A synthesis of the efficacy of fisheries enhancement methods for integration into the fisheries management toolbox

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

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Abbreviations

BCR	Benefit-cost ratio
DAF	Department of Agriculture and Fisheries, Queensland
FAD	Fish attracting device
FRDC	Fisheries Research and Development Corporation
NPV	Net present value
NSW	New South Wales
QLD	Queensland
WA	Western Australia

Executive Summary

What the report is about

Increasing stress is being placed on the profitability and long-term sustainability of many Australian fisheries. Even well-managed fishery stocks are unlikely to yield increased harvests in the immediate future using traditional harvest control management approaches. Increasing attention is therefore being directed towards pro-active fishery management options. The Queensland Department of Agriculture and Fisheries (DAF) conducted an in-depth review on the cost-effectiveness and applicability of a range of fisheries enhancement techniques for Australian fisheries management. The review was paired with a survey of fishery managers to identify attitudes and barriers to uptake for enhancement strategies, as well as the data output formats required to enable rapid adoption into current decision making processes. This final report only provides a brief synopsis of the major findings from the two project components. Much more comprehensive discussions on each component are contained in Appendices C & D.

Background

Fisheries enhancement refers to the deliberate application of measures aimed at enhancing fisheries productivity and long-term sustainability beyond that which is achievable by good harvest management alone. Fisheries enhancement strategies expand the options available to fisheries managers beyond the use of traditional input-output controls. They provide opportunities for significant socio-economic benefits, through actively improving aquatic habitat and management of fish at the population level. Such approaches may simply offer alternative routes to a particular outcome, or they may support or create outcomes that cannot be achieved by other fisheries management measures (e.g. stocked impoundment fisheries). Enhancement strategies also have the potential to help manage the sometimes high social costs associated with harvest regulations.

Within Australia, fishery enhancement strategies have been applied across a variety of fisheries, but broad and consistent uptake has been limited. Constraints to uptake include fishery manager knowledge levels and their ability to incorporate information on relative merits of different enhancement techniques into their fisheries management decision making processes. Quantitative comparison will enable decisions to be made with greater certainty and to deliver the best value from an investment.

Project aims

1. To provide a consolidated fisheries enhancement knowledge base to enable robust comparisons of the relative return on investment for different enhancement approaches across various fisheries, and assessment of their long-term viability and impact on fishery productivity and sustainability.
2. Synthesize information on the socio-economic costs and benefits of fisheries enhancement strategies to provide managers with a more comprehensive suite of data to inform their management decisions.
3. Evaluate the current knowledge levels, experience with, and attitudes towards using fisheries enhancement strategies for fisheries managers in Australia.
4. Identify the perceived manager knowledge levels, knowledge gaps, the type of data managers would like to receive, and the format which would be most useful to incorporate into the decision-making process.

Methodology

A two-part approach was used to review the use, attitudes towards, effectiveness and applicability of fisheries enhancement methods in Australia.

Firstly, a systematic review of literature was undertaken to identify quantitative data on the costs, benefits and socio-economic evaluations of fisheries enhancement projects, both within Australia and globally. The review targeted three categories of enhancement activities: habitat enhancement with artificial reefs and fish attracting devices (FADs); fish stocking; and rehabilitation of natural habitat. Within each of these categories, data was collated from both academic (peer-reviewed) and professional (technical) literature. Economic valuation and economic impact analysis were used to compare the economic outcomes to fisheries between projects. Whilst a broad range of ecological and socio-economic benefits can be generated by enhancement projects, this review focussed only on the benefits accruing to fisheries. As long as the net benefits to fisheries exceeded the net costs of implementation, the enhancement activity will provide positive net benefits from a fisheries management perspective. Benefit cost analyses were used to compare the indicative net present value (NPV) and benefit-cost ratio (BCR) between different enhancement techniques to help inform managers of the relative potential for each approach.

Secondly, fisheries managers from across Australia were surveyed to evaluate their current knowledge levels, experience with, and attitudes towards using fisheries enhancement strategies. The survey identified the perceived knowledge gaps, types of data managers would like to receive to inform decisions and the data and decision support tool formats which would be most useful to incorporate such information into the decision making process.

Key findings

A measured and responsible approach to the use of fisheries enhancement strategies has generally been undertaken in Australia, particularly in the past two decades. Comprehensive research and planning now underpins most new enhancement projects (e.g. NSW marine stocking strategy, Western Australian artificial reef program etc.). However, better data collection on the socio-economic impacts is required to provide greater confidence in positive outcomes, facilitate greater uptake by fishery managers and develop support from stakeholders. New projects need to incorporate the appraisal or evaluation of socio-economic outcomes as a core component of their design, not only to further our knowledge base, but to also justify to stakeholders and investors that the expenses outlaid have been warranted and will provide a positive socio-economic return.

Habitat enhancement has primarily been undertaken for the purpose of recreational fisheries in Australia. The installation of artificial reefs has typically increased local fish abundance, biomass and diversity when installed at sites where the existing habitat is bare or homogenous. Purpose-built reefs, constructed of sufficient size and complexity, are capable of both attracting and producing fish of recreational and commercial importance. There is a growing consensus that most artificial reef projects have warranted the expense. However, the economic value of habitat enhancement projects whilst positive, typically returns relatively low benefit cost ratios (median BCR = 1.29, internal rate of return = 8.55%).

Stocking practices in Australia generally comply with world best practice, but require better socio-economic evaluation. Significant species level differences in enhancement success have been reported. Strategically planned fish stocking can make significant contributions to fishery catches and deliver substantial socio-economic benefits under the right circumstances. However, there are significant ecological risks that need to be well-managed, especially the genetic impacts on wild populations. The majority of fish stocking in Australia has occurred for freshwater recreational fisheries, but estuarine stocking is becoming more prevalent. Our understanding of the full impacts of stocking has been hindered by the inability to discriminate between hatchery-reared and wild fish. Stocking produced the highest benefit cost ratios. Angler willingness to pay has demonstrated the socio-economic feasibility and public support of stock enhancement programs for recreational fisheries improvement. The greatest economic benefits were achieved for recreational fisheries in enclosed waterbodies (e.g. freshwater impoundments) with limited natural recruitment and where emigration of stocked fish was restricted. Few studies have demonstrated stocking to have an additive effect on regional fish abundance.

Large-scale habitat enhancement conducted for fisheries development has experienced slow uptake in Australia, in part due to manager uncertainty regarding the likely outcomes. The socio-economic costs and benefits are rarely fully quantified, making it difficult to compare and justify costs between different projects or management options. Based on the published socio-economic literature available, mangrove rehabilitation appears likely to generate the best return on investment from a fisheries perspective. Rehabilitation of river habitats, seagrass and shellfish reefs are also likely to provide positive economic returns for fisheries, but the high cost of coral reef restoration and the low value of fishery production from salt marshes mean rehabilitation of these habitats is not likely to be economically feasible for fisheries enhancement. However, these results are only indicative, and care needs to be taken because they are sensitive to the input values of the cost and benefits. The benefit-cost ratio for preserving natural habitats can be as high or higher than rehabilitation activities, suggesting that investing in maintaining and preserving existing natural habitats may in some instances be more cost-effective and deliver greater benefits than rehabilitating degraded systems. There is considerable community support for utilising habitat rehabilitation to enhance fisheries, with a willingness to pay amongst both users and non-users. Such user or community support is vital to encourage backing by politicians and uptake by managers of habitat rehabilitation as a fisheries enhancement tool.

The fisheries manager survey results indicated that enhancement strategies were used almost twice as commonly in recreational fisheries than the commercial sector in Australia. Stakeholder and political support are likely significant drivers behind this difference. Survey respondents identified a perceived lack of quantitative data available on fisheries enhancement projects as one of the main reasons that enhancement projects are not undertaken more frequently in suitable situations. This knowledge gap hinders the efficient allocation of management resources and effective comparisons between alternative management options. Improving manager access to quantitative data on the outcomes of enhancement projects will improve their confidence in utilising enhancement strategies and likely lead to greater consideration and uptake.

High implementation costs and resource limitations were perceived as key barriers to uptake of enhancement strategies. Additionally, when sufficient funds were available, the lack of predictable economic return on the investment appeared to be more important than the absolute investment required. Results from additional economic analysis may shift the focus away from initial and on-going investment by providing a greater focus on the overall economic outcomes achievable.

There was a strong desire amongst managers for access to specific decision support tools to better incorporate fisheries enhancement options into current fisheries management decision frameworks. However, there was no clear consensus on the design and level of complexity of such decision support tools that would be universally appropriate. Disagreement also existed on whether such tools should be stand-alone processes or be able to fully integrate into existing decision frameworks.

Implications for relevant stakeholders

Clearly understanding the threats and stressors impacting fisheries systems, identifying realistic and quantitative management objectives and increased use of bio-economic modelling will be core to pro-actively managing commercial and recreational fisheries in Australia in a sustainable way using fishery enhancement strategies. Incorporating enhancement options into decision making processes will expand the options available to fisheries managers beyond the use of traditional input-output controls.

There is potential to expand the value of recreational fisheries and create niche fishing opportunities that can drive regional development. Rehabilitation of aquatic habitat has the potential to sustainably increase the productivity, yield and value of Australia's fisheries and improve resilience against adverse events and climate change. Fish stocking has significant potential for expansion, particularly in closed and semi-closed estuarine and impoundment systems. There are opportunities to expand the suite of species that are currently stocked, to diversify recreational fishing opportunities and attract more angler to areas with unique fisheries. Artificial reefs and FADs currently have high recreational fisher support, and their installation can improve access and fishing options. Undertaken appropriately, habitat enhancement can also increase overall fishery productivity by supporting the life-history requirements of fish and invertebrates and help systems become more resilient to climate change.

For commercial fisheries, habitat rehabilitation has the potential to increase wild recruitment that may be limited due to the degradation and loss of essential fish habitats, such as nursery areas. Better recruitment is likely to result in increased yields and greater long-term sustainability within fisheries. Stock enhancement has the potential in some species to help recover depleted wild stocks more rapidly or to create new fisheries. The greatest potential for stock enhancement in the short-term remains with stocking less mobile, high-value invertebrate species.

Fishery enhancement approaches should not be seen as a replacement for good fishery management, but instead as part of a suite of potential management tools that can be utilised together to deliver strong, sustainable fisheries outcomes. Integrating different fishery enhancement strategies has the potential to deliver substantial socio-economic benefits. The greatest benefits are likely to occur when different strategies are integrated to comprehensively address the issues limiting fisheries production or expansion. Combining management of habitat to increase carrying capacity and responsible stock enhancement to overcome recruitment limitations will help optimise stock levels and harvest potential in the most efficient way. Bio-economic modelling is key to appraising the potential of integrated habitat or stocking initiatives relative to other fisheries management measures and evaluating the cost–benefits of individual programs.

Decision-support frameworks and modelling tools already exist which could be readily adapted to assess the outcomes of fisheries enhancement scenarios. Application of these tools to evaluate the potential for multiplicative gains and the relative costs and benefits of such endeavours, will allow informed decision making prior to any large investments being made. However, until sufficient data is available in Australia to support these existing tools, it is recommended that a suitability matrix for fisheries enhancement options should be developed for all fisheries in Australia to provide managers with a rapid method for identifying appropriate enhancement strategies that align to strategic management objectives.

Recommendations

The following recommendation will help clarify our understanding of the outcomes of fisheries enhancement activities and enable more cost-effective implementation:

- All new major projects should incorporate socio-economic evaluation on their impacts.
- Stocking cost-efficiency gains could be achieved by improving release strategies via pre-release training, acclimation and improvement of release habitats. The value of these actions is likely to vary among species and potentially locations, depending on predator abundance.
- A national approach to identification of hatchery-reared fish is critically needed. Genetic marking through lineage and parental analysis holds great promise and should be considered for national adoption.
- The use of different fisheries enhancement strategies should be integrated to potentially deliver multiplicative benefits across the entire life-history of target species.
- Standardised analysis and reporting guidelines should be developed for all enhancement activities.
- Adaptive management should be employed in fishery enhancement projects to enable the results from monitoring and research to be rapidly adopted to maximise outcomes.
- A suitability matrix for fisheries enhancement options should be developed for the various fisheries in Australia to provide managers with a rapid method for identifying appropriate enhancement strategies.
- The potential of developing a generic bio-economic model and an associated database containing relevant biological and economic parameters for a range of species and fisheries should be investigated.
- Co-investment for fisheries enhancement projects should be sought from various stakeholder groups where relevant, to capitalise on the broad social benefits and ecosystem services that can be delivered.

Keywords

Fishery enhancement, habitat enhancement, stocking, habitat rehabilitation, FAD, artificial reef, economic impact analysis, benefit cost analysis, net present value, decision support tool, fishery manager experience.

Introduction

This final report provides a brief synopsis of the major findings from the two project components investigating historic use and outcomes of fisheries enhancement techniques and the attitudes of Australian fisheries managers towards their application. More comprehensive data and discussions on the topics discussed are contained within Appendices C & D.

Many fisheries resources worldwide are fully or over-exploited, and Australia is no exception (FAO 2022). Fisheries resources are experiencing ever-growing pressure from population growth, habitat degradation, access restrictions, climate change, rising consumer demand, expanding focus on food security, economic development and overfishing (Munro and Bell 1997, Crowder *et al.* 2000, Morgan *et al.* 2001, Brown and Day 2002, Post *et al.* 2002, Molony and Bird 2002, Molony *et al.* 2003, Bell *et al.* 2006, Lorenzen *et al.* 2013). These are placing increasing stress on the profitability and long-term sustainability of many fisheries. Fish stocks and therefore fisheries productivity can also be constrained by factors such as recruitment, habitat, trophic webs and genetic bottlenecks (Becker *et al.* 2018). Even well-managed fishery stocks are unlikely to yield increased harvests in the immediate future. It is likely that future demands on fisheries resources will intensify public pressure to augment natural resources through enhancement activities. Increasing attention is therefore being directed towards pro-active management options to potentially alleviate these constraints.

Traditional input-output management approaches will continue to play an important role in helping to sustain fisheries in the face of these pressures, but it is unlikely to have the capacity to fully mitigate the broad challenges faced (Hollowed *et al.* 2013). Over the last few decades there has been an increasing shift towards the utilisation of techniques that involve manipulation of the aquatic environment and direct enhancement of fishery stocks (Ross 1997, Lorenzen 2014).

A range of techniques have been employed around the world to enhance the value and sustainability of recreational and commercial fisheries (Florisson *et al.* 2018). In many instances these techniques have proven to be extremely effective and become core components of fisheries management (Florisson *et al.* 2018). In other instances, successful results have not been achieved or the risks have been considered to outweigh the potential benefits.

Fisheries enhancement refers to the deliberate application of measures aimed at enhancing productivity and long-term sustainability beyond what is achievable by good harvest management alone (Taylor *et al.* 2018). In theory, successful fisheries enhancement has the potential to yield significant productivity, social and ecological benefits. Natural fisheries productivity can theoretically be increased, providing higher harvests at a lower cost (Lorenzen *et al.* 2000). Alternatively, fisheries enhancement could create new economic opportunities for fisheries-related industries (Lorenzen 2005) or help address the depletion of key fish stocks from overfishing (Brummett *et al.* 2013). Enhancement approaches are often socially and politically preferable because they reduce the likelihood of applying additional unpopular restrictions under traditional management approaches (Grimes 1998, Borg 2004).

To be successful, techniques must contribute to a broad set of biological, economic, social and institutional management objectives, typically within complex fisheries systems (Lorenzen 2008). For fishery enhancement techniques to value-add, or outperform the alternative measures of traditional input-output controls, specific conditions may be necessary. Enhancement measures often encompass technical solutions that address natural or human-induced ecological limitations in natural systems to restore existing fisheries, increase productivity or develop new fisheries.

Manipulation of the environment or stocking of fish to provide or improve a fisheries resource is an ancient practice (Riggio *et al.* 2000, Seaman 2000). Since earliest times fishermen have sought ways to increase their catch or reduce the effort needed. Initial efforts focussed on building artificial reefs to attract fish and translocating fish to create new fisheries or to enhance existing populations. Since then, significant research and management effort has been invested trying to determine how this can be achieved most successfully and cost-effectively. More recently, greater emphasis has been placed upon the potential biological and non-target impacts of using fishery enhancements, including impacts to trophic food webs, genetics of wild stocks and large-scale stock depletion (Blankenship and Leber 1995, Lorenzen *et al.* 2010).

Fisheries enhancement can be classified into three broad categories:

1. Habitat enhancement (artificial reefs and fish attracting devices).
2. Fish stocking (stock augmentation, restocking, stock creation, ranching).
3. Habitat rehabilitation (rehabilitation of key habitats or ecosystem processes).

Each of these approaches have been employed by managers and fishers around the world in attempts to enhance fisheries outputs.

Fisheries enhancement has been utilised in all fishery sectors, from recreational, subsistence and artisanal fishers and commercial operations. The relative levels of use and the types of approach taken by different sectors varies between countries. For example, in Australia and the USA, fisheries enhancement has primarily focussed on improving recreational fishing. In contrast, Japan and South Korea have almost exclusively focussed their enhancement efforts on improving commercial fisheries. In Europe, the focus has been on the protection of sensitive habitat areas important to commercial fisheries, such as seagrass and other fish nurseries, whilst in many south-east Asian and Pacific Island countries, the focus of fisheries enhancement has been to improve subsistence and artisanal fisheries.

Within Australia, numerous enhancement approaches have been applied within a variety of fisheries, but broad and consistent uptake across different fishery sectors has been limited. Constraints to uptake are assumed to include fishery manager knowledge levels and their ability to incorporate information on relative merits of different enhancement techniques into their fisheries management decision making processes. Quantitative comparison between the relative effectiveness of different enhancement approaches is often lacking. This has in part been due to the lack of effective quantitative socio-economic evaluation conducted on projects, but also because the decision to use fisheries enhancement techniques are often heavily influenced by politics. This is especially the case in the recreational fishing sector where enhancement projects are generally well received by the community and frequently derived from political promises.

Need

This project was identified by the South Australia Research Advisory Committee (SA RAC) as a FRDC priority in its January 2021 funding round, with funding commencing in October of 2021.

Despite a general trend for positive results from most fishery enhancement projects, not all approaches may deliver the best return on investment. Quantitative comparison of techniques is required to enable decisions to be made with greater certainty and to deliver the best value from an investment. A recent review into the value of man-made aquatic structures to fisheries by Harvey *et al.* (2021) concluded that understanding socio-economic values and benefits is a key component to guide any future decisions about fishery enhancement activities.

Broad uptake and application of some fisheries enhancement techniques by Australian fisheries managers has been limited. One key constraint has been the absence of clear comparative data on the relative costs and benefits for each approach and how they can be most effectively applied in different scenarios. Fisheries enhancement is widely practiced globally, and quantitative assessments exist for some techniques. Cost-benefit analyses have also been conducted for a few projects in Australia, but the results have yet to be combined and considered in the context of broader application by fisheries managers.

A consolidated fisheries enhancement knowledge base will enable robust comparisons of the relative return on investment for different approaches across various fisheries, and assessment of their long-term viability, and impact on fishery productivity and sustainability. Such information will assist managers more clearly identify the most appropriate techniques to adopt and their potential benefits for their specific fishery, encouraging increased uptake and implementation. Clearer understanding of the relative merits and risks of different enhancement techniques will also enable appropriate techniques to be better incorporated into decision making processes, such as harvest strategies, and help identify critical knowledge gaps that need addressing.

Other key constraints to uptake of enhancement strategies include fishery manager knowledge levels and their ability to incorporate information on the relative merits of different enhancement techniques into their fisheries management decision making processes (Ruckelshaus *et al.* 2015, Taylor *et al.* 2017). It is therefore important to understand how mangers currently make decisions regarding the use of fishery enhancement techniques and what they consider to be the critical characteristics of decision support tools needed to improve uptake and application of such strategies. At the national and multi-fisheries scale, such information is rare, and typically limited to very specific scenarios. Access to such knowledge will enable more appropriate and effective promotion of suitable enhancement strategies. It will also allow these factors to be incorporated into decision support tools to help increase manager’s consideration and uptake of different enhancement strategies in the fisheries they manage.

Objectives

The objectives of this review were to:

1. Conduct a literature review of fisheries enhancement techniques, focussing on quantitative costs, benefits and socio-economic data.
2. Conduct a cost benefit analysis to identify the relative efficiency of various enhancement techniques in different scenarios.
3. Understand fishery managers’ awareness and use of fishery enhancement strategies.
4. Identify key factors currently used in their fishery management decision making processes.
5. Identify desirable and undesirable parameters for a fishery enhancement decision support tool.

Originally two additional objectives were included in the project: a) to develop a decision support tool (DST) for managers and b) to extend training on the use of the DST. However, the results from the survey of managers could not identify a consensus on the design and complexity of a universal DST, and thus this component of the project was discontinued.

Methods

Literature review

This review consisted of multiple steps to ensure a comprehensive suite of appropriate data was collated and presented in a manner useable by fisheries managers. Initially, a systematic literature review was conducted to identify potential data sources. The review encompassed projects from both Australia and worldwide, in order to identify sufficient data for analysis. This information was combined into a cost benefit analysis to compare the relative benefits and value of different enhancement techniques in different scenarios. Each of the three categories of fisheries enhancement were initially addressed separately, before this information was combined to provide a more holistic approach.

Data collection

A systematic review of literature was undertaken to identify quantitative data on the costs, benefits and socio-economic evaluations of fisheries enhancement projects, both within Australia and globally. As interest in using enhancement strategies in fisheries management has grown, multiple literature reviews and meta-analyses of the different fields of fisheries enhancement have been conducted. The main focus of many of these reviews has been on the biological responses, such as changes in relative fish abundance and ecosystem evolution following fisheries enhancement activities. Although understanding of these processes is critical for their use in fisheries management and assessing the effectiveness of projects, the objective of the current review was to specifically focus on the cost, benefits and socio-economic impacts derived from such projects. Therefore, only a brief overview was provided on ecological outcomes and the review primarily reported on documented socio-economic outcomes.

Three broad categories of fisheries enhancement techniques were identified: habitat enhancement, fish stocking and habitat rehabilitation. Within each of these categories, project data was collated from both academic (peer-reviewed) and professional (technical) reports. All relevant articles were stored in a reference library in Endnote™. Literature was then screened based on three criteria: title, abstract and complete manuscript.

The literature search was initially conducted on articles from 1969 to 2022 that were indexed in English and examined any aspect related to the cost and benefits of fishery enhancement practices. Studies from all disciplines, ranging from economics, fisheries management, environmental management and rehabilitation, tourism and ecology were included. Only studies that provided data on the effectiveness, or costs and benefits of fishery enhancement techniques were included. Articles describing activities whose principal function was not to support fisheries development (e.g. breakwaters, shipwrecks, conservation stocking, offshore wind turbines) were not included. Journal articles and books published by reputable publishers were deemed as high-quality research, and therefore, included in the review. A significant number of technical reports also contained highly relevant data. These were included if they were published by a government agency, university or other reputable group, were of high-quality and well referenced.

Due to the broad scope of terms describing fishery enhancement projects, a substantial list of search keywords was necessary. Leading databases were searched using synonyms for ‘fisheries enhancement’, ‘habitat enhancement’, ‘fish stocking’, ‘habitat rehabilitation’, ‘cost-benefit’ and ‘socio-economic value’.

The citation of each publication from each search was downloaded and used to create a reference library in Endnote™. The search was conducted within the title, abstract and keywords using the terms related to the subject. Duplicate indexed articles were excluded and considered as only one document. Articles were also excluded if the complete document was not available online or accessible via inter-library loan. At first, the title of the literature was studied; if found relevant, then the abstract of the literature was carefully read. Finally, the full text of the literature was studied if the abstract was found relevant. All papers were given a relevance rating (1-5) in the Endnote database. Papers with a rating of two or less were not included in the final analyses.

The initial search returned insufficient articles for some areas of interest. Therefore, a secondary manual search was undertaken using a snowball technique analysing the reference lists of relevant studies and a broader internet search using the Google™ search engine. This approach identified a substantial number of additional relevant references, particularly in the professional literature (only published as technical reports).

From each article, information was extracted on the following four subtopics: (1) details of the fishery enhancement activities (e.g. location, scale, nature of activities undertaken, target species, fishery sector), (2) costs associated with implementation, (3) fishery benefits attributable to the enhancement activities, and (4) any socio-economic values or analyses.

A total of 2,303 citations were extracted from the initial and secondary searches. These were reduced to 1,869 when duplicate publications were removed, with 1,541 of these being accessible and had at least the abstract written in English. Screening by abstract further reduced this to 809 articles, whilst screening after reading the full manuscript left 224 articles. Of the three main categories of fisheries enhancement, habitat enhancement (83) contained the greatest number of relevant publications, followed by fish stocking (78) and habitat rehabilitation (63).

Economic comparison

Economic impact analysis and economic valuation are two widely used but distinctly different economic measures that can be used to evaluate and compare the economic outcomes from fisheries enhancement projects. The first provides information on the actual or potential impacts of a fishery enhancement project, whilst the second determines whether the project is an efficient investment. It is important to distinguish between these concepts because they are commonly confused (Burgan and Mules 2001, Watson *et al.* 2007). More information was available on economic values; however, the results from the literature review report both type of results where information is available. For public sector projects (such as fishery enhancement), an economic appraisal using cost benefit analysis is typically more appropriate than a financial appraisal using impact economic analysis because both externalities (costs and benefits) and intangible impacts need to be considered (Whitmarsh and Pickering 2000).

The costs incurred undertaking fishery enhancement and the benefits generated, arise over a period of time. This characteristic is of central importance, given that the biological processes underlying fisheries productivity do not occur instantaneously and that the physical life of the enhancement activities may extend over several decades (Whitmarsh and Pickering 2000). These costs and benefits need to be discounted to reduce future values to bring them into line with today's values. In Australia, discount rates between 4-7% are commonly used for environmental resource projects, but there is no single definitive value (Walker *et al.* 2008, Hone *et al.* 2022). Therefore, we selected a rate of 5% for our cost benefit analyses, which was the median value from those used in the reviewed studies and matched those previously used in Australia.

The aim of this review was not to evaluate the total economic value for enhancement activities, but instead to investigate how the costs of different approaches compared with the resultant benefits to fisheries. Investment in enhancement projects for fisheries development is undertaken to improve fisheries value and sustainability. Additional socio-economic benefits will value-add to an enhancement approach, but are likely to be secondary considerations for fisheries managers when determining activities that will be undertaken. Therefore, this review focussed only on benefits accruing to fisheries from enhancement (*e.g.* van Vuuren and Roy 1993).

In total, 224 articles examining socio-economic benefits of fisheries enhancement approaches were analysed to identify the country and year of study, enhancement type, the measured value types, valuation method and the valuation context or question. To enable accurate economic comparison between studies, all economic value estimates were converted to 2021 AUD values using the Reserve Bank of Australia's historical currency conversion data for the relevant countries (available at https://www.rba.gov.au/statistics/historical-data.html#exchange-rates) and the Consumer Price Index published by the Australian Tax Office (https://www.ato.gov.au/rates/consumer-price-index/).

In this review, economic impacts and economic valuations resulting from fishery enhancement studies were reported separately for each of the three main enhancement categories. Where sufficient information was available, data within each category was further grouped to provide an overview of socio-economic benefits for various actions or scenarios (e.g. estuarine artificial reefs, offshore artificial reefs, freshwater artificial reefs). The data grouping facilitated comparison between activity types and the environments where they were undertaken. For each group where sufficient cost and benefit information was available, a cost benefit analysis was conducted using mean or median values, based on a 30-year time horizon and 5% discount rate. Where necessary, delays in the full realisation of benefits were incorporated to account for cumulative biologically driven increases in productivity. The results from the cost benefit analyses were used to compare the indicative NPV and BCR between groups and techniques, to help inform managers of the relative potential for each approach.

Limited primary socio-economic data has been collected on fishery enhancement activities in Australia. Therefore, global data was included in the analyses and comparison. While some of the costs and benefits values of fishery enhancement activities from other countries can be generalised and transferred to Australia, the usefulness of the information depends on the location specificity (i.e. local fine scale location specific areas of interest) required by proponents or decision makers (Harvey *et al.* 2021).

Manager survey

A national online survey of people involved in fisheries management decisions was undertaken to understand their awareness and use of fisheries enhancement strategies, identify the key factors currently used when making fisheries management decisions, and to identify desirable and undesirable parameters for fisheries enhancement decision support tools.

The study collected information from project participants through an online survey and some direct, unstructured follow-up interviews. The survey questions were divided into four sections exploring survey participant's:

- current role in the fishery,
- knowledge and experience regarding the use of enhancement strategies,
- current management decision making processes,
- desired criteria and potential willingness to use fishery enhancement decision support tools.

Initial survey questions covered respondent characteristics, including their location, role in fisheries management, and the specific fisheries they provide input into. Harvey *et al.* (2021) identified significant differences in the perspectives towards man-made marine structures between commercial and recreational fishers. Similar differences may also be evident in how these two fisheries sectors are managed. Respondents were therefore also asked to self-allocate whether their fisheries management role related to either recreational fisheries, commercial fisheries or both, to investigate whether experience with fisheries enhancement and management practices varied between the two sectors.

The online survey used a combination of question types to collect both quantitative and qualitative data. Five-point Likert scale questions (Tugend *et al.* 1999, Fitzsimmons 2008, Watson and Preedy 2010) were applied to employed to convert qualitative information into quantitative data on respondents' perceptions of fisheries enhancement (ranging from strongly disagree to strongly agree) and the importance of various values when making decisions (ranging from not at all important to extremely important). Open-ended questions were used to capture qualitative data, such as descriptions of benefits and limitations, explanations, comments or identify suitable reference material for the cost benefit analysis. In this way, further information on values and perceptions that could extend the closed response questions were gathered. Several questions required respondents to rank lists of answers to grade their relative importance, while other closed questions required respondents to select the relevant answers from a list or provide Yes or No responses.

The survey was pilot tested by a small focus group of fisheries managers within DAF. The pilot enabled the survey to be refined to ensure it addresses all of the topics in a concise yet comprehensive manner, and that it was not too onerous for participants.

The survey targeted people involved in the management decisions for various fisheries in Australia, both stock and harvest management, and policy development. Researchers and lead industry representatives who play a key role in management decisions were also be included because of their advisory role. The potential broad scope of enhancement technique application across fisheries means that as wide a profile as possible of fisheries managers were surveyed to ensure all views and experience levels were captured. The level of experience and current use of fishery enhancement techniques varies greatly between states in Australia. Therefore, fisheries managers from across Australia were asked to participate to capture regional views, issues and experiences.

Potential participants were initially approached by email. All participants in the survey were volunteers and did not receive any payment or incentive to participate. Following acknowledgement of their willingness to participate, they were allocated a Unique Identifier Code (UIC) and emailed a link to the survey. A total of 98 people were sent invitations to participate, of which 43 completed the survey. The survey was open for a period of four weeks to allow participants sufficient time to respond. All participants received the same questionnaire, but their personal information was kept confidential through allocation of the UIC. Only the principal investigator had access to this information and at the end of the project, the UIC code key was deleted to permanently de-identify individual survey responses.

In some instances where respondents provided examples on scenarios where particular fishery enhancement techniques have been used, follow-up telephone conversations were used to gather more details for a literature review and cost-benefit analysis These conversations were unstructured and explore the costs, benefits, success and learnings from that application of enhancement strategies.

Results and discussion

Literature review

This final report contains an abridged version of the literature review results. More detailed results and economic analyses can be found in the full literature review in Appendix C.

A measured and responsible approach to the employment of fisheries enhancement strategies has generally been undertaken in Australia, particularly in the past two decades. Comprehensive research and planning now underpins most new enhancement projects (e.g. NSW marine stocking strategy, WA artificial reef program). However, better data collection on the socio-economic impacts is required to demonstrate the potential socio-economic benefits from enhancement activities and facilitate greater uptake by fishery managers and develop support from stakeholders. New projects need to incorporate socio-economic appraisal or evaluation as a core component of their design, not only to further our knowledge base, but to also justify to stakeholders and investors that the expenses outlaid have been warranted and will provide a positive socio-economic return.

The following sections summarise the key findings from the full literature (Appendix C) on the cost-effectiveness of the three fisheries enhancement categories: habitat enhancement, fish stocking and habitat rehabilitation.

Habitat enhancement

The application of habitat enhancement for fisheries management is widespread and has varied regionally. The primary focus is on commercial fisheries in Japan, China, Korea, and Taiwan, small-scale and artisanal fisheries in Europe, Brazil, the south Pacific and south-east Asia, and recreational fisheries in Australia and the USA. The number of locations where artificial reefs and FADs are being installed is increasing. In Australia, there is an increasing trend for more structures to be installed, being driven primarily by demand from the recreational sector. There appears to be a high willingness from anglers for licence fee revenue to be invested in the creation of new habitat enhancement sites, using both purpose-built reefs and FADs.

Habitat enhancement can have significant ecological impacts, particularly on the composition and structure of fish assemblages. The installation of artificial reefs typically increases fish abundance, biomass and diversity when installed at sites where the existing habitat is bare or homogenous. The composition of the resultant fish assemblages is rarely identical to those at nearby natural reefs or other complex structure, but often contains higher abundances of exploitable fish. The higher abundance and biomass of fish species recorded at artificial reefs typically lead to higher catch values for exploited species. These characteristics suggests that purpose-built structures containing traits desirable to exploitable fish have potential as a fisheries management tool to improve the economic value of some fisheries.

The role of artificial reefs in both the attraction and production of exploitable fish has historically been debated and identified as one of the main constraints in greater uptake of artificial reefs by fisheries managers. However, results from recent research clearly demonstrate that purpose-built reefs, constructed of sufficient size and complexity, are capable of both attracting and producing fish of recreational and commercial importance (Smith *et al.* 2015, Lima *et al.* 2020, Vivier *et al.* 2021). Succession in the community assemblage influences the relative contributions of each process to the standing fish stocks (Cresson *et al.* 2019). Attraction is likely to initially be highest until sufficient epibenthic flora and fauna develop to encourage production to occur. This process can take a decade or more to reach stable, high fish production levels (Roa-Ureta *et al.* 2019, Folpp *et al.* 2020).

The impact of reef installation is most pronounced in species which are habitat-limited at stages of their life-history, especially in regions where hard structure is naturally limited (Bortone 2008). The level of new fish production and existing stock status play a large role in the marginal fishery benefits achieved (Becker *et al.* 2018). Higher productivity levels of exploitable biomass can sustain greater harvest effort without impacting on nearby standing stock.

Despite the high prevalence in the use of artificial reefs and FADs for fishery enhancement, comparatively few studies have quantified the socio-economic benefits derived. Nevertheless, the findings available in the literature suggest that habitat enhancement can generate significant ecological and socio-economic benefits and create substantial economic value (e.g. Whitmarsh *et al.* 2008, Nous 2019, Harvey *et al.* 2021). Habitat enhancement is generally considered an economic asset by stakeholders and managers, who are usually willing to contribute towards construction and maintenance. The often high construction cost and attraction to non-resident anglers typically led to high economic outputs for regions where structures had been installed (e.g. Bell 2003).

While the economic benefits of artificial reefs may potentially be quite large, it is widely accepted overseas that in commercial fisheries the benefits may be offset where an expansion in harvesting pressure leads to overexploitation. Harvest management appears to play a pivotal role in how well fisheries at artificial reefs perform. The comparatively lower fishing mortality from artisanal and recreational fishing efforts are less likely to have long-term detrimental impacts on fishery stocks at artificial reefs than more intense commercial exploitation. However, in Australia most artificial reefs are established and managed primarily for recreational benefit and commercial fishing is often excluded or strictly regulated. Therefore, commercial overexploitation is unlikely.

Where a stock is already regionally heavily exploited, or harvest pressure is predicted to be high, locating artificial reefs in protected areas or restricting access to particular harvest techniques may prove more socio-economically beneficial than permitting open-access. The reefs can then act as a source for emigration to other nearby reefs. A more complex version of this approach has effectively been applied in the Mediterranean, where artificial reef complexes consist of two zones: a production zone surrounded by an exploitation zone (Gonclaves *et al.* 2003, Roa-Ureta *et al.* 2019). Harvest is banned within the more densely constructed production zone, whilst the exploitation zone has a more dispersed format designed to facilitate harvest.

The potential of reef complexes to attract exploitable species was demonstrated to have socio-economic benefits for artisanal and recreational fishermen, but few examples could be found for larger scale commercial harvest operations outside of overseas ranching projects (habitat enhancement plus stocking). Although cost benefit analysis has generally been lacking, there is a consensus that most artificial reef projects have warranted the expense. However, the economic value of habitat enhancement projects whilst positive, typically returns relatively low benefit cost ratios (BCR). Median BCR from the literature covered in this review was only 1.29 (excluding one outlier), and median internal rate of return of 8.55%. Within the limited dataset analysed (n=19), the economic value was greater generally for recreational fishery enhancement projects than for those undertaken for commercial fisheries.

The costs for installing artificial reefs in marine areas is typically quite high, with most structures in Australia costing over $1 million to complete. The use of artificial reefs in estuaries, bays and freshwater impoundments has lower costs because the reefs generally consist of multiple smaller modular units, which are cheaper to construct and deploy. Their use in inshore and inland waterways is still being explored, but the initial results have been promising. One potential use of habitat enhancement structures is to attract fish to sites where shore-based anglers have ready access, such as piers, jetties and parks. This improves access to fish and opportunities for anglers, especially those who are mobility limited. This type of enhancement has already occurred in several locations in Australia. The approach has successfully been used extensively in lake and impoundment systems in the USA, where it has delivered substantial economic returns for their inland fisheries and become a core management tool to achieve improved recreational catches and angling experiences. Similar results can be expected in Australia if enhancement is undertaken appropriately, especially in stocked put-grow-take impoundment fisheries where overharvest is less of a concern.

Research and monitoring programs that assess artificial reefs against their goals will be increasingly important in future. This is principally driven by growing environmental awareness and a social licence based on the expectation of rigorous evaluation and environmentally sustainable outcomes. Demonstrating the performance of artificial reefs and FADs against quantitative goals is likely to support this social licence into the future.

Only limited socio-economic studies have been conducted on Australian habitat enhancement projects. There is great opportunity to collect critical socio-economic information on new projects or to evaluate the outcomes of existing ones. One area that urgently needs attention is the use of FADs in recreational fisheries. Despite being extremely popular with anglers, who often travel significant distances to use them, little information on their economic value is available. These structures are comparatively cheap to install compared to purpose-built reefs and host a number of highly desired fast growing pelagic species. It is expected that cost benefit analyses of the FAD programs run in most states will demonstrate substantial positive economic returns. In Queensland, as part of the 'Switch your fish' campaign, FADs were installed in an attempt to divert some angling pressure away from heavily fished demersal species. Understanding the socio-economic and ecological impacts of this project would provide valuable insight into the use of FADs or artificial reefs as management tools. Retrospective evaluation of the King Integrated Artificial Reef in Exmouth (WA) presents another great opportunity for confirming the accuracy of the values used in the initial economic appraisal and to validate assumptions on important socio-economic parameters. The results would inform and strengthen future economic appraisals for similar reef installation proposals.

Fish stocking

Strategically planned fish stocking can make significant contributions to fishery catches and deliver substantial socio-economic benefits under the right circumstances. However, the mass release of hatchery-reared fish occurs at considerable cost and does not always lead to increases in the abundances of target fishery stocks, with few studies showing stocking to have an additive effect on total or regional fish abundance. Inadequate monitoring and the inability to effectively discriminate between released and wild fish have restricted evaluations, as has a lack of scrutiny of the economic feasibility. In recent years there has been greater focus on research, monitoring and evaluation, which has provided clearer evidence that in enhancement operations, overall benefits can exceed costs. Conclusions regarding the potential of stock enhancement as a management tool to create, sustain or recover fish stocks can only be made if biological information is coupled with economic information to predict the economic costs associated with stock enhancement relative to the costs associated with alternative management approaches.

The majority of stocking projects have been conducted in degraded or overfished systems to recover fisheries, but there can also be opportunities for enhancement in healthy fisheries, provided that the biology and population impacts of enhancement are well understood. Stocking can improve catch consistency, particularly where inter-annual natural recruitment is highly variable. In commercial fisheries, large fluctuations in catches can lead to poor economic performance in fleet and processing operations, and erratic supply to markets. A continuous supply of product allows the market share to be maintained and maximises the efficiency and profitability of the fishery (Loneragan *et al.* 2004).

Stock enhancement through the release of hatchery-reared juveniles is not suitable for all species, therefore target species must be carefully selected and an appropriate long-term strategy developed to shift the fishery from one of catch only, to catch and enhancement. Species with unfavourable ecological profiles, high dispersal, low harvest value and high costs of hatchery production are less likely to be economically feasible to stock at a large scale. Focus should be on high-value species to achieve the best return on investment

The benefits of stocking vary with scale. Often significant benefits can be detected at the local scale (e.g. bay, impoundment or river reach), but limited changes are observed at the whole-of-stock scale. The mobility and dispersal of the released organism and the connectivity of the stocked environment, both appear to play a significant role in the success and economic feasibility of stocking programs. The best results have generally been reported for resident species in closed systems, such as impoundments or bays, whilst few stocking studies have demonstrated economic viability in fully open systems or for highly mobile species. In commercial fisheries, releasing hatchery-reared invertebrates has been more than twice as economically efficient than releasing fish. High-value sedentary invertebrate fisheries have been recognised as good candidates for commercial scale stock enhancement, whilst popular angling species in impoundments or estuaries provide good candidates for recreational fishery stock enhancement. Stocking technologies and strategies need far more scientific development before stocking can be generally accepted as an economically effective fishery-management tool in coastal regions**.**

Angler willingness to pay has demonstrated the socio-economic feasibility and public support for implementing stock enhancement programs for recreational fisheries improvement, with consumer surplus typically exceeding the costs of undertaking fisheries enhancement activities. Anglers were often willing to pay significant amounts for stocking activities to maintain existing fisheries, enhance fisheries and to create new angling opportunities (e.g. impoundment fisheries). These results suggest that expansion of the species and locations stocked in Australia is likely to be economically viable and have the potential to generate significant regional benefits.

The cost-effectiveness and return on investment from stocking have been evaluated using a variety of methods. In many stocking programs, data on the environmental costs, annual costs for harvest, management and interest rates, and induced and indirect socio-economic benefits were not collected or unavailable. Therefore, Net Present Value (NPV) or Economic Efficiency have been used as indices to compare the economic efficiencies between different projects and species. Overall, the NPV and Economic Efficiency analyses, comparing the direct economic benefits and direct production costs, produced economically marginal results, with only a few positive exceptions. If capital, staffing and management costs were included, most stocking projects would probably be economically unviable. Far fewer studies conducted comprehensive cost-benefit analyses encompassing a much broader scope, primarily because of the added difficulty and expense associated with determining the indirect and induced costs and benefits required to calculate the total economic value. Greater application of the cost-benefit analysis approach is expected to identify more stocking projects as economically viable, because the broader economic benefits to the community are captured. This will enable better comparison between the relative impacts of stocking compared to other fishery enhancement measures.

Stocking practices in Australia can generally be considered to be undertaken in a responsible manner (refer to Appendix C for more details), but require better evaluation, particularly of socio-economic factors. The conservative approach taken aligns well with the globally accepted "Responsible Approach" outlined by Blankenship and Leber (1995) and Lorenzen *et al.* (2010). The application of bio-economic modelling by Loneragan *et al.* (2004), Ye *et al.* (2005), Gardner (2012), Hart *et al.* (2013), Broadley *et al.* (2016) and Taylor (2017) in recent Australian marine stocking programs demonstrated world best-practice. However, despite significant ongoing stocking in Australia's inland waterways, monitoring and evaluation of stocked freshwater species for post-release success and impacts is still woefully insufficient and requires urgent attention. Developments in marking and tagging technologies (including genetic discrimination) now allow for better identification of hatchery-reared fish and should be applied to all stocked fish programs (Fitzpatrick *et al.* 2023).

Opportunities exist to improve the cost-effectiveness of stock enhancement programs. Cost efficiency gains can be achieved primarily through improved survival and fitness of released fish and reducing production costs. Research into these areas is likely to deliver positive economic returns on investment for stocking projects. If habitat in the area to be stocked is insufficient or degraded, it should be rehabilitated prior to the release of the hatchery-reared juveniles to improve survival, growth and carrying capacity. This is especially important for nursery areas utilised immediately upon release. The optimal size of released juveniles and timing of release are also critical considerations that affect survival of released fish and cost-effectiveness and should be determined prior to releasing juveniles. Acclimatization and pre-release conditioning programs to improve the survival, growth and reproductive success of hatchery-reared fish can be utilised to improve the rates of survival to harvest and/or spawning size, providing a better return on investment for stocking programs if the additional costs these incur are not too high. For some species, collection of highly abundant wild larvae and post larvae can provide a source of juveniles for rearing programs that helps eliminate some of the genetic risks associated with captive spawning and greatly reduces the costs of collecting, holding and spawning broodstock. Alternatively, in other species there is potential to concurrently produce juveniles for stocking and aquaculture to reduce juvenile production cost. Implementing these approaches is likely to decrease juvenile production costs, but few studies have evaluated how these impact on economic feasibility. The key to developing all of these fields is the adequate and reliable marking of all stock being released to facilitate adaptive management to enable more cost-effective responses to fluctuating natural recruitment levels and environmental conditions.

The effectiveness of stock enhancement depends on how well stocking is integrated with other management strategies. Stock enhancement works best when combined with strong harvest regulations and environmental rehabilitation and protection. Construction of artificial habitats and restoration of lost or degraded areas can increase the carrying capacity and habitat quality for released cultured juveniles. If poor quality of insufficient habitat is present, releasing hatchery-reared fish is unlikely to deliver positive results and may waste management resources.

We still do not understand enough about the effects of stocking on receiving populations or fisheries productivity to use it effectively in some scenarios. Effective stocking programs need to be informed by quantitative appraisals and evaluated to assess likely costs and benefits of outcomes (refer to Appendix C for details). For stocking to become a practical fishery-management tool, cost-effective stocking strategies must be clearly defined. Stocking plans with protocols for critical stocking variables are needed to deliver safe and cost-effective outcomes.

Three key components should be incorporated to maximise the potential socio-economic feasibility of future fish stocking programs:

1. Pilot studies - Pilot releases should always be conducted prior to launching full-scale enhancement programs to inform cost-effective development of optimal management strategies. Pilot releases identify enhancement capabilities and limitations and also provide the empirical data needed to plan enhancement objectives, test assumptions about survival and cost-effectiveness, and improve model predictions of enhancement potential. Thus, pilot-release studies that reveal ways to maximize survival of stocked fish without necessarily increasing rearing costs, can improve cost efficiency in stocking programs.
2. Bio-economic modelling - Bio-economic modelling should be considered essential for all new stocking proposals. Bio-economic models provide a mechanism for integrating biological information with fisheries data and economic information to better assess the potential costs and benefits of release programs and predict the likely economic outcomes resulting from alternative stocking strategies. Such modelling helps identify the main parameters influencing economic outcomes and can be used to examine their sensitivity to determine the necessary requirements for economic feasibility. Pilot studies are essential to inform the bio-economic models and enable development of optimal stocking strategies.
3. Adaptive management framework - Active adaptive management is the single most important measure that can be taken to improve the potential for success in stocking programs (Leber 2004). Having an adaptive management framework enables the results from research,

monitoring and evaluation to be rapidly incorporated into management plans and provides the capacity necessary for flexible responses to capitalise on new opportunities, address unforeseen threats and variations in natural recruitment.

Habitat rehabilitation

Strategically planned wetland habitat rehabilitation can make significant contributions to fishery productivity and deliver substantial socio-economic benefits under the right circumstances. However, habitat rehabilitation can be costly, and the benefits of restoration are rarely quantified sufficiently to understand whether these costs are justified. As highlighted by Tan *et al. (*2020), while sound polices and legislation may provide a firm foundation for upscaling habitat rehabilitation efforts, investment may be quickly undermined if resources are not carefully targeted to areas where threats to habitat persistence have been removed or reduced, successful habitat restoration is feasible, stakeholders are willing and able to invest, and the benefits to other environmental and social values are the greatest.

Given the often limited budget available for fishery enhancement objectives, a clear understanding of the costs and potential fishery benefits resulting from different habitat rehabilitation efforts is essential for resource managers to maximize investment returns. The aim of rehabilitation for fisheries should be to recreate key functional habitats and connectivity between these habitats, and the target should be a quality of environment that maximises productivity of fish (Cowx and Gerdeaux 2004). This is where the development of coupled population-fishery models is needed to explore the potential fishery benefits from habitat rehabilitation using habitat-fishery linkages (Taylor *et al.* 2018, Taylor and Creighton 2019). The costs and feasibility of restoration projects over relevant spatial scales must be reliably estimated to ensure resources are invested optimally. Where possible, to achieve a significant net gain of wetland habitats and their associated fisheries values, the scale of rehabilitation should at least match the scale of degradation.

The high costs of complete restoration projects highlight the importance of considering an alternative, 'partial restoration' scheme. In partial restoration, the maximal ecosystem rehabilitation and public benefit are compromised for a more affordable combination of restoration elements (Becker *et al.* 2018). The question of whether to undertake complete restoration or compromise on partial restoration is a complex one, involving the assessment of interactions between its components (Wohl *et al.* 2015, McMillan and Noe 2017). This approach would be particularly relevant to habitat rehabilitation undertaken for fisheries enhancement. Activities could be targeted at delivering the maximum fisheries benefit for the minimum cost, rather than trying to develop the highest total economic value or outputs. Supplementary investment from other stakeholders with different output objectives could be used to deliver additional ecosystem service benefits.

Rehabilitation activities often needs to be prioritised between multiple habitats and geographical locations to maximise the benefits (Rogers *et al.* 2018). The benefits of rehabilitation are rarely quantified in consistent terms making it difficult to compare justification of costs between different projects or options. Standardised approaches are needed to make the investment value of rehabilitation clear, potentially unlocking access to new financial resources for these activities. Although this section has focussed on the provision of exploitable fishery resources, habitats also provide other valuable ecosystem services. Capturing the value of these and including them in cost benefit analyses may strengthen the case for undertaking habitat rehabilitation, especially where the fishery benefits alone may be insufficient economic justification. If a rehabilitation project is not effective in enhancing the overall level of ecosystem services, the derived economic benefits will probably be low (Holmes *et al.* 2004).

Creighton *et al.* (2017) outlined a framework for informing investment in habitat rehabilitation and restoration for fisheries. The framework shows how to make effective restoration decisions despite different levels of risk and uncertainty. The authors stress that whilst our biological understanding of the magnitude of stock increase associated with any specified repair action remains rudimentary, and predicting the return on investment is difficult, delaying decisions to invest also carries the costs of foregone benefits. Although the true magnitude of the fishery response may not be known, expert judgment can be used to estimate the probability of a discrete set of possibilities and estimate associated improvements in productivity or potential harvest. The results can be used to determine which investments are likely to deliver positive returns under different scenarios, and which are most likely to deliver the best return on investment or benefit cost ratio.

Using cost benefit analysis will help establish an evidence-base to inform prioritisation of fisheries habitat rehabilitation. Benefit cost ratios are used as the test metric in order to facilitate comparison across the differing investments. They can provide a guide to compare predicted results across the different restoration techniques. The results show that mangrove rehabilitation is likely to generate the best return on investment from a fisheries perspective. Rehabilitation of rivers habitat, seagrass and shellfish reefs are also likely to provide positive economic returns for fisheries, but the high cost of coral reef restoration and the low value of fishery production from salt marshes mean rehabilitation of these habitats is not likely to be economically feasible for fisheries enhancement. These results are only indicative, and care needs to be taken because they are sensitive to the input values of the cost and benefits. Additionally, the exploitable species benefiting in each rehabilitated habitat type are not the same. Comparisons therefore should be based on the outcomes between habitat types for a similar species or species assemblage.

One other issue deserving consideration is that the benefit cost ratio for preserving natural habitats can be as high or higher than rehabilitation activities (Su *et al.* 2021). Investing in maintaining and preserving existing natural habitats may in some instances be more cost-effective and deliver greater benefits than rehabilitating degraded systems. The costs and benefits from preservation should be included when conducting comparative cost benefit analyses, along with the base case of doing nothing.

Cost benefit analysis involves analysis of investments at the margin. Values estimated at the margin are likely to vary depending on the scale of the margin under investigation. The theory of diminishing marginal utility recognises that each additional unit of a commodity will be valued slightly lower than the unit before it – so the 1000th hectare of seagrass is worth slightly less than the 999th hectare, and probably much less than the 100th hectare (Hanley and Barbier 2009). Therefore, as more and more area of habitat is restored, it is likely that the marginal benefit from an extra hectare of rehabilitated habitat will decline in line with the law of diminishing marginal utility (Abrina and Bennett 2021). Furthermore, as the scale of restoration investment increases, marginal costs may decrease as economies of scale are achieved. Cost benefit analyses conducted across differing scales must allow for such variations at the margin.

There appears to be considerable community support for utilising habitat rehabilitation to enhance fisheries. Non-market valuations have identified a willingness to pay amongst both users and non-users. The aggregated value generated can be substantial and often significantly larger than the values derived from improved commercial harvests. Some of this value is likely attributable to the generally positive community sentiment towards environmental restoration, but some reflects the consumer surplus of recreational fishers who value their fisheries more than they are currently paying to access them. Such user or community support is vital to encourage backing by politicians and uptake of habitat rehabilitation as a fisheries enhancement tool by managers.

Socio-economic outcomes for different enhancement approaches

The three previous sections demonstrated that habitat enhancement, fish stocking and habitat rehabilitation all have the potential to improve fishery productivity and/or sustainability and deliver positive socio-economic fishery outcomes. The full literature review in Appendix C also included examples for each section where using these enhancement strategies did not produce positive socio-economic outcomes based on fisheries investment and return alone.

Comparison of results from projects is difficult because the unitised value metrics applied varied between enhancement strategies. The base unit of artificial reefs differed between per reef, per hectare and per cubic meter of reef installed. In contrast, for habitat rehabilitation, values were typically reported per hectare, except for riverine rehabilitation which generally reported values per kilometre of rehabilitated river length. No standardised base units were apparent for reporting on socio-economic outcomes for fish stocking. These inconsistencies made comparison between the various economic analyses difficult, even within similar fisheries or enhancement approaches.

The one universal metric that could be utilised to compare across the different fisheries enhancement strategies was benefit cost ratio. This ratio is independent of project units or scale (excluding cost-efficiency savings that can occur in some larger projects). Overall, the BCR for fish stocking was almost twice as high as any other enhancement strategy (Table 1), indicating that investing in this strategy is likely to return the best economic value. This was followed by a habitat rehabilitation in mangroves, rivers, seagrass meadows and shellfish reefs. Installation of artificial reefs appears to be economically feasible, but likely cost neutral, whilst data for saltmarsh and coral reef rehabilitation indicate they are unlikely to be economically feasible from a fisheries enhancement perspective. However, there are a number of significant ecological risks associated with the release of hatchery-reared individuals and these have yet to be quantified and considered in benefit cost models. Valuing and incorporating such costs into economic analyses is likely to substantially reduce the economic feasibility of stocking, because restoration of such impacts is either impractical or extremely expensive.

The BCR for stocking recreational fisheries was by far the highest for any of the enhancement strategies examined This was partially because more studies on recreational stocking have captured and utilised a wider range of values in socio-economic calculations compared to valuations for commercial fisheries enhancement which are typically based primarily on producer surplus. Given the relative expense of hatchery-based fishery release programs, it is important that the benefits and costs associated with the activity are identified, quantified and effectively communicated (Taylor *et al.* 2017). As already highlighted, this has not happened sufficiently in Australia. Stocking targets specific species only and thus it is relatively straightforward to identify the end-users. The high BCR for stocking is likely due to the high value placed on recreational fishing and fish stocking by the recreational angler end-users (Garlock and Lorenzen 2017), the direct fisheries link between fish stocking and consumer surplus (Gregg and Rolfe 2013), and creation of highly valuable new or improved fisheries in impoundments and lakes (e.g. Rutledge *et al.* 1990, Gregg and Rolfe 2013, Hunt *et al.* 2017). Garlock and Lorenzen (2017) found that in general, most anglers supported release programs, but the level of support for stocking compared with other fisheries management options, varied with the level of motivation and fishing intensity or specialisation of the angling group.

Stocking for commercial fisheries produced much more mixed results and the overall BCR, whilst still positive, was almost five times lower than that for recreational fisheries stocking. The necessary conditions for success appear to be far more restrictive and fishery specific. Internationally, large stocking programs for diadromous salmon species returned poor socio-economic results, whilst little difference in success was observed between stocking of finfish and invertebrates. Only limited commercial stocking currently occurs in Australia, but there are potential opportunities to generate positive economic returns on high-value species, particularly invertebrates such as lobster, abalone and scallops. Future research on improving survival of released individuals is necessary to make such stockings more broadly commercially viable.

In general, the return on investment for stocking was also closely linked with how connected the receiving system was, because this strongly influenced the recapture rate. Fully closed systems (impoundments and lakes) typically returned the highest benefits, followed by rivers, estuaries, bays and then open coastal and marine stocking. These results suggest that stocking should focus on enclosed or semi-enclosed waterways in order to generate the best economic return. In more open systems, emigration and the number of individuals that need to be released to generate a detectable benefit are limiting.

Strategically planned habitat rehabilitation can make significant contributions to fishery productivity and deliver substantial socio-economic benefits under the right circumstances, providing good justification for undertaking habitat repair for most habitat types (Table 1). However, habitat rehabilitation can be costly, and the benefits of restoration are rarely quantified sufficiently to understand whether these costs are justified from a fisheries perspective**.** Compared to stock enhancement and even habitat enhancement, habitat rehabilitation offers the potential advantages of a lower technical barrier to implementation and a wider range of benefits, including enhanced fisheries for a broader range of species and the return of additional ecosystem services provided by many habitats (Walters 2005, Walton *et al.* 2006a, Walton *et al.* 2006c, Barbier 2007).

Mangrove rehabilitation demonstrated the highest BCR, partially due to the high value of exploitable species frequently associated with that habitat. Coral reefs also have high-value species associated with them, but the costs for coral reef rehabilitation are so high as to make it economically unfeasible from a fisheries enhancement perspective. Rehabilitation efforts for rivers and seagrass meadows overall provided good returns on investment, whilst shellfish reef restoration provided more moderate socio-economic returns to fisheries, despite delivering substantial productivity increases. Again, the cost of reef construction limits net economic value. Only limited information was available on the economics of saltmarsh rehabilitation, but it suggested that the fisheries benefits were clearly outweighed by the costs in most cases.

Unfortunately, the scale of rehabilitation has often been at an experimental level (<1ha), meaning that substantial contributions to regional fisheries were rarely detected. Investment for upscaling may be quickly undermined if resources are not carefully targeted to areas where threats to habitat persistence have been removed or reduced. Successful habitat restoration is feasible when stakeholders are willing and able to invest, and the demonstrated benefits to other environmental and social values are the greatest.

Globally, habitat enhancement is generally considered an economic asset by stakeholders and managers, who are usually willing to contribute towards construction and maintenance. The often high construction cost and attraction to non-resident anglers has typically led to high economic outputs for regions where structures had been installed. The potential of reef complexes to attract exploitable species had socio-economic benefits for artisanal and recreational fishermen, but few examples of economic feasibility could be found for larger scale commercial fishing reefs outside of ranching projects. In Australia there is an increasing trend to install more habitat enhancement structures due to demand from the recreational sector. However, only limited socio-economic evaluation has been conducted on Australian habitat enhancement projects so far. Anglers have a high willingness to fund creation of new habitat enhancement sites, using both purpose-built reefs and FADs, but the recreational fishing value for artificial reefs was often lower than that of natural reefs. This suggests that in some instances, better value may be obtained by protecting and rehabilitating natural reefs, rather than creating new complexes. The costs for installing artificial reefs in marine areas is typically quite high, with most reefs in Australia costing over $1 million to complete. FADs cost far less to install, but their socio-economic impacts on recreational fisheries have yet to be evaluated. The median benefit cost ratio for artificial reefs whilst positive, generally remains low. Median BCR values across all studies was only 1.29, whilst recreational fishing reefs in Australia were essentially cost neutral, with a BCR closer to 1.

Analysis of artificial reef projects sometimes included economic impact assessment to investigate the benefits realised to the local economy. This form of economic analysis was rare amongst the other fisheries enhancement strategies, possibly because the links of the other enhancement activities to local economies are harder to quantify. The economic impacts from installing artificial reefs and FADs were generally positive, delivering significant jobs, income, expenditure and value added, particularly for recreational fisheries. The size of the economic impact was closely related to the scale of the habitat enhancement activity, but there was also a trend for declining marginal benefits with scale (Sutton and Bushnell 2007).

In summary, enhancement activities which target recreational fisheries are currently more likely to return higher benefit cost ratios than comparable activities for commercial fisheries. Fish stocking resulted in the most favourable socio-economic returns on investment, but contains the greatest ecological risks (see Appendix C). Rehabilitation of mangroves, river habitat, seagrass meadows and shellfish reefs should return positive economic outcomes for fisheries, but saltmarsh and coral reef rehabilitation are unlikely to be economically viable. Artificial reefs, whilst extremely popular with recreational anglers, currently have limited value for most commercial fisheries, and are likely to generate only slightly positive socio-economic outcomes unless they increase fishery productivity substantially. Artificial reefs can also pose an ecological risk from overharvest if appropriate management policies are not also put in place.

Table 1 Indicative economic values reported in the literature for various enhancement strategies based on the standardised cost benefit analyses. Net Present Values (NPVs) were calculated based on data collated in Appendix C. Refer to the Appendix for the full details on the base data and calculation. A 5% social discount was applied over a 30-year time horizon, except for offshore artificial reefs which used a 7% discount rate. All values been standardised to AUD 2021.

Enhancement strategy	Units	Habitat value ($)	Enhancement cost ($)	30 yr NPV ($)	BCR	Comments
Offshore artificial reefs	Per reef (1,600 m^3)	55,900,000 use value over 30 yr	1,100,000	200,461	1.01	BCR = 1.1-1.18 on construction costs alone
Fish stocking – all fisheries	Not standardised per unit				7.41	
Fish stocking – recreational	Not standardised per unit				11.83	
Fish stocking - commercial	Not standardised per unit				2.43	
Mangrove rehabilitation	Per hectare	20,092	48,469	184,359	4.8	
Seagrass rehabilitation	Per hectare	21,880	139,913	176,000	2.3	
Shellfish reef rehabilitation	Per hectare	27,533	223,933	95,122	1.42	
Saltmarsh rehabilitation	Per hectare	1,095	83,465	-68,668	0.17	
Coral reef rehabilitation	Per hectare	7,394	586,399	-500,317	0.15	
River rehabilitation	Per kilometre	n/a	n/a	n/a	2.57	Unitised habitat value and costs not available

Integration of approaches

Lorenzen *et al.* (2013) proposed that controlling fishing effort, habitat management (restoration, rehabilitation and deployment of artificial habitats), and fish stocking are the three principal means by which fisheries can be sustained and improved. However, it is possible that multiplicative gains may be made through a combination of these approaches. Fishery enhancement approaches should not be seen as a replacement for good fishery management, but instead as part of a suite of potential management tools that can be utilised together to deliver strong, sustainable fisheries outcomes. Different fisheries enhancement strategies do not need to be undertaken in isolation and seen as alternatives to each other. The greatest benefits are likely to occur when different strategies are integrated to comprehensively address the issues limiting fisheries production or expansion. Depending on the situation, employment of different enhancement approaches or combinations of approaches may improve the likelihood that enhancement or restoration goals will be achieved. It is therefore desirable to move toward developing a common framework for integrating enhancement approaches.

Evidence of this potential may lie in some recent examples where artificial habitats have been deployed specifically to enhance the outcomes from hatchery-releases. For example, the fisheries and socio-economic benefits derived from habitat rehabilitation provide a good justification for undertaking habitat repair, but the full realisation of potential fisheries benefits relies on an adequate supply of wild recruits to utilise that habitat (Taylor *et al.* 2017). Inadequate supply of wild recruitment could be overcome by also combining stock enhancement with the habitat provision. The release of exploitable species that do not readily recruit to rehabilitated sites, but naturally occur in such habitats, may help to enhance the benefits of the habitat rehabilitation. The successful stocking of native fish in impoundments where they cannot naturally recruit is a great example of this.

A more commercial approach to combining strategies is ranching, where artificial habitat is introduced with the intent of supporting fish stocked for both commercial and recreational harvest. As in the above example, inadequate wild recruitment may limit the magnitude of fisheries enhancement that can be achieved from the introduction of habitat alone. Stocking can bypass this recruitment limitation to deliver better yields. While stock enhancement represents the effort to improve annual recruitment, ranching represents an attempt to increase the annual yield of a species (Moskness *et al. 1998*). Ranching is similar to farming, in that stock is released into areas of improved habitat (or pasture) to grow and then be harvested. The Ocean Grown Abalone ranching project in Western Australia, provides a great commercial example of the economic benefits that can be achieved by combining habitat enhancement and stock enhancement in a suitable scenario.

Large-scale commercial ranching has been widely used in China, Japan and South Korea (Seaman *et al.* 2011, Kim *et al.* 2017, Kitada 2020), and historically focussed mainly on non-migratory invertebrate species. Greater attention is now being given to incorporate non-migratory finfish into programs (e.g. Kim *et al.* 2017). Establishing marine fishing ranches can deliver significant socio-economic benefits from the resulting recreational and commercial fisheries. Ranching is considered to be at the boundary between capture fisheries and aquaculture. This boundary is becoming less distinct as natural habitats are modified by the introduction of artificial reefs (Bartley and Bell 2008).

In Korea, using the combination of artificial reefs and stock enhancement in the Gyeong-Nam Province has delivered significant economic impacts. Construction of the Large Sea Ranch increased commercial fish production more than five-fold and increased fishermen's incomes by 26% (Kim *et al.* 2017). Additionally, recreational anglers spent $26 million at the site (Pyo 2009).

Although rarely used in Australia, this integrated approach to fisheries enhancement has received growing attention, especially following the success of commercial abalone ranching in the south-west of Western Australia.

Manager survey

Full details of the survey of managers' perceptions on fisheries enhancement can be found in Appendix D. The following section contains a synopsis of the work and main results.

Fisheries enhancement strategies can expand the options available to fisheries managers beyond the use of traditional input-output controls and can provide opportunities for significant socio-economic benefits. However, the strategies need to be well understood by managers, incorporated into management decision making frameworks and be supported by stakeholders if they are to be broadly applied.

Different fisheries stakeholders can be strongly divided in their perception of the utility of fishery enhancement strategies (Hilborn 1999, Leber 2002, Arlinghaus and Mehner 2005, Lorenzen 2005, Hasler *et al.* 2011). The manager survey results indicated that enhancement strategies were used almost twice as commonly in recreational fisheries than the commercial sector. Stakeholder and political support are likely significant drivers behind this difference. There is strong belief amongst anglers that enhancement projects will improve recreational fisheries (Hilborn 1999, Hasler *et al.* 2011, van Poorten *et al.* 2011). Anglers also typically have a high willingness to pay for using enhancement strategies, because the cost to the individual is typically low (Garlock and Lorenzen 2017). Enhancement approaches are often politically seen as socially preferable because they have the potential to help manage the sometimes high social costs associated with harvest restrictions under traditional management approaches (Beard *et al.* 2003, Johnston *et al.* 2011, Haglund *et al.* 2016). In contrast, the potentially higher per-user cost, and the lack of demonstrated quantitative economic outcomes from past commercial fishery enhancement trials, likely limits confidence in value and use of enhancement strategies in the commercial sector. Therefore, commercial stakeholder pressure for their implementation is lower.

A common theme observed in the survey responses was the perceived lack of quantitative data available on fisheries enhancement projects. A similar response has previously been observed in survey of managers on the use of artificial reefs in the USA (Murray 1994). Bortone (2011a) pointed out that one of the most common reasons that artificial reefs are not deployed as a fisheries enhancement tool by managers in suitable situations, is the relative lack of reports or published examples which properly quantify impacts of reef deployments. This leads to managers overlooking the use of artificial reefs as suitable management options (Layman *et al.* 2016, Becker *et al.* 2018). Quantitative assessment of enhancement contributions to fisheries management goals, such as increases in population abundance, yield, or economic rent, is essential for incorporating these strategies into management actions.

Key review papers on fisheries enhancement all lament the lack of empirical data that has been collected (e.g. Blankenship and Leber 2008, Lorenzen *et al.* 2010, Lorenzen 2014, Taylor *et al.* 2017, Becker *et al.* 2018, Florisson *et al.* 2018, Hunt and Jones 2018, Kitada 2020), and highlight the importance for enhancement projects to quantitatively demonstrate cost-effectiveness. Such assessment is critical for effective fisheries management because it permits the efficient allocation of management resources and enables comparisons between alternative management options. Well-conducted research can provide the supporting lines of evidence that support decision-making regarding the use and/or appropriateness of enhancement strategies (Claudet and Pelletier 2004, Grove and Wilson 1994, Bortone 2011b). Improving manager access to quantitative data on the outcomes of enhancement projects will improve their confidence in utilising enhancement strategies and likely lead to greater consideration and uptake. This can only occur if future enhancement projects more comprehensively collect socio-economic data on project outcomes.

Another common theme amongst survey responses was that high implementation costs and resource limitations were a barrier to uptake. Interestingly, the level and duration of investment were not deemed to be of high importance. These results suggest that the lack of predictable economic return on the investment is therefore potentially the limiting factor, rather than the absolute investment required. More cost benefit analysis results may shift the focus away from initial and on-going investment by providing a greater focus on the overall economic outcomes achievable.

The survey indicated that there was a strong desire for access to specific decision support tools to better incorporate fisheries enhancement options into current fisheries management decision frameworks. However, there was no consensus on the design and level of complexity of such decision support tools that would be universally appropriate. The level of detail required by managers, ranged from simple decision matrices to help identify which enhancement approaches were appropriate to a particular fishery, through to highly detailed bio-economic models, whose parameters could be manipulated to estimate the fishery and socio-economic outcomes across various management options and response scenarios. Disagreement also existed on whether such tools should be stand-alone or able to fully integrate into existing frameworks.

Decision-support frameworks and modelling tools already exist which could be readily adapted to assess the outcomes of fisheries enhancement scenarios (*e.g.* Lorenzen 2008) and evaluate the ability of hatchery releases to integrate and add-value to habitat rehabilitation or enhancement. Application of these tools to evaluate the potential for multiplicative gains and the relative costs and benefits of such endeavours, will allow informed decision making prior to any large investments being made. However, until sufficient data is available in Australia to support these existing tools, it is recommended that a suitability matrix for fisheries enhancement options should be developed for all fisheries in Australia to provide managers with a rapid method for identifying appropriate enhancement strategies. Such a matrix could be based on the constraints across various life-history stages for target species and be used to identify and prioritise where enhancement activities will have the greatest benefits (Grant *et al.* 2017, Florisson *et al.* 2018). Much of the biological data required to drive such a matrix is likely already available and used in existing stock population models.

Conclusions

Clearly understanding the threats and stressors impacting fisheries systems, identifying realistic and quantitative management objectives and increased use of bio-economic modelling will be core to pro-actively managing commercial and recreational fisheries in Australia in a sustainable way using fishery enhancement strategies. Incorporating enhancement options into decision making processes will expand the options available to fisheries managers beyond the use of traditional input-output controls.

In this project, enhancement activities have been viewed purely through the lens of the resultant socio-economic outcomes to fisheries. However, enhancement activities can deliver a broad range of beneficial ecosystem services which provide substantial value beyond fisheries. These activities can also improve environmental health, species conservation, and support provision of a suite of other non-fisheries related environmental, social, recreational and commercial opportunities. The cost benefit results presented in this review have deliberately not taken these additional benefits into account, in order to provide a clearer picture of the directly relevant outcomes for fisheries managers, and because they can be difficult to monetarily quantify. However, the substantial additional or value-added benefits that can be generated should be used to seek and justify co-investment in projects from non-fishery sectors. Collaborating with relevant non-fishery stakeholders has the potential to greatly reduce the direct contribution costs from fisheries agencies for some enhancement projects, which would lead to significantly better benefit cost ratios than those reported in this review. Where possible fisheries enhancement projects should pro-actively seek support from non-fishery sectors to more cost-efficiently achieve their fishery management objectives.

Different fisheries stakeholders can be strongly divided in their perception of the utility of fishery enhancement strategies (Hilborn 1999, Leber 2002, Arlinghaus and Mehner 2005, Lorenzen 2005, Hasler *et al.* 2011). Decision support tools can help fisheries managers identify the best management options in a transparent and justifiable way. Decision support frameworks and modelling tools already exist which can be readily adapted to assess the outcomes of fisheries enhancement scenarios (*e.g.* Lorenzen 2008) and evaluate the ability of hatchery releases to integrate and add-value to habitat rehabilitation or enhancement. Application of these tools to evaluate the potential for multiplicative gains and the relative costs and benefits of such endeavours will allow informed decision making prior to any large investments being made.

The survey of Australian fisheries managers indicated that there was a strong desire for access to specific decision support tools to better incorporate fisheries enhancement options into current fisheries management decision frameworks. However, there was no consensus on the level of complexity of such decision support tools that would be universally appropriate. The level of detail required by managers, ranged from simple decision matrices to help identify which enhancement approaches were appropriate to a particular fishery, through to highly detailed bio-economic models whose parameters could be manipulated to estimate the fishery and socio-economic outcomes across various management options and response scenarios. Disagreement also existed on whether such tools should be stand-alone or able to fully integrate into existing frameworks.

Bio-economic modelling is key to appraising the potential of habitat or stocking initiatives relative to other fisheries management measures and evaluating the cost–benefits of individual programs (Broadley *et al.* 2017). Several excellent contemporary studies in Australia have used bio-economic modelling to appraise the viability of proposed fishery enhancement projects (e.g. Ye *et al.* 2005, Hart *et al.*2013, Broadley *et al.* 2017, Taylor *et al.* 2018, Raoult *et al.* 2022). Management actions such as harvest regulations and stocking will likely not be equally effective at achieving various objectives, because they differentially affect fish populations and fishers (Lorenzen 2014).

Whilst this review and many others focus on cost benefit analysis to compare socio-economic outcomes between fisheries enhancement options, it may not always be the most appropriate approach. Where there are clear and commonly agreed objectives or targets to be reached in a specific policy or management context, then the most appropriate approach is likely to be cost-effectiveness analysis (Ledoux and Turner 2002). On the other hand, when targets cannot be pre-defined but must be determined within the assessment exercise, and all or most of the impacts can be expressed in money terms, then cost–benefit analysis will be favoured. A comprehensive adaptive management framework is required to guide fishery enhancement decisions about the most appropriate tools and approaches to use, integrate priorities and flexible respond to new scientific knowledge arising from monitoring programs (Lorenzen *et al.* 2010, Talley *et al.* 2018).

Given the generally species-specific and site-specific outcomes from many enhancement activities, a two-step process may be merited to improve cost efficiency. An initial support tool can be used to rapidly identify potentially suitable enhancement strategies, based on the threats, issues and limitation of the specific fishery in question. Fishery-specific bio-economic modelling can then be used to examine how the suitable enhancement strategies can best be integrated using cost-benefit analysis or cost-effectiveness analysis.

Implications

There is potential to expand the value of recreational fisheries and create niche fishing opportunities that can drive regional development. Rehabilitation of aquatic habitat has the potential to sustainably increase the productivity, yield and value of Australia's fisheries and improve resilience against adverse events and climate change. Fish stocking has significant potential for expansion, particularly in closed and semi-closed estuarine and impoundment systems. There are opportunities to expand the suite of species that are currently stocked, to diversify recreational fishing opportunities and attract more angler to areas with unique fisheries. Artificial reefs and FADs currently have high recreational fisher support, and their installation can improve access and fishing options. Undertaken appropriately, habitat enhancement can also increase overall fishery productivity by supporting the life-history requirements of fish and invertebrates.

For commercial fisheries, habitat rehabilitation has the potential to increase wild recruitment that may be limited due to the degradation and loss of essential fish habitats, such as nursery areas. Better recruitment is likely to result in increased yields and greater long-term sustainability within fisheries. Stock enhancement has the potential in some species to more rapidly help recover depleted wild stocks or create new fisheries. The greatest potential for stock enhancement in the short-term remains with stocking less mobile, high-value invertebrate species.

Recommendations

The following recommendation will help clarify our understanding on the outcomes of fisheries enhancement activities and enable more cost-effective implementation:

- All new major projects should incorporate some form of socio-economic analysis to understand the outcomes of the activities and develop a knowledge database that can assist in the feasibility analysis of new projects.
- Implementation of stocking cost-efficiency gains should be undertaken by improving release strategies through better survival and fitness from pre-release training, acclimation and improvement of release habitats.
- Standardised analysis and reporting guidelines should be developed to provide consistent and comparable results.
- Adaptive management should be employed in fishery enhancement projects to enable the results from monitoring and research to be rapidly adopted to maximise outcomes.
- A suitability matrix for fisheries enhancement options should be developed for the various fisheries in Australia to provide managers with a rapid method for identifying appropriate enhancement strategies.
- Co-investment for fisheries enhancement projects should be sought from various stakeholder groups where relevant, to capitalise on the broad ecosystem services that can be delivered.
- The use of different fisheries enhancement strategies should be integrated to potentially deliver multiplicative benefits across the entire life-history of target species. Habitat and recruitment are both essential to achieve sustained fishery outcomes, and enhancement projects should integrate both where possible to improve fitness across the entire life cycle of target species.
- A national approach to identification of hatchery-reared fish is critically needed. Genetic marking through lineage and parental analysis holds great promise and should be considered for national adoption.
- A suitability matrix for fisheries enhancement options should be developed for major fisheries in Australia to provide managers with a rapid method for identifying appropriate enhancement strategies.

Further development

Bio-economic modelling is key to appraising the potential of habitat or stocking initiatives relative to other fisheries management measures and evaluating the cost–benefits of individual programs. Development of a generic, broadly applicable bio-economic model and a collection of relevant parameters to populate it for key fishery species, would enable managers to relatively time and cost-effectively explore the impacts of different fishery enhancement in their fisheries.

Extension and Adoption

This project involved extensive engagement and collaboration with fishery stakeholders from a wide range of sectors and regions. Managers from all major fisheries in each state and territory were contacted with regards to identifying reports and grey literature relating to fisheries enhancement projects that had been undertaken in their jurisdiction, and also invited to participate in the online survey. Follow-up discussions were had with key staff in each state to ensure a comprehensive understanding of enhancement projects was achieved. The project was also raised at the Research Providers Network to ensure agencies were aware of the work and to encourage participation. The final report, literature review and results from the survey of managers will be circulated through state fisheries agencies to inform them of the data collected, provide potentially relevant case studies and summarise the key research findings and knowledge gaps.

Appendix A – Project staff

Appendices should include (where applicable):

- Dr Andrew Norris, Queensland Department of Agriculture and Fisheries
- Dr Michael Hutchison, Queensland Department of Agriculture and Fisheries
- Dr Michael Lowry, NSW Fisheries

Appendix B - References

Abrina, T.A.S. and Bennett, J. (2021) A benefit-cost comparison of varying scales and methods of coral reef restoration in the Philippines. *The science of the total environment 799*: 149325. https://doi.org/10.1016/j.scitotenv.2021.149325

Arlinghaus, R. and Mehner, T. (2005) Determinants of management preferences of recreational anglers in Germany: Habitat management versus fish stocking. *Limnologica* 35(1-2): 2-17. https://doi.org/10.1016/j.limno.2004.10.001.

Barbier, E.B. (2007) Valuing ecosystem services as productive inputs. *Economic Policy* 22: 177-229. https://doi.org/10.1111/j.1468-0327.2007.00174.x .

Bartley, D. and Bell, J. (2008) Restocking, stock enhancement and sea ranching: Arenas of progress. *Reviews in Fisheries Science* 16: 357-365. https://doi.org/10.1080/10641260701678058.

Beard Jr., T.D., 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. https://doi.org/10.1577/M01-227AM

Becker, A., Taylor, M.D., Folpp, H. and Lowry, M.B. (2018) Managing the development of artificial reef systems: the need for quantitative goals. *Fish and Fisheries* 19: 740–752. https://doi.org/10.1111/faf.12288.

Bell, J.D., Bartley, D.M., Lorenzen, K. and Loneragan, N.R. (2006) Restocking and stock enhancement of coastal fisheries: Potential, problems and progress. *Fisheries Research* 80(1): 1-8. https://doi.org/10.1016/j.fishres.2006.03.008.

Bell, K.P., Huppert, D. and Johnson, R.L. (2003) Willingness to Pay for Local Coho Salmon Enhancement in Coastal Communities. *Marine Resource Economics* 18(1): 15-31. https://doi.org/10.1086/mre.18.1.42629381

Blankenship, H. and Leber, H. (1995) A responsible approach to marine stock enhancement. *American Fisheries Society Symposium* 15: 165-175. https://doi.org/10.1080/10641262.2010.491564.

Borg, J. (2004) *Fish stock and fishery enhancement in Western Australia: A discussion paper*. Fisheries management paper no. 175, Department of Fisheries, Perth. 91 pp.

Bortone, S.A. (2008) Coupling fisheries with ecology through marine artificial reef deployments. In: Nielsen, J., Dodson, J.J., Friedland, K., Hamon, T.R., Musick, J., and Verspoor, E. (eds) *Reconciling Fisheries with Conservation: Proceedings of the Fourth World Fisheries Congress*. American Fisheries Society, Bethesda, Maryland. pp. 917-924.

Bortone, S.A. (2011a). Introduction to the role artificial reefs play in fisheries management. In: Bortone, S.A., Brandini, F.P., Fabi, G. and Otake, S. (eds) *Artificial reefs in fisheries management*. CRC Press, Boca Raton, Florida. pp. 1-5.

Bortone, S.A. (2011b). A pathway to resolving an old dilemma: Lack of artificial reefs in fisheries management. In Bortone, S.A., Brandini, F.P., Fabi, G. and Otake, S. (eds) *Artificial reefs in fisheries management*. CRC Press, Boca Raton, Florida. pp. 311-321.

Broadley, A.D., Tweedley, J.R. and Loneragan, N.R. (2017) Estimating biological parameters for penaeid restocking in an Australian temperate estuary. *Fisheries Research* 186: 488-501. https://doi.org/10.1016/j.fishres.2016.09.007.

Brown, C. and Day, R.L. (2002) The future of stock enhancement: lessons for hatchery practice from conservation biology. *Fish and Fisheries* 3: 79–94. https://doi.org/10.1046/j.1467-2979.2002.00077.x.

Brummett, R.E., Beveridge, M.C.M. and Cowx, I.G. (2013) Functional aquatic ecosystems, inland fisheries and the Millennium Development Goals. *Fish and Fisheries* 14: 312–324. https://doi.org/10.1111/j.1467-2979.2012.00470.x.

Burgan, B. and Mules, T. (2001) Reconciling cost-benefit and economic impact assessment for event tourism. *Tourism Economics*, *7*(4), 321– 330. https://doi.org/10.5367/000000001101297892.

Claudet, J. and Pelletier, D. (2004) Marine protected areas and artificial reefs: A review of the interactions between management and scientific studies. *Aquatic Living Resources* 17: 129-138. https://doi.org/10.1051/alr:2004017

Cowx, I.G. and Gerdeaux, D. (2004) The effects of fisheries management practises on freshwater ecosystems. *Fisheries Management and Ecology* 11(3-4): 145-151. https://doi.org/10.1111/j.1365-2400.2004.00411.x.

Creighton, C., Walshe, T., McLeod, I., Prahalad, V., Sheaves, M. and Taylor, M. (2017) *Repairing and conserving Australia's saltmarshes and seascapes*. https://doi.org/10.13140/RG.2.2.25385.08807.

Cresson, P., Le Direach, L., Rouanet, E., Goberville, E., Astruch, P., Ourgaud, M. and Harmelin-Vivien, M. (2019) Functional traits unravel temporal changes in fish biomass production on artificial reefs. *Marine Environment Research* 145: 137–146. https://doi.org/10.1016/j.marenvres.2019.02.018

Crowder, L.B., Lyman, S.J., Figueira, W.F. and Priddy, J. (2000) Source-sink populations dynamics and the problem of siting marine reserves. *Bulletin of Marine Science* 66: 799–820.

FAO (2022) The state of world fisheries and aquaculture in 2022: Towards blue transformation. Food and Agriculture Organisation of the United Nations, Rome. 156 pp. https://doi.org/10.4060/cc0461en.

Fitzpatrick, K. B., Overgaard Therkildsen, N., Marcy-Quay, B., Borchardt-Wier, H.B. and Sethi, S.A. (2023) Parentage-based tagging using mothers balances accuracy and cost for discriminating between natural and stocked recruitment for inland fisheries. *Fisheries Management and Ecology* 00: 1-11. https://doi.org/10.1111/fme.12614.

Fitzsimmons, G. J. (2008) Death to dichotomizing. *Journal of Consumer Research* 35(1): 5−8. https://doi.org/10.1086/589561.

Florisson, J.H., Tweedley, J.R., Walker, T.H.E. and Chaplin, J.A. (2018). ReefVision: a citizen science program for monitoring the fish faunas of artificial reefs. *Fisheries Research* 206: 296–308. https://doi.org/10.1016/j.fishres.2018.05.006.

Folpp, H., Schilling, H.T., Clark, G.F., Lowry, M.B., Maslen, B., Gregson, M. and Suthers, I.M. (2020) Artificial reefs increase fish abundance in habitat-limited estuaries. *Journal of Applied Ecology* 57: 1752–1761. https://doi.org/10.1111/1365-2664.13666

Gardner, C. (2012) *An economic evaluation of management strategies for the Tasmanian rock lobster fishery*. Master of Economics Thesis, University of Tasmania, Hobart. 155 pp.

Garlock, T.M. and Lorenzen, K. (2017) Marine angler characteristics and attitudes toward stock enhancement in Florida. *Fisheries Research* 186(2): 439-445. https://doi.org/10.1016/j.fishres.2016.08.017.

Gonçalves, J., Bentes, L., Coelho, R., Correia, C., Lino, P., Monteiro, C.C., Ribeiro, J and Erzini, K. (2003) Age and growth, maturity, mortality and yield-per-recruit for two banded bream (*Diplodus vulgaris* Geoffr.) from the south coast of Portugal. *Fisheries Research*. 62. 349-359. https://doi.org/10.1016/S0165-7836(02)00280-1.

Grant, W.S., Jasper, J., Bekkevold, D. and Adkinson, M. (2017) Responsible genetic approach to stock restoration, sea ranching and stock enhancement of marine fishes and invertebrates. *Reviews in Fish Biology and Fisheries* 27: 615–649. https://doi.org/10.1007/s11160-017-9489-7

Gregg. D. and Rolfe, J. (2013) *An economic assessment of the value of recreational angling at Queensland dams involved in the Stocked Impoundment Permit Scheme*. Central Queensland University, Rockhampton. 49 pp.

Grimes, C.B. (1998) Marine stock enhancement: sound management or techno-arrogance? *Fisheries* 23: 18–23. https://doi.org/10.1577/1548-8446(1998)023<0018:MSE>2.0.CO;2.

Grove, R.S. and Wilson, C.A. (1994) Introduction. *Bulletin of Marine Science* 55: 265–267.

Haglund, J.M., Isermann, D.A. and Sass, G.G. (2016) Walleye population and fishery responses after elimination of legal harvest on Escanaba Lake, Wisconsin. *North American Journal of Fisheries Management* 36: 1315–1324. https://doi.org/10.1080/02755947.2016.1221002

Hanley, N. and Barbier, E.B. (2009) *Pricing nature: cost-benefit analysis and environmental policy*. Edward Elgar, Cheltenham.

Hart, A.M., Strain, L.W.S. and Hesp, S.A. (2013) Stock enhancement in Greenlip abalone part III: Bioeconomic evaluation. *Reviews in Fisheries Science* 21(3-4): 354-374. https://doi.org/10.1080/10641262.2013.812506.

Hart, A.M., Strain, L.W.S. and Hesp, S.A. (2013) Stock enhancement in Greenlip abalone part III: Bioeconomic evaluation. *Reviews in Fisheries Science* 21(3-4): 354-374. https://doi.org/10.1080/10641262.2013.812506.

Harvey, E.S., Ackermann, F., Burton, M., Clifton, J., Elrick-Barr, C.E., Zimmerhackel, J.S., Hill, G., Newman, S.J., Shaw, J.L., Pagano, M., McLeod, P., McLean, D.L., and Partridge. J.C. (2021) *Enhancing the understanding of the value provided to fisheries by man-made aquatic structures*.

Hasler, C.T., Colotelo, A.H., Rapp, T., Jamieson, E., Bellehumeur, K., Arlinghaus, R. and Cooke, S.J. (2011) Opinions of fisheries researchers, managers, and anglers towards recreational fishing issues: an exploratory analysis for North America. *American Fisheries Symposium* 75: 51-74. https://doi.org/10.47886/9781934874240.ch4

Hilborn, R. (1999) Confessions of a reformed hatchery basher. *Fisheries* 24(5): 30-32.

Hollowed, A.B., Barange, M., Beamish, R.J., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M.G.G., Hare, J.A., Holt, J., Ito, S.I., Kim, S., King, J.R., Loeng, H., MacKenzie, B.R., Mueter, F.J., Okey, T.A., Peck, M.A., Radchenko, V.I., Rice, J.C., Schirripa, M.J., Yatsu, A. and Yamanaka, Y. (2013) Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science* 70: 1023–1037. https://doi.org/10.1093/icesjms/fst081.

Holmes, T.P., Bergstrom, J.C., Huszar, E., Kask, S.B. and Orr III, F. (2004) Contingent valuation, net marginal benefits, and the scale of riparian ecosystem restoration. *Ecological Economics* 49: 19-30. https://doi.org/10.1016/j.ecolecon.2003.10.015.

Hone, S., Gooday, P., Hafi, A. and Greenville, J. (2022) *Discount rates and risk in the economic analysis of agricultural projects.* ABARES Working Paper 22.02, Canberra. 22 pp.

Hunt, T.L., Scarborough, H., Giri, K., Douglas, J.W. and Jones, P. (2017) Assessing the cost-effectiveness of a fish stocking program in a culture-based recreational fishery. *Fisheries Research* 186(2): 468-477. https://doi.org/10.1016/j.fishres.2016.09.003.

Johnston, F.D., Arlinghaus, R., Stelfox, J. and Post, J.R. (2011) Decline in angler use despite increased catch rates: anglers' response to the implementation of a total catch-and-release regulation. *Fisheries Research* 110: 189–197. https://doi.org/10.1016/j.fishres.2011.04.006

Kim, D., Seung, C.K. and Seo, Y.I. (2017) Multi-regional economic impacts of recreational fisheries: Analysis of Small Sea Ranch in Gyeong-Nam Province, Korea. *Marine Policy* 84: 90-98. https://doi.org/10.1016/j.marpol.2017.07.011.

Kitada, S. (2020) Lessons from Japanese marine stock enhancement and sea ranching programs over 100 years. *Reviews in Aquaculture* 12: 1944-1969. https://doi.org/10.1111/raq.12418.

Layman, C.A., Allgeier, J.E. and Montana, C.G. (2016) Mechanistic evidence of enhanced production on artificial reefs: a case study in a Bahamian seagrass ecosystem. Ecological Engineering 95: 574-579. https://doi.org/10.1016/j.ecoleng.2016.06.109.

Leber, K. (2002) Advances in marine stock enhancement: shifting emphasis to theory and accountability. In: Stockney, R.R. (ed) *Responsible marine aquaculture*. Mote marine laboratory, Florida. pp 79-90. https://doi.org/10.1079/9780851996042.0079

Leber, K. (2004) Summary of case studies of the effectiveness of stocking aquacultured fishes and invertebrates to replenish and enhance coastal fisheries. In: Bartley, D. and Leber, K. (eds) *Marine Ranching*. FAO Fisheries Department, Rome, Italy. pp 203-213.

Ledoux, K. and Turner, R.K. (2002) Valuing ocean and coastal resources: A review of practical examples and issues for further action. *Ocean & Coastal Management* 45(9): 583-616. https://doi.org/10.1016/S0964-5691(02)00088-1

Lima, J.S., Sanchez-Jerez, P., dos Santos, L.N. and Zalmon, I.R. (2020) Could artificial reefs increase access to estuarine fishery resources? Insights from a long-term assessment. *Estuarine, Coastal and Shelf Science* 242: 106858. https://doi.org/10.1016/j.ecss.2020.106858

Loneragan, N.R., Crocos, P.J., Rothlisberg, P.C., Barnard, R.M., Mcculloch, R.R., Penn, J.W. and Ward, R.D. (2004). An approach to evaluating the potential for stock enhancement of Brown tiger prawns (*Penaeus esculentus* Haswell) in Exmouth Gulf, Western Australia. In: Leber, K.M., Kitada, S., Blankenship, H.L. and Svåsand, T. (eds.) *Stock enhancement and sea ranching: developments, pitfalls and opportunities, 2nd Edition*. Wiley-Blackwell, Oxford, UK. pp. 444-464. https://doi.org/10.1002/9780470751329.ch32

Lorenzen, K. (2000) Allometry of natural mortality as a basis for assessing optimal release size in fish stocking programmes. *Canadian Journal of Fisheries and Aquatic Sciences* 57(12): 2374-2381. https://doi.org/10.1139/f00-215.

Lorenzen, K. (2005) Population dynamics and potential of fisheries stock enhancement: Practical theory for assessment and policy analysis. *Philosophical transactions of the Royal Society of London Series B* 36: 171-89. https://doi.org/10.1098/rstb.2004.1570.

Lorenzen, K. (2008) Understanding and managing enhancement fisheries systems. *Reviews in Fisheries Science* 16: 10–23. https://doi.org/10.1080/10641260701790291.

Lorenzen, K. (2014) Understanding and managing enhancements: why fisheries scientists should care. *Journal of Fisheries Biology* 85: 1807–1829. https://doi.org/10.1111/jfb.12573.

Lorenzen, K., Agnalt, A.L., Blankenship, H.L., Hines, A.H., Leber, K.M., Loneragan, N.R. and Taylor, M.D. (2013) Evolving context and maturing science: aquaculture-based enhancement and restoration enter the marine fisheries management toolbox. *Reviews in Fisheries Science* 21: 213–221. https://doi.org/10.1080/10641262.2013.837358.

Lorenzen, K., Leber, K.M. and Blankenship, H.L. (2010) Responsible approach to marine stock enhancement: an update. *Reviews in Fisheries Science* 18: 189–210. https://doi.org/10.1080/10641262.2010.491564.

McMillan, S.K. and Noe, G.B. (2017) Increasing floodplain connectivity through urban stream restoration increases nutrient and sediment retention. *Ecological Engineering* 108: 284–295. https://doi.org/10.1016/j.ecoleng.2017.08.006.

Moksness, E., Støle, R. and van der Meeren, G. (1998) Profitability of sea ranching with Atlantic salmon (*Salmo salar*), Artic charr (*Salvelinus alpinus*) and European lobster (*Homarus gammarus*) in Norway. *Bulletin of Marine Science* 62: 689–699.

Molony, B., Lenanton, R.C.J., Jackson, G., Norriss, J. (2003) Stock enhancement as a fisheries management tool. *Reviews in Fish Biology and Fisheries* 13: 409–432. https://doi.org/10.1007/s11160-004-1886-z.

Molony, B.W. and C. Bird. (2002) *Annual report on the monitoring of the recreational marron fishery in 2000, with an analysis of long-term data and changes within this fishery*. Fisheries Research Report 137. Department of Fisheries, Western Australia. 44 pp.

Morgan, I.J., McDonald, D.G. and Wood, C.M. (2001) The costs of living for freshwater fish in a warmer, more polluted world. *Global Change Biology* 7: 345–355. https://doi.org/10.1071/MF02047.

Munro, J.L. and Bell, J.D. (1997) Enhancement of marine fisheries resources. *Reviews in Fisheries Science* 5: 185–222. https://doi.org/10.1080/10641269709388597.

Murray, J.D. (1994). A policy and management- assessment of US artificial reef programs. *Bulletin of Marine Science* 55: 960-969.

Nous (2019) *Social return on investment of NSW artificial reef program*. Nous Group, Sydney, 52 pp.

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. https://doi.org/10.1577/1548-8446(2002)027<0006:CRF>2.0.CO;2.

Pyo, H. (2009) Assessing the economic feasibility of a Marine Ranching Project in Tong Young. *Ocean and Polar Research* 31(4): 305-318. https://doi.org/10.4217/OPR.2009.31.4.305

Raoult, V., Taylor, M.D., Schmidt, R.K., Cresswell, I.D., Ware, C. and Gaston, T.F. (2022) Valuing the contribution of estuarine habitats to commercial fisheries in a seagrass-dominated estuary. Estuarine, *Coastal and Shelf Science* 274: 107927.

Riggio, S., Badalamenti, F. and D'Anna, G. (2000) Artificial reefs in Sicily: an overview. In: Jensen, A.C., Collins, K.J., Lockwood, A.P.M. (eds) *Artificial reefs in European seas.* Dordrecht: Springer. pp. 65–73. https://doi.org/10.1007/978-94-011-4215-1_4.

Roa-Ureta, R.H., Santos, M.N. and Leitão, F. (2019) Modelling long-term fisheries data to resolve the attraction versus production dilemma of artificial reefs. *Ecological Modelling* 407: 108727. https://doi.org/10.1016/j.ecolmodel.2019.108727.

Rogers, A.A., Nedosyko, A., McLeod, I.M., Gillies, C. and Burton, M.P. (2018) *Benefit-Cost Analysis of the Windara shellfish reef restoration project.* Report to the National Environmental Science Program, Marine Biodiversity Hub. The University of Western Australia, Perth. 36 pp.

Ross, M.R. (1997) *Fisheries conservation and management*. Prentice Hall, Upper Saddle River, New Jersey. 374 pp.

Ruckelshaus, M., McKenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., Polasky, S., Ricketts, T., Bhagabati, N., Wood, S.A. and Bernhardt, J. (2015) Notes from the field: Lessons learned from using ecosystem service approaches to inform real-world decisions. *Ecological Economics* 115: 11-21. https://doi.org/10.1016/j.ecolecon.2013.07.009.

Rutledge, W., Rimmer, M., Russell, J., Garrett, R. and Barlow, C. (1990) Cost-benefit of hatchery-reared barramundi, *Lates calcarifer* (Bloch) in Queensland. *Aquaculture Research* 21: 443-448.

Seaman, W. (2000). *Artificial reef evaluation: with application to natural marine habitats*. CRC Press, Boca Raton. 264 pp.

Seaman, W., Grove, R., Whitmarsh, D., Santos, M., Fabi, G., Kim, C., Relini, G. and Pitcher, T. (2011) Artificial reefs as unifying and energizing factors in future research and management of fisheries and ecosystems. In: Bortone, S.A., Brandini, F.P., Fabi, G., Otake, S. (eds) *Artificial reefs in fisheries management*. CRC Press, London. pp. 7-29. https://doi.org/10.1201/b10910-3.

Smith, J.A., Lowry, M.B., and Suthers, I.M. (2015) Fish attraction to artificial reefs not always harmful: a simulation study. *Ecology and evolution* 5(20): 4590-4602. https://doi.org/10.1002/ece3.1730

Su, J., Friess, D.A. and Gasparatos, A. (2021) A meta-analysis of the ecological and economic outcomes of mangrove restoration. *Nature Communications* 12: 5050. https://doi.org/10.1038/s41467-021-25349-1

Sutton, S.G. and Bushnell, S.L. (2007) Socio-economic aspects of artificial reefs: Considerations for the Great Barrier Reef Marine Park. *Ocean & Coastal Management* 50(10): 829-846. https://doi.org/10.1016/j.ocecoaman.2007.01.003.

Talley, T.S., Venuti, N., Starr, R. and Myrick, C. (2018) Evaluation of White seabass (*Atractroscion nobilis*) enhancement program in California. In: Kideghesho, J.R. and Rija, A.A. (eds) Wildlife management – Failures, successes and prospects. IntechOpen, London. https://doi.org/10.5772/intechopen.77310

Tan, Y.M., Dalby, O., Kendrick, G.A., Statton, J., Sinclair, E.A., Fraser, M.W., Macreadie, P.I., Gillies, C.L., Coleman, R.A., Waycott, M., Dijk, K., Verges, A., Ross, J., Campbell, M., Matheson, F., Jackson, E., Irving, A., Govers, L., Connolly, R., McLeod, I., Rasheed, M., Kirkman, H., Flindt, M., Lange, T., Miller, A. and Sherman, C. (2020) Seagrass restoration is possible: Insights and lessons from Australia and New Zealand. *Frontiers of Marine Science* 7: 617. https://doi.org/10.3389/fmars.2020.00617.

Taylor, M.D. (2017) Preliminary evaluation of the costs and benefits of prawn stocking to enhance recreational fisheries in recruitment limited estuaries. *Fisheries Research* 186: 478-487. https://doi.org/10.1016/j.fishres.2016.05.030.

Taylor, M.D. and Creighton, C. (2018) Estimating the potential fishery benefits from targeted habitat repair: a case study of School prawn (*Metapenaeus macleayi*) in the lower Clarence River estuary. *Wetlands* 38: 1199–1209. https://doi.org/10.1007/s13157-018-1022-9.

Taylor, M.D., Chick, R., Lorenzen, K., Agnalt, A., Leber, K., Blankenship, H., Vander Haegen, G. and Loneragan, N. (2017) Fisheries enhancement and restoration in a changing world. *Fisheries Research* 186: 407-412. 1 https://doi.org/0.1016/j.fishres.2016.10.004.

Taylor, M.D., Gaston, T.F. and Raoult, V. (2018) The economic value of fisheries harvest supported by saltmarsh and mangrove productivity in two Australian estuaries. *Ecological Indicators* 84: 701–709. https://doi.org/10.1016/j.ecolind.2017.08.044.

Tugend, K.I., Allen, M.S. and Webb, M. (2002), Use of artificial habitat structures in U.S. lakes and reservoirs: A survey from the Southern Division AFS Reservoir Committee. *Fisheries* 27: 22-27. https://doi.org/10.1577/1548-8446(2002)027<0022:UOAHSI>2.0.CO;2.

van Poorten, B.T., Arlinghaus, R., Daedlow, K. and Heartel-Borer, S.S. (2011) Social-ecological interactions, management panaceas, and the future of wild fish populations. *Proceedings of the National Academy of Sciences* 108: 12554–12599. https://doi.org/10.1073/pnas.1013919108.

van Vuuren, W. and Roy, P. (1993) Private and social returns from wetland preservation versus from wetland conversion to agriculture. *Ecological Economics* 8(3): 289-305. https://doi.org/10.1016/0921-8009(93)90063-C.

Vivier, B., Dauvin, J., Navon, M., Rusig, A., Mussio, I., Orvain, F., Boutouil, M. and Claquin, P. (2021) Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness. *Global Ecology and Conservation* 27: e01538. https://doi.org/10.1016/j.gecco.2021.e01538.

Walker, T., Maredia, M., Kelley, T., La Rovere, R., Templeton, D., Thiele, G., and Douthwaite, B. (2008) *Strategic Guidance for ex post impact assessment of agricultural research*. Report prepared for the Standing Panel on Impact Assessment, CGIAR Science Council. Science Council Secretariat: Rome, Italy. 95 pp.

Walters, B.B. (2005) Ecological effects of small-scale cutting of Philippine mangrove forests. *Forest Ecology and Management* 206: 331–348. https://doi.org/10.1016/j.foreco.2004.11.015.

Watson, P., Thilmany, D., Wilson, J. and Winter, S. (2007) Determining economic contributions and impacts: What is the difference and why do we care? *Journal of regional Analysis and Policy* 37: 140-146.

Watson, R. and Preedy, V. (2010) 5-Point Likert Scale. In: Preedy, V.R. and Watson, R.R. (eds) *Handbook of disease burdens and quality of life measures.* Springer, New York. pp. 4288. https://doi.org/10.1007/978-0-387-78665-0_6363.

Whitmarsh, D. and Pickering, H. (2000) Investing in artificial reefs. In: Jensen, A.C., Collins, K.J., Lockwood, A.P.M. (eds) *Artificial reefs in European seas*. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-4215-1_27.

Whitmarsh, D., Santos, M.N., Ramos, J. and Monteiro, C.C. (2008) Marine habitat modification through artificial reefs off the Algarve (southern Portugal): an economic analysis of the fisheries and the prospects for management. *Ocean and Coastal Management* 51: 463–468. https://doi.org/10.1016/j.ocecoaman.2008.04.004

Wohl, E., Lane, S.N., and Wilcox, A.C. (2015) The science and practice of river restoration. *Water Resources Research* 51: 5974–5997. www.yarok.org.ilhttp://www.reformrivers.eu/home

Ye, Y., Loneragan, N., Die, D., Watson, R. and Harch, B. (2005) Bioeconomic modelling and risk assessment of tiger prawn (*Penaeus esculentus*) stock enhancement in Exmouth Gulf, Australia. *Fisheries Research* 73: 231–249. https://doi.org/10.1016/j.fishres.2004.12.004.

Appendix C – Literature review

The full literature review "*A review of fisheries enhancement methods to promote profitability and sustainability in Australian fisheries*." can be accessed at:

https://www.frdc.com.au/sites/default/files/products/2020-102%20Appendix%20C%20-%20Literature%20review%20on%20fisheries%20enhancement.pdf

Appendix D – Survey of fisheries managers

The full manager survey "*Manager perspectives on enhancement strategies and decision support tools and their uptake in fisheries management*." can be accessed at:

https://www.frdc.com.au/sites/default/files/products/2020-102%20Appendix%20D%20-%20Manager%20survey%20on%20fisheries%20enhancement.pdf