. PIRSA and VFA will develop an efficient data sharing agreement and schedule that incorporates each party's privacy requirements.

8. Confidentiality

8.1. Both parties agree to comply with any privacy requirements in relation to shared data.

9. Funding

9.1. Each party is responsible to participate in accordance to this MOU at their own cost.

9.2. No party is liable for any costs incurred by the other party in the operation of this MOU except where agreed by both parties.

10. Duration and review

10.1. The MOU will commence upon signing by the senior contacts from PIRSA and the VFA.

10.2. Performance and progress in implementing this MOU will be reviewed annually and the MOU will be renewed every three years subject to mutual agreement.

11. Termination and/or changes to scope

11.1. This MOU may only be reduced in scope through written agreement of both parties.

11.2. A party may withdraw from the MOU after providing written notice of their intention to the other party.

12. Not legally binding

12.1. This MOU is not legally binding of any party.

13. Operational contacts

	Victorian Fisheries Authority	*Primary Industries and Regions SA*
Fisheries Manager contact	Kate Simpson ☎(03) 5258 0205 🖂 Kate.Simpson@vfa.vic.gov.au	Jonathan McPhail ☎(08) 8429 0508 🖂 jonathan.mcphail@sa.gov.au
Science and data contact	Dr Paul Hamer ☎(03) 5258 0288 🖂 Paul.Hamer@vfa.vic.gov.au	Dr Michael Steer ☎(08) 8429 0342 🖂 michael.steer@sa.gov.au
Senior Contact	Dallas D'Silva ☎(03) 8392 6846 🖂 Dallas.D'silva@vfa.vic.gov.au	Alice Fistr ☎(08) 8429 0187 🖂 alice.fistr@sa.gov.au

14. Signatories

14.1. This MOU became effective upon signing by the authorized officials from both parties, and will remain in effect until terminated by either party or mutual agreement.

14.2. The undersigned agree to the terms of this MOU.

Organisation: Victorian Fisheries Authority

Signature:

Date: 23/10/18

Name: Travis Dowling

Position: Chief Executive Officer

Organisation: Primary Industries and Regions South Australia

Signature:

Date: 22/10/2018

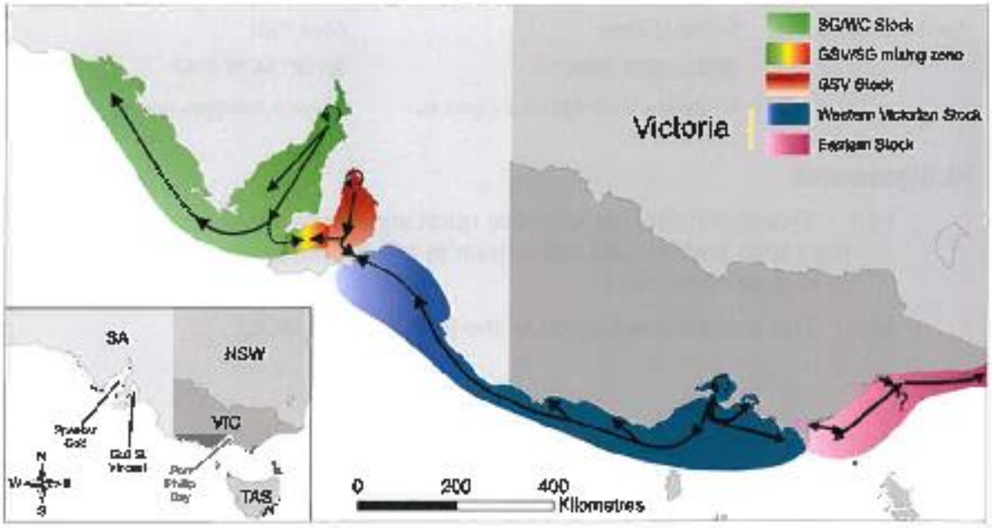
Name: Sean Sloan

Position: Executive Director, Fisheries and Aquaculture

Appendix 1: Snapper stock in South Australia and Victoria

Map from Fowler (2016) showing the region of the western Victorian snapper stock (blue) and other recognised snapper stocks in Victorian and South Australian waters.

Fowler, A. (2016) The influence of fish movement on regional fishery production and stock structure for South Australia's snapper (*Chrysophrys auratus*) fishery. Final Report. Fisheries Research and Development Corporation Project No. 2012/020



6

FRDC FINAL REPORT CHECKLIST

Project Title:	Developing tools to inform management risk and improve recreational fishery monitoring for a complex multi-sector, multi-jurisdiction fishery: the 'Western Victorian Snapper Stock'		
Principal Investigators:	Paul Hamer, Athol Whitten, Khageswor Giri		
Project Number:	2013/201		
Description:	This project involved the 'Western Victorian Snapper (*Chrysophrys auratus*) Stock' (WVSS) which supports a highly important fishery for Victoria. The WVSS is a straddling stock shared with South Australia. The project addressed concerns about lack of approaches for considering management risks associated with increased fishing pressure across sectors and jurisdictions, and the inability to track recreational harvest trends and adequately incorporate recreational fishing pressure into stock assessment and management. The project developed methods using boat ramp cameras and creel surveys to monitor recreational boat fishing effort and relative harvest trends for the key Snapper fishing areas in Victoria (Port Phillip Bay and Western Port Bay). A new management strategy evaluation (MSE) model was created utilising Stock Synthesis (SS3 and ss3sim) and R for informing management risk, and scenario studies were conducted focussing on implications of alternative fishing mortality (harvest control rules) and recruitment dynamics/regimes. To support advice on implications of size and bag limit changes for managing recreational harvest, an empirical management advice tool was developed in R that uses recent creel survey data to estimates immediate effects of size and bag limit changes on recreational Snapper harvest. Finally, the project facilitated the development of an MOU agreement between the Victorian (VFA) and South Australian (PIRSA, Primary Industries and Regions South Australia) management jurisdictions to guide cross-jurisdictional collaboration on stock assessment and management issues for the WVSS.		
Published Date:	May	**Year:**	2019
ISBN:	**ISBN** 978-1-76090-121-9 (Print) **ISBN** 978-1-76090-126-4 (pdf/online/MS word)	**ISSN:**	NA
Key Words:	Snapper, *Chrysophrys auratus*, management strategy evaluation, boat ramp cameras, cross-jurisdictional management, western Victorian Snapper stock, recreational fishing effort		

Please use this checklist to self-assess your report before submitting to FRDC. Checklist should accompany the report.

	Is it included (Y/N)	**Comments**
Foreword (optional)	N	
Acknowledgments	Y	
Abbreviations	Y	
Executive Summary		
− **What the report is about**	Y	
− **Background – why project was undertaken**	Y	
− **Aims/objectives – what you wanted to achieve at the beginning**	Y	
− **Methodology – outline how you did the project**	Y	

− **Results/key findings – this should outline what you found or key results**	Y	
− **Implications for relevant stakeholders**	Y	
− **Recommendations**	Y	
Introduction	Y	General introduction is included
Objectives	Y	
Methodology	Y	Written specifically for each chapter
Results	Y	Written specifically for each chapter
Discussion	Y	Written specifically for each chapter
Conclusion	Y	General conclusions section is included
Implications	Y	
Recommendations	Y	
Further development	Y	
Extension and Adoption	Y	
Project coverage	Y	
Glossary	N	
Project materials developed	N	None
Appendices	Y	

References

AFMA (2018). Southern and Eastern Scalefish and Shark Fishery Management Arrangements Booklet 2018.

Allen, M., Sumpton, W., O'Neill, M.F., Courtney, A.J. and Pine. B. (2006). Stochastic stock reduction analysis for assessment of the pink snapper (*Pagrus auratus*) fishery in Queensland. Department of Primary Industries and Fisheries, Queensland, project report QI06069.

Anderson, S.C., Monnahan, C.C., Johnson, K.F., Ono,K., and Valero, J.L. (2014). ss3sim: An R package for fisheries stock assessment simulation with Stock Synthesis. *PLoS ONE* **9(4)**: e92725.

Arlinghaus, R., Cooke, S. J. and Potts, W. (2013). Towards resilient recreational fisheries on a global scale through improved understanding of fish and fisher behaviour. *Fisheries Management and Ecology* **20,** 91–98.

Arlinghaus, R., and Cooke, S. J. (2005). Global impact of recreational fisheries. *Science* **307**, 1561–1562.

Arreguin-Sanchez, F. (1996). Catchability: a key parameter for fish stock assessment. *Reviews in Fish Biology and Fisheries* **6,** 221-241.

Askey, P.J., Ward, H., Godin, T., Boucher, M. and Northrup, S. (2018) Angler effort estimates from instantaneous aerial counts: use of high-frequency time-lapse camera data to inform model-based estimators. *North American Journal of Fisheries Management* **38,** 194-209.

Attwood, C.G. and Bennett, B.A. (1995). A procedure for setting daily bag limits on the recreational shore-fishery of the South-Western Cape, South Africa. *South African Journal of Marine Science* **15,** 242-251.

Beaudreau, A.H., and Whitney, E.J. (2016). Historical patterns and drivers of spatial changes in recreational fishing activity in Puget Sound, Washington. *PLoS ONE* **11(4)**: e0152190.

Bellanger, M., and Levrel, M. (2017). A cost-effectiveness analysis of alternative survey methods used for the monitoring of marine recreational fishing in France. *Ocean & Coastal Management* **138**, 19 - 28.

Black, K.P., Longmore, A.R., Hamer, P.A., Lee, R., Swearer, S.E., and Jenkins, G.P. (2016). Linking nutrient inputs, phytoplankton composition, zooplankton dynamics and the recruitment of pink snapper, *Chrysophrys auratus*, in a temperate bay. *Estuarine Coastal and Shelf Science* **183**, 150 -162.

Beard, D.T. Jr, Cox, S.P., and Carpenter, S.R. (2003) Impacts of daily bag limit reductions on angler effort in Wisconsin walleye lakes. *North American Journal of Fisheries Management* **23**, 1283-1293.

Broadhurst, M.K., Butcher, P.A., Hall, K.C., Cullis B.R., and McGrath, S.P. (2012). Resilience of inshore, juvenile snapper *Pagrus auratus* to angling and release. *Journal of Fish Biology* **80,** 683–650.

Butcher, P.A., Broadhurst, M. K., Hall, K.C., Cullis, B.R., and Raidal, S.R. (2012). Assessing barotrauma among angled snapper (*Pagrus auratus*) and the utility of release methods. *Fisheries Research* **128,** 49–55.

Butterworth, D.S. and Punt, A.E. (1999) Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science* **56**, 985–998.

Butterworth, D.S. (2007). Why a management procedure approach? Some positives and negatives, *ICES Journal of Marine Science* **64**, 613–617.

Buxton, C.D. (1992). The application of yield-per-recruit models to two South African sparid reef species, with special consideration to sex change. *Fisheries Research* **15**, 1-16.

Campbell, B. and Hanich, Q. (2015). Principles and practice for the equitable governance of transboundary natural resources: cross-cutting lessons for marine fisheries management. *Maritime Studies* **14**, 8.

Campbell, A. B., O'Neill, M. F., Sumpton, W., Kirkwood, J. and Wesche, S. (2009.) Stock assessment of the Queensland snapper fishery (Australia) and management strategies for improving sustainability. https://www.daf.qld.gov.au/__data/assets/pdf_file/0009/58293/Stock-assessment-Qld-snapper-fishery-Summary-Apr2009_.pdf.

Carter, D.W., Crosson, S., and Liese, C. (2015) Nowcasting intraseasonal recreational fishing harvest with internet search volume. *PLoS ONE* **10(9)**: e0137752.

Chapman, D. G., and Robson, D.S. (1960). The analysis of a catch curve. *Biometrics* **16,** 354–368.

Cochran, W. G. (1977). Sampling techniques, 3rd edition. Wiley, New York.

Coleman, F.C., Figueira, W.F., Ueland, J.S., and Crowder, L.B. (2004). The impact of United States recreational fishers on marine fish populations. *Science* **305**, 1958–1960.

Conron, S. and Bridge, N. (2014) Estimating the recreational catch of key species in Victoria – Survey Design. Fisheries Victoria Internal Report Series No. 56.

Cooke, S. J., and Cowx, I. G. (2006). Contrasting recreational and commercial fishing: searching for common issues to promote unified conservation of fisheries resources and aquatic environments. *Biological Conservation* **128**, 93–108.

Cooke, S. J., and Cowx, I. G. (2004). The role of recreational fishing in global fish crisis. *BioScience* **5**, 857–859.

Coutin, P.C., Cashmore, S., and Sivakumuran, K.P. (2003). Assessment of the snapper fishery in Victoria. Final report to Fisheries Research and Development Corporation, Australia. Project No 97/127, p. 210. Marine and Freshwater Resources Institute Queenscliff, Victoria.

Cox, S.P. and Walters, C. (2002) Modelling exploitation in recreational fisheries and implications for effort management on British Columbia rainbow trout lakes. *North American Journal of Fisheries Management* **22**, 21–34.

Cox, S.P., Beard, D.T., and Walters, C. (2002). Harvest control in open-access sport fisheries: hot rod or asleep at the reel? *Bulletin of Marine Science* **70**, 749-76.

DAFF (2007). Commonwealth Fisheries Harvest Strategy. Policy and Guidelines, Department of Agriculture, Fisheries and Forestry, Canberra, 55 pp.

Department of Primary Industries (2007). Victorian recreational snapper fisheries. Discussion Paper-Issues and Future Management Options. Fisheries Victoria Management Report Series Report No. 46, Victoria, Australia

Dowling, N.A., Dichmont, C.M., Haddon, M., Smith, D.C., Smith, A.D.M., and Sainsbury, K. (2015). Empirical harvest strategies for data-poor fisheries: A review of the literature. *Fisheries Research* **171**, 141-153.

Eero, M., Strehlow, H.V., Adams, C.M. and Vinther, M. (2015). Does recreational catch impact the TAC for commercial fisheries? *ICES Journal of Marine Science* **72**, 450-457.

Forrest, R.E., Holt, K.R. and Kronlund, R.A. (2018). Performance of alternative harvest control rules for two Pacific groundfish stocks with uncertain natural mortality: Bias, robustness and trade-offs. *Fisheries Research* **206,** 259-286.

Fowler, A.J. (2016). The influence of fish movement on regional fishery production and stock structure for South Australia's Snapper (*Chrysophrys auratus*) fishery. Final Report to Fisheries Research and Development Corporation Project No. 2012/020, 181 pp.

Fenichel, E. P., J. K. Abbott, and B. Huang. (2013). "Modelling angler behaviour as a part of the management system: synthesizing a multi-disciplinary literature. *Fish and Fisheries* **14,** 137–57.

Fowler, A.J., McGarvey, R., Carroll, J., Feenstra, J.E., Jackson, W.B. and Lloyd, M.T. (2016). Snapper (*Chrysophrys auratus*) fishery. Fishery assessment report to Primary Industries and Regions South Australia (Fisheries and Aquaculture), South Australian Research and Development Institute (Aquatic Sciences), Adelaide. F2007/000523-4. SARDI Research Report Series No. 930. 82 pp.

Fowler, A.J., Hamer, P.A., and Kemp, J. (2017). Age-related otolith chemistry profiles help resolve demographics and meta-population structure of a widely-dispersed, coastal fishery species. *Fisheries Research* **189**, 77-94.

Fowler, A., Jackson, G., Stewart, J., Hamer, P., and Roelofs, A. (2018). Snapper *Chrysophrys auratus,* in Carolyn Stewardson, James Andrews, Crispian Ashby, Malcolm Haddon, Klaas Hartmann, Patrick Hone, Peter Horvat, Stephen Mayfield, Anthony Roelofs, Keith Sainsbury, Thor Saunders, John Stewart, Simon Nicol and Brent Wise (eds) 2018, Status of Australian fish stocks reports 2018, Fisheries Research and Development Corporation, Canberra.

Francis R.I.C.C., and McKenzie, J.R. (2015). Assessment of the SNA 1 stocks in 2013. New Zealand Fisheries Assessment Report 2015/76. 82 p.

Gilbert D. J., Davies N. M., and McKenzie J. R. (2006). Development of an age–length structured model of the Hauraki Gulf–Bay of Plenty snapper (*Pagrus auratus*) population. *Marine and Freshwater Research* **57,** 553-568.

Greenberg, S. and Godin, T. (2015) A tool for supporting the extractions of angling effort data from remote camera images. *Fisheries* **40**, 267-287.

Griffiths, S.P., and Fay, G. (2015). Integrating recreational fisheries data into stock assessment: implications for model performance and subsequent harvest strategies. *Fisheries Management and Ecology* **22**, 197–212.

Grixti, D., Conron, S.D., and Morison, A. (2010). Post-release survival of recreationally caught snapper, *Pagrus auratus*, in Port Phillip Bay, south-eastern Australia. *Fisheries Management and Ecology* **17,** 1–9.

Gwinn, D.C., Allen, M.S., Johnston, F.D., Brown, P., Todd, C.R. and Arlinghaus, R. (2015). Rethinking length-based fisheries regulations: the value of protecting old and large fish with harvest slots. *Fish and Fisheries* **16**, 259–281.

Hamer, P.A., Acevedo, S., Jenkins, G.P. and Newman, A. (2011). Connectivity of a large embayment and coastal fishery: spawning aggregations in one bay source local and broad-scale fishery replenishment. *Journal of Fish Biology* **78**, 1090-1109.

Hamer, P., and Conron, S. (2016). Snapper Stock Assessment 2016. Fisheries Victoria Science Report Series No. 10, Fisheries Victoria, Queenscliff.

Hamer, P. and Mills, K. (2017). Anglers tune in to find out why Port Phillip Bay is so important to snapper. Recreational Fishing Grants Program Research Report. Victorian Government, Department of Economic Development, Jobs, Transport and Resources.

Hansen, M. J., Beard, T. D., and Hewett, S.W. (2000). Catch rates and catchability of walleyes in angling and spearing fisheries in northern Wisconsin lakes. *North American Journal of Fisheries Management* **20**, 97–106.

Harasti, D., Davis, T.R., Jordan, A., Erskine, L., and Moltschaniwskyj, N. (2019). Illegal recreational fishing causes a decline in a fishery targeted species (Snapper: *Chrysophrys auratus*) within a remote no-take marine protected area. *PLoS ONE* 14(1): e0209926.

Hartill, B.W., Cryer, M., Lyle, J.M., Rees, E.B., Ryan, K.L., Steffe, A.S., Taylor, S.M., West, L., and Wise, B.S. (2012). Scale- and context-dependent selection of recreational harvest estimation methods: the Australasian experience. *North American Journal of Fisheries Management* **32**, 109–123.

Hartill, B., Bian, R., Rush, N., and Armiger, H. (2013). Aerial-access recreational harvest estimates for snapper, kahawai, red gurnard, tarakihi and trevally in FMA 1 in 2011–12. New Zealand Fisheries. Association Report 2013/70, pp. 44

Hartill, B. (2015). Evaluation of web camera based monitoring of levels of recreational fishing effort in FMA 1. New Zealand Fisheries Association Report 2015/22, pp. 12.

Hartill, B.W., Thomas, C., and Edwards, T. (2015). Comparison of recreational harvest estimates provided by onsite and offsite surveys: detecting bias and corroborating estimates. *Canadian Journal of Fisheries and Aquatic Sciences* **72**, 1379-1389.

Hartill, B.W., Payne, G.W., Rush, N., and Bian, R. (2016). Bridging the temporal gap: Continuous and cost-effective monitoring of dynamic recreational fisheries by web cameras and creel surveys. *Fisheries Research* **183**, 488-497.

Henry, G.W., and Lyle, J.M. (2003). The National Recreational and Indigenous Fishing Survey. Final Report for Fisheries Research and Development Corporation Project No. 99/158. Australian Government Department of Agriculture, Fisheries and Forestry, Canberra.

Hunt, L.M., Arlinghaus, R., Lester, N., and Kushneriuk, R. (2011). The effects of regional angling effort, angler behaviour, and harvesting efficiency on landscape patterns of overfishing. *Ecological Applications* **21**, 2555–2575.

Ihde, T.F., Wilberg, M.J., Loewensteiner, D.A., Secor, D.H., and Miller, T.J. (2011). The increasing importance of marine recreational fishing in the US: challenges for management. *Fisheries Research* **108**, 268–276.

Jiorle, R.N., Ahrens, M. and Allen, M.S. (2016) Assessing the utility of a Smartphone App for recreational fishery catch data. *Fisheries* **41**, 758-766.

Johnson, B. M., and Carpenter, S.R. (1994). Functional and numerical responses: a framework for fish-angler interactions? *Ecological Applications* **4**, 808–821.

Keller, K., Steffe, A.S., Lowry, M., Murphy. J.J., and Suthers, I.M. (2016). Monitoring boat-based recreational fishing effort at a near shore artificial reef with a shore-based camera. *Fisheries Research* **18,** 84–92.

Kirchner, C. (2001). Fisheries regulations based on yield per-recruit analysis of the linefish silver kob *Argyrosomus inodorus* in Namibian waters. *Fisheries Research* **52**, 155-167

Langley, A.D. (2015). Stock assessment of snapper in SNA 7. New Zealand Fisheries Assessment Report 2015/42. 46 p

Lenanton, R., St John, J., Wise, B., Keay, I. and Gaughan, D. (2009). Maximising survival of released undersize west coast reef fish. Final report to Fisheries Research and Development Corporation on Project No. 2000/194. Fisheries Research Report No. 191. Department of Fisheries, Western Australia. 130p.

Lee, M., Steinback, S. and Wallmo, K. (2017). Applying a bioeconomic model to recreational fisheries management: Groundfish in the Northeast United States. *Marine Resource Economics* **32,** 191-216

Lewin, W.C., Arlinghaus, R., and Mehner, T. (2006). Documented and potential biological impacts of recreational fishing: insights for management and conservation. *Reviews in Fisheries Science* **14**, 305–367.

Little, R.L., Punt, A.E., Mapstone, B., Pantus, F., Smith, A.D.M., Davies, C.R., and McDonald, A.D. (2007). ELFSim — a model for evaluating management options for spatially structured reef fish populations: an illustration of the “larval subsidy” effect. *Ecological Modelling* **205 (3-4),** 381-396.

Little, R.L., Punt, A.E., Mapstone, B., Begg, G.A., Goldman, B. and Ellis, N. (2009). Different responses to area closures and effort controls for sedentary and migratory harvested species in a multispecies coral reef line fishery. *ICES Journal of Marine Science* **66,** 1931–1941.

Mace, P.M. (1994). Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. *Canadian Journal of Fisheries and Aquatic Science* **51,** 110-122.

Marchal, P., Andersen, B., Caillart, B., Eigaard, O., Guyader, O., Hovgaard, H., Iriondo, A., Le Fur, F., Sacchi, J., and Santurtu´n, M. (2007). Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets. *ICES Journal of Marine Science* **64**, 192–209.

MacDonald, C. M. (1980). Population structure, biochemical adaptation and systematics in temperate marine fishes of the genera Arripis and Chrysophrys (Pisces: Perciformes). Ph.D. Thesis, Australian National University. 336 pp.

McGarvey, R. (2004). Model comparison of seasonal closure and maximum size for management of the South Australian snapper fishery. *Ecological Management & Restoration* **5,** 139-141.

McGarvey, R., Burch, P., and Feenstra, J.E. (2010). Management strategy evaluation for South Australian snapper. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000226-1. SARDI Research Report Series No. 441, 32p.

McPhee, D.P., Leadbitter, D. and Skilletter, G.A. (2002). Swallowing the bait: Is recreational fishing in Australia ecologically sustainable? *Pacific Conservation Biology* **8**, 40–51.

McLennan, M.F., Campbell, M.J., and Sumpton, W.D. (2014). Surviving the effects of barotrauma: assessing treatment options and a ‘natural’ remedy to enhance the release survival of line caught pink snapper (*Pagrus auratus*). *Fisheries Management and Ecology* **21,** 330–337.

Maunder, M.N., and Punt, A.E. (2013). A review of integrated analysis in fisheries stock assessment, *Fisheries Research* **142,** 61-74.

Maunder, M.N. (2014). Management strategy evaluation (MSE) implementation in stock synthesis: application to Pacific bluefin tuna. Inter-American Tropical Tuna Commission Stock Assessment Report 15: 100-117.

Methot, R.D., and Taylor, I.G. (2011). Adjusting for bias due to variability of estimated recruitments in fishery assessment models. *Canadian Journal of Fisheries and Aquatic Science*s **68,** 1744-1760.

Methot, R.D., and Wetzel, C. (2013). Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research* **142,** 86-99.

Methot, R.D., A'mar, T., Wetzel, C., and Taylor, I. (2017). Stock Synthesis User Manual Version 3.30 beta. NOAA Fisheries, Seattle, WA USA.

Methot, R.D. (2013). User Manual for Stock Synthesis Model Version 3.24s. NOAA Fisheries, Seattle, WA USA.

Murphy, H.M., Jenkins, G.P., Hamer, P.A., and Swearer, S.E. (2013). Interannual variation in larval abundance and growth in snapper *Chrysophrys auratus* (Sparidae) is related to prey availability and temperature. *Marine Ecology Progress Series* **487**, 151-162.

National Research Council (1998). Improving Fish Stock Assessments. Washington, DC: The National Academies Press.

Pauly, D., and Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature Communications* **7,** 10244.

Pecl, G., Ward, T., Briceno, F., Fowler, A., Frusher, S., Gardner, C., Hamer, P., Hartmann, K., Hartog, J., Hobday, A., Hoshino, E., Jennings, S., Le Bouhellec, B., Linnane, A., Marzloff, M., Mayfield, S., Mundy, C., Ogier, E., Sullivan, A., Tracey, S., Tuck, G., and Wayte, S. (2014). Preparing fisheries for climate change: identifying adaptation options for four key fisheries in south eastern Australia. Final Report to the Fisheries Research and Development Corporation, Project 2011/039, Canberra, ACT, Australia.

Pereira, D.L., and Hansen, M.J. (2003). A perspective on challenges to recreational fisheries management: Summary of the Symposium on Active Management of Recreational Fisheries. *North American Journal of Fisheries Management* **23**, 1276–1282.

Pine, W.E., Pollock, K.H., Hightower, J.E., Kwak, T.J. and Rice, J.A. (2014). A review of tagging methods for estimating fish population size and components of mortality. *Fisheries* **28,** 10-23**.**

PIRSA (2013). Management Plan for the South Australian Commercial Marine Scalefish Fishery. PIRSA Fisheries and Aquaculture, Adelaide, 143 pp. The South Australian Fishery Management Series, Paper No. 59.

PIRSA (2017). Management plan for recreational fishing in South Australia. PIRSA Fisheries and Aquaculture, Adelaide, 56 pp. The South Australian Fishery Management Series, Paper No. 73.

PIRSA (2011). Management plan for the South Australian Charter Boast Fishery. PIRSA Fisheries and Aquaculture, Adelaide, 66 pp.

Pollock, K.H., Hoenig, J.M., Jones, C.M., Robson, D.S., and Greene, C.J. (1997). Catch rate estimation for roving and access point surveys. *North American Journal of Fisheries Management* **17**, 1-19.

Pollock, K.H., Jones, C.M., and Brown, T.L. (1994). Angler survey methods and their application in fisheries management. American Fisheries Society, Bethesda, Maryland, Special Publication 25, pp. 371.

Porch, C.E., Eklund, A., Scott, G.P. (2006). A catch-free stock assessment model with application to goliath grouper (*Epinephelus itajara*) off southern Florida. *Fishery Bulletin* **104,** 89-101.

Post, J.R., Sullivan, M., Cox, S., Lester, N.P., Walters, C.J., Parkinson, E. A., Paul, A.J., Jackson, L., and Shuter, B.J. (2002). Canada's recreational fisheries: the invisible collapse? *Fisheries* **27**, 6–17.

Post, J. R., Mushens, C., Paul, A. and Sullivan, M. (2003). Assessment of alternative harvest regulations for sustaining recreational fisheries: model development and application to Bull Trout. *North American Journal of Fisheries Management* **23,** 22–34.

Post J.R. (2013) Resilient recreational fisheries or prone to collapse? A decade of research on the science and management of recreational fisheries. *Fisheries Management and Ecology* **20,** 99-110.

Powers, S.P., and Anson, K. (2016). Estimating recreational effort in the Gulf of Mexico red snapper fishery using boat ramp cameras: reduction in federal season length does not proportionally reduce catch. *North American Journal of Fisheries Management* **36**,1156–1166.

Productivity Commission (2016). Marine Fisheries and Aquaculture, Final Report, Canberra. (https://www.pc.gov.au/inquiries/completed/fisheries-aquaculture/report)

Punt, A.E., and Smith, A.D.M. (2001). The gospel of Maximum Sustainable Yield in fisheries management: birth, crucifixion and reincarnation. In: Reynolds, J.D., Mace, G.M., Redford, K.H., Robinson, J.G. (Eds.), Conservation of Exploited Species. Cambridge University Press, Cambridge, pp. 41–66.

Punt, A. E., Smith, A. D. M., and Cui, G. R. (2001). Review of progress in the introduction of management strategy evaluation (MSE) approaches in Australia's South East Fishery. *Marine and Freshwater Research,* **52**, 719-726.

Punt, A. E., Butterworth, D. S., Moor, C. L., De Oliveira, J. A. and Haddon, M. (2016). Management strategy evaluation: best practices. *Fish and Fisheries* **17**, 303-334.

Punt, A.E. (2017) Strategic management decision-making in a complex world: quantifying, understanding, and using trade-offs. *ICES Journal of Marine Science* **74,** 499-510.

Quinn, T. J., and Szarzi, N. J. (1993). Determination of sustained yield in Alaska's recreational fisheries. In Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations, Oct 21-24, 1992, Anchorage, Alaska. Ed. by G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn.

Rademeyer, R.A., Plaga´nyi, E., and Butterworth, D. S. (2007). Tips and tricks in designing management procedures. *ICES Journal of Marine Science* **64**, 618–625.

Radomski, P. J., Grant, G. C., Jacobson, P. C. and Cook, M. F. (2001). Visions for recreational fisheries regulations. *Fisheries* **26**, 7–18.

Radomski, P. (2003). Initial attempts to actively manage recreational fishery harvest in Minnesota. *North American Journal of Fisheries Management* **23**, 1329–1342.

R Core Team (2017). R: A Language and Environment for Statistical Computing. https://www.R-project.org/

Ryan, K.L., Morison, A.K., and Conron, S. (2009). Evaluating methods of obtaining total catch estimates for individual Victorian bay and inlet recreational fisheries. Final report to Fisheries Research and Development Corporation Project No. 2003/047. Department of Primary Industries, Queenscliff

Sanders, M. J. (1974). Tagging indicates at least two stocks of snapper, *Chrysophrys auratus*, in south-eastern Australian waters. *New Zealand Journal of Marine and Freshwater Research* **8**, 371-374.

Sloan S.R., Smith A.D., Gardener C., Crosthwaite K., Triantafillos, L., Jeffries, B., and Kimber, N. (2013). National Guidelines to Develop Fishery Harvest Strategies. Final Report for Fisheries Research and Development Corporation Project 2010/061, Canberra.

Smallwood, C.B., Pollock, K.H., Wise, B.S., Hall, N.G., and Gaughan, D.J. (2012). Expanding aerial–roving surveys to include counts of shore-based recreational fishers from remotely operated cameras: benefits, limitations, and cost effectiveness. *North American Journal of Fisheries Management* **32**, 1265–1276.

Smith, A. D. M. (1994). Management strategy evaluation: The light on the hill. In ‘Population Dynamics for Fisheries Management’. (Ed. D. A. Hancock.) pp. 249–253. (Australian Society for Fish Biology: Perth.)

Smith, A. D. M., Smith, D. C., Haddon, M., Knuckey, I., Sainsbury, K. J., and Sloan, S. (2014). Implementing harvest strategies in Australia: 5 years on. *ICES Journal of Marine Science* **71**, 195–203.

Smith, A.D.M., Smith, D.C., Tuck, G.N., Klaer, N., Punt, A, Knuckey, I., Prince, J., Morison, A., Kloser, R., Haddon, M., Wayte, S., Day, J., Fay, G., Pribaca, F., Fuller, M., Taylor, B., and Little, R. (2008). Experience in implementing harvest strategies in Australia's south-eastern fisheries. *Fisheries Research* **94**, 373-379.

Steffe, A.S., and Chapman, J.P. (2003). A survey of daytime recreational fishing during the annual period, March 1999 to February 2000, in Lake Macquarie, New South Wales. NSW Fisheries Final Report. 124pp.

Steffe, A.S., Murphy, J.J., and Reid, D.D. (2008). Supplemented access point sampling designs: a cost-effective way of improving the accuracy and precision of fishing effort and harvest estimates derived from recreational fishing surveys. *North American Journal of Fisheries Management* **28**, 1001–1008

Steffe, A.S., Taylor, S.M., Blight, S.J., Ryan, K.L., Desfosses, C.J., Tate, A.C., Smallwood, C.B., Lai, E.K., Trinnie, F.I. and Wise, B.S. (2017). Framework for integration of data from remotely operated cameras into recreational fishery assessments in Western Australia. Fisheries Research Report No. 286, Department of Primary Industries and Regional Development, Western Australia. 36pp.

Stewardson, C., Andrews, J. Ashby, C., Haddon, M., Hartmann, K., Hone, P., Horvat, P., Mayfield, S., Roelofs, A., Sainsbury, K., Saunders, T., Stewart, J., Stobutzki, I. and Wise, B. (eds) (2016). Status of Australian fish stocks reports 2016, Fisheries Research and Development Corporation, Canberra.

Stunz, G.W., Johnson, M. J., Yoskowitz, D., Robillard, M. and Wetz, J. (2014) iSnapper: design, testing, and analysis of an iPhone-based application as an electronic logbook in the for-hire Gulf of Mexico red snapper fishery. National Oceanic and Atmospheric Administration Final Report NA10NMF4540111, 64 pp.

Sutinen, J.G., and Johnston, R.J. (2003). Angling management organizations: Integrating the recreational sector into fishery management. *Marine Policy* **27**, 471-487.

Swartz, W., and Ishimura, G. (2014). Baseline assessment of total fisheries-related biomass removal from Japan's Exclusive Economic Zones: 1950–2010. Fisheries Science **80**, 643.

Taylor, I., Stewart, I., Hicks, A., Garrison, T., Punt, A., et al.. (2013). r4ss: R code for Stock Synthesis. R package version 1.20.

Then, A. Y., Hoenig, J. M., Hall, N.G. and Hewitt, D.A. (2015). Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. *ICES Journal of Marine Science* **72,** 82-92.

Thorson J.T. and Prager, M.H. (2011). Better catch curves: Incorporating age-specific natural mortality and logistic selectivity. *Transactions of the American Fisheries Society* **140,** 356–366.

Thurstan, R.H., Buckley, S.M., and Pandolfi, J.M. (2018). Trends and transitions observed in an iconic recreational fishery across 140 years. *Global Environmental Change* **52**, 22-36.

Tuck, G.N. (2008) Updated stock assessment of blue grenadier *Macruronus novaezelandiae* based on data up to 2007. Report to Slope Resource Assessment Group, 2008, CSIRO, Hobart, Tasmania.

Van Poorten, B. T., Cox, S.P., and Cooper, A.B. (2013). Efficacy of harvest and minimum size limit regulations for controlling short-term harvest in recreational fisheries. *Fisheries Management and Ecology* **20**, 258–267.

Valero, J.L., Aires-da-Silva, A., Maunder, M.N., Minte-Vera, C., Martínez-Ortiz, J., Torrejón-Magallanes, E.J. and Carranza, M.N. (2016). Exploratory management strategy evaluation (MSE) of dorado (*Coryphaena hippurus*) in the southeastern Pacific Ocean. Inter-American Tropical Tuna Commission, SAC-07-06a(ii)

Venturelli, P.A., Hyder, K., and Skov, C. (2017) Angler apps as a source of recreational fisheries data: opportunities, challenges and proposed standards. Fish and Fisheries **18**, 578–595.

Victorian Fisheries Authority (2017). Review of key Victorian fish stocks — 2017 Victorian Fisheries Authority Science Report Series No. 1.

Walters, C.J. and Martell, S.J.D. (2004). Fisheries ecology and management. Princeton University Press, Princeton, New Jersey.

Wayte, S. E., and Klaer, N.L. (2010). An effective harvest strategy using improved catch curves. *Fisheries Research* **106,** 310–320

Ward, H.G.M., Askey, P.J. and Post, J.R. (2013). A mechanistic understanding of hyperstability in catch per unit effort and density-dependent catchability in a multistock recreational fishery. *Canadian Journal of Fisheries and Aquatic Sciences* **70,** 1542-1550.

Wise, B.S., and Fletcher, W.J. (2013). Determination and development of cost effective techniques to monitor recreational catch and effort in Western Australian demersal finfish fisheries. Final Report for Fisheries Research and Development Corporation Project 2005/034 and WAMSI Subproject 4.4.3. Fisheries Research Report No. 245. Department of Fisheries, Western Australia. 168pp.

Wolf-Christian, L., Arlinghaus, R., and Mehner, T. (2007). Documented and potential biological impacts of recreational fishing: insights for management and conservation. *Reviews in Fisheries Science* **14**, 305-367.

Woodward, R.T., and Griffin, W.L. (2003). Size and bag limits in recreational fisheries: theoretical and empirical analysis. *Marine Resource Economics* **18**, 239–262.

J. Wortmann, J., O'Neill, M.F., Sumpton, W., Campbell M.J., and Stewart, J. (2018). Stock assessment of Australian east coast snapper, *Chrysophrys auratus*: Predictions of stock status and reference points for 2016. Queensland, Department of Agriculture and Fisheries.

Zeller, D., Darcy, M., Booth, S., Lowe, M.K., and Martell, S. (2008). What about recreational catch? Potential impact on stock assessment for Hawaii's bottom fish fisheries. *Fisheries Research* **91**, 88–97.