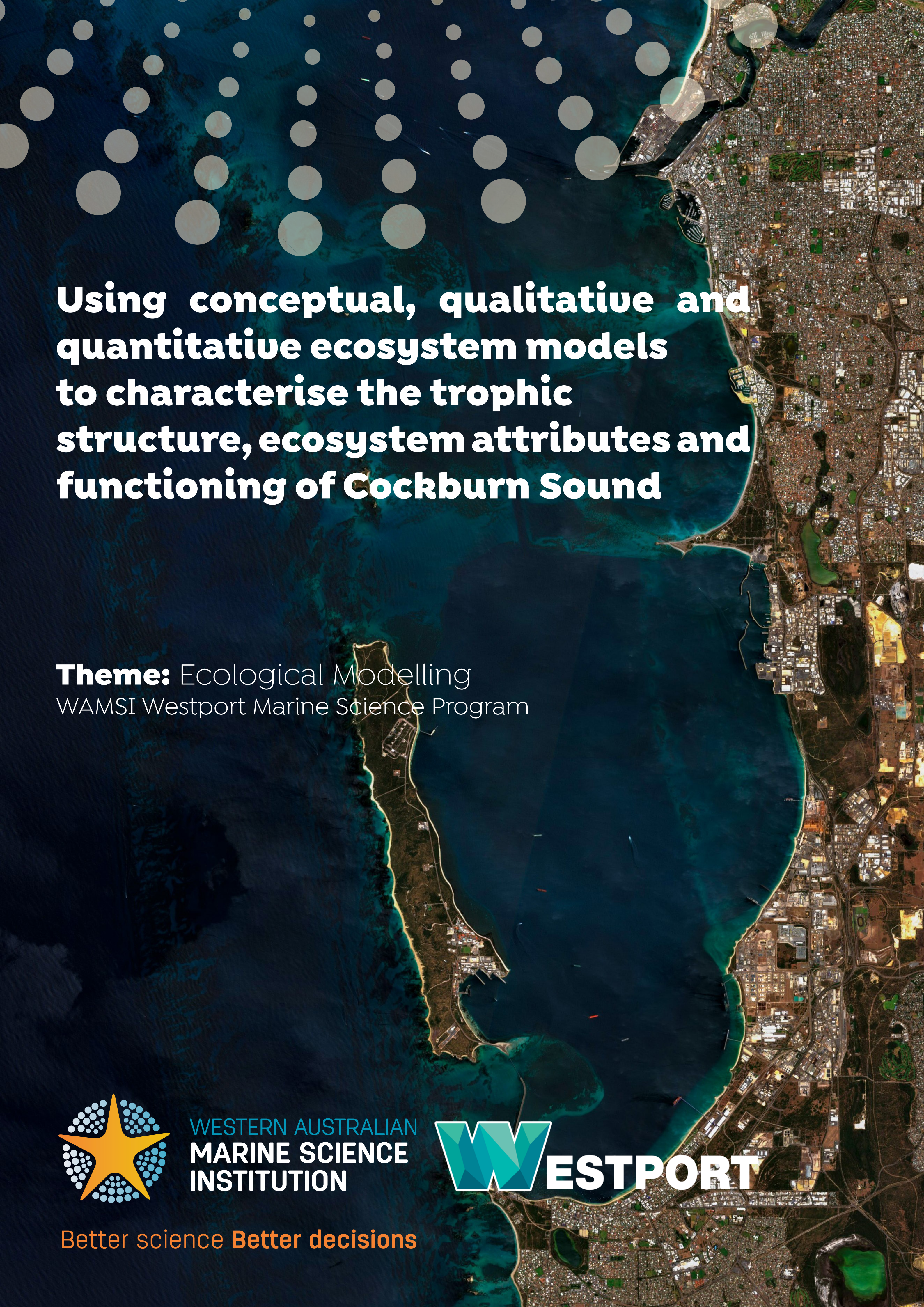

Using conceptual, qualitative and quantitative ecosystem models to characterise the trophic structure, ecosystem attributes and functioning of Cockburn Sound

Theme: Ecological Modelling

WAMSI Westport Marine Science Program

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ABOUT THE MARINE SCIENCE PROGRAM

The WAMSI Westport Marine Science Program (WWMSP) is a $13.5 million body of marine research funded by the WA Government. The aims of the WWMSP are to increase knowledge of Cockburn Sound in areas that will inform the environmental impact assessment of the proposed Westport development and help to manage this important and heavily used marine area into the future. Westport is the State Government's program to move container trade from Fremantle to Kwinana, and includes a new container port and associated freight, road and rail, and logistics. The WWMSP comprises more than 30 research projects in the biological, physical and social sciences that are focused on the Cockburn Sound area. They are being delivered by more than 100 scientists from the WAMSI partnership and other organisations.

FUNDING SOURCES
The $13.5 million WAMSI Westport Marine Science Program was funded by the Western Australian Government, Department of Transport. WAMSI partners provided significant in-kind funding to the program to increase the value to >$22 million.

DATA
Finalised datasets will be released as open data, and data and/or metadata will be discoverable through Data WA and the Shared Land Information Platform (SLIP).

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WAMSI Westport Marine Science Program

Photo source: Kwinana Industries Council (*www.kic.org.au*)

USING CONCEPTUAL, QUALITATIVE, AND QUANTITATIVE ECOSYSTEM MODELS TO CHARACTERISE THE TROPHIC STRUCTURE, ECOSYSTEM ATTRIBUTES AND FUNCTIONING OF COCKBURN SOUND

Final Report

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Executive Summary

Background

Cockburn Sound (CS) is highly valued by the community for its ecological, economic, and recreational attributes. This ecosystem is home to a vital part of Western Australia's economy, and incorporating the Kwinana industrial area, international shipping, port facilities, national defence, and one of Perth's desalination plants. The diversity of activities in CS places it under increasing environmental pressure from industrial, urban, and recreational use. CS is one of the most intensively used marine areas in Western Australia and has had a history of major industrial development and nutrient pollution. This has contributed to significant losses of seagrass meadows (~80%) between the 1950s and early 2000s and declines in exploited species such as pink snapper (PS; *Chrysophrys auratus*) and blue swimmer crab (BSC; *Portunus armatus*).

Biological communities in CS are organized in food webs and the nature of key ecosystem linkages (who eats who) and other trophic processes (how and when material flows between populations) are not fully quantified. Resolving this knowledge gap is a fundamental step required for informed environmental and biodiversity management. This study developed a series of conceptual, qualitative, and quantitative ecosystem models of CS that provided the basis needed to explore solutions to manage current and future risks, including a better understanding of ecological flow-on effects from impacts associated with development. These models provided a baseline understanding of key ecosystem processes, drivers, and pressures in CS. The models were developed using local biological surveys from the WAMSI-Westport Marine Research Program (WWMSP) 2021-2022, expert consultation, searches of the literature and three project workshops that engaged a wide range of participants across the WWMSP.

Objectives

1. Develop conceptual and qualitative models based on potential impacts of the port (including ecological and socio-economic inputs).
2. Develop a quantitative ecosystem model to characterise the trophic structure, key ecosystem attributes and overall functioning of CS using Ecopath software.
3. Integrate data from other themes into a quantitative ecosystem model to support a synthesis of current knowledge of ecological and ecosystem processes.

Methods

a) Conceptual and Qualitative modelling of Cockburn Sound

We developed sixteen conceptual models that include a wide range of environmental, biological, and anthropogenic factors that may influence the health of CS. Nine of these models describe key pressures (e.g. climate change, dredging, groundwater quality, desalination) and threats for species of conservation interest (e.g. little penguin [*Eudyptula minor*], seagrass [*Posidonia sinuosa*]). They were presented in the first workshop of the project (May 2022) and feedback received from these models provided the basis for the development of four additional conceptual models for seagrass (roles of seagrass in ecosystem services, and seagrass vulnerability for periods of the 1960s, 1980s and 2020) and three models describing the life cycle of fished species (PS, BSC, and scaly mackerel [SM; *Sardinella lemuru*]) in CS.

The conceptual models were used to guide the development of qualitative models using signed digraphs to describe the relationships between species, the environment and influencing factors (Dambacher *et al*. 2002a; 2015). We built 14 qualitative models for five key species in CS to explore the effects of climate change and infrastructure development. These models focussed on three fished species (PS, BSC, and SM) and two components of conservation interest (little penguins and seagrass).

The process of developing these qualitative models involved collecting knowledge and building social capacity such as: the building of relationships with key stakeholders, knowledge development through three project workshops, expert meetings, and collaboration with scientists from government agencies (i.e. DPIRD, DBCA, CSIRO), universities (i.e. ECU, UWA, MU) and independent researchers, to integrate ecological knowledge of CS. The conceptual and qualitative models synthesised knowledge of key species, processes, and pressures in the region, and were used to inform the development of the Ecopath quantitative model.

b) Quantitative modelling of Cockburn Sound using Ecopath software

The Ecopath with Ecosim (EwE) modelling software is free software (under the terms of the GNU General Public Licence), and downloadable online (www.ecopath.org), with more than 400 Ecopath models for aquatic systems published worldwide (Colléter *et al.,* 2015). The EwE package has three main components: (1) Ecopath - a static, mass-balanced food web model; (2) Ecosim – a time dynamic simulation module primarily designed for simulation and evaluation of different future development scenarios; and (3) Ecospace – a spatial and temporal dynamic module for exploring impact and placement of protected areas. In this study, Ecopath allowed us to characterize trophic structure, ecosystem attributes, and the functioning of CS. Ecosim was used for fitting of the model to commercial catch data (see details below), and sensitivity analysis of the food web model (using Monte Carlo simulations). The development of environmental and management scenarios using Ecosim is beyond the scope of this project.

Ecopath creates a static mass-balanced food web snapshot of the resources and their interactions, including biomass and energy flows. The Ecopath model requires at least four data points for each functional group: biomass (in $t \cdot km^{-2}$); the ratio of production over biomass (P/B; in yr^{-1}); the ratio of consumption over biomass (Q/B; in yr^{-1}); and ecotrophic efficiency (EE; unitless and a measure of the proportion of the net annual production consumed by higher trophic levels). The Ecopath ecosystem model developed for CS contains 73 functional groups, including one non-living group (detritus). The functional groups were identified based on discussions with experts, stakeholders and feedback from the first project workshop. These groups include species of significance to commercial and recreational fishing (e.g. PS, BSC), those of conservation significance (e.g. little penguins, seagrass, dolphins) and those likely to be of ecological significance (e.g. demersal fish, habitat-forming species such as corals, sponges and macroalgae).

Abundance and biomasses of fish and invertebrate communities in CS for the Ecopath model were obtained from WAMSI sampling of CS in 2021 and 2022 by Project 2.4 "*Benthic communities in soft-sediment and hard substrates: baseline data, pressure response relationships of key biota for EIA, and mitigation strategies for artificial reefs*", and Project 4.2.1 "*Spatial distribution and temporal variability in life stages of key fish species in Cockburn Sound*". DPIRD provided fisheries data, including total catch (kg) and CPUE (catch per unit effort), for three of the commercially fished species in CS: BSC, western rock octopus (*Octopus djinda*) and squid (*Sepioteuthis spp.*). The diet matrices assembled for the Ecopath model were reviewed by experts from DPRID (Department of Primary Industries and Regional Development), CCWA (Conservation Council of Western Australia), DBCA (Department of Biodiversity, Conservation and Attractions), UWA (University of Western Australia), ECU (Edith Cowan University), and MU (Murdoch University) for the main components of the food web.

Once the basic Ecopath parameters were entered, the model required mass-balancing to maintain the laws of thermodynamics. It was mass-balanced by reducing predation mortality rates and then calibrated to time series of commercial catch and CPUE data for BSC, western rock octopus, and squid. We conducted a sensitivity analysis (500 Monte Carlo simulations) to reduce the error Sum of Square (SS) of the Ecopath input parameters. Results from this analysis showed that functional groups with trophic levels <2.5 (invertebrates and primary producers) were associated with the highest uncertainty in Biomass and they displayed the largest changes in Biomass. Further results and methods of this analysis are presented in Appendix 9.

Results

a) Conceptual and qualitative models

The 16 conceptual models (Table 2.1) developed in the project and presented during the first two workshops allowed us to gain an understanding of key groups, pressures, and interactions in the CS ecosystem. This understanding was used to further develop 14 qualitative models (Table 2.4) for five key species in the region (PS, BSC, SM, little penguin, and seagrass), and they focused on: 1) the importance of predation and food resources on different stages in the life cycles; 2) the interactions of the species with port activities, including dredging, shipping traffic and port maintenance; 3) the influence of climate change, including increments of SST, and changes in dissolved oxygen; and 4) anthropogenic activities, including boat strikes. Some of the more novel conclusions of our qualitative modelling work relate to the three fished species. Analysis of these models predicted strong negative reactions of adults and many life stages to an increase in port activities, such as dredging and shipping traffic. Increased management in general was predicted, in all models, to have a positive effect on the fished species and species of conservation significance in the system. In the PS infrastructure model, management was split into water management and fisheries management and both nodes were predicted to positively impact PS spawners and pre-spawners. These results highlight the vital role of management agencies and the need for effective coordination and cooperation among agencies and industry to implement management strategies focused on both the marine environment and the food webs it supports. The results from our qualitative models for PS, seagrass and little penguin show predicted negative responses to infrastructure development and port activities. These findings are consistent with predictions of previous qualitative modelling of seagrass and fish in CS and their response to increases in sediment loads which were predicted to be detrimental to seagrass and fish (Metcalf *et al*., 2009).

Further development in some of the qualitative models is recommended. For example, in the seagrass climate change model (section 2.3.3.4) some of its predictions did not match the sign of the community matrix resulting in ambiguous responses. This instability is mainly explained by a positive loop between established meadows and the vegetative growth nodes in the model Further research on the ecology of vegetative reproduction of seagrass could provide basis for the resolution of this ambiguity. Ecosystem interactions with vegetative seagrass growth in CS are relatively uncertain. Qualitative models might also be used to explore the significance of zooplankton, detritus and detritivorous species in the system and other small pelagic fish species such as blue sprat (*Spratelloides robustus*).

Understanding the factors that govern the relationship between structure, stability and functioning of food webs has been a central problem in ecology for many decades. The first steps in answering key questions about the structure and functioning of CS ecosystem was the construction of the Ecopath model for the present-day conditions (2020-2022). The model developed in this study describes the energy and mass fluxes, the trophic interactions of predators, prey, and fisheries. The network of species connections within this food web is useful for a better understanding of ecological roles of fished species (i.e. BSC, PS, SM, western rock octopus, and squid) and species of conservation significance (i.e. little penguin, bottlenose dolphin, Australian sea lion) in CS.

b) The quantitative model

The quantitative Ecopath ecosystem model developed in this study integrates the information and data available in CS and provides a summary of our current knowledge of the biomass, consumption, production, and trophic flows in the region. We used descriptors from the network analysis to estimate trophic interactions, trophic transfer, and energy flows among the 73 groups of the CS food web. The results suggested that compared with four other systems along the Western Australian coast (Kimberley, North West Shelf, Ningaloo, Jurien Bay; Table 3.4), CS is a small energetic system (Total System Throughput [TST] of 10,517 $t \cdot km^{-2} \cdot yr^{-1}$), but complex and highly connected (System Omnivory Index [SOI] of 0.34) in a late state of development (Total Primary Production/Total Respiration [TPP/TR] of 0.6), with an important dependency on external energy entering the Sound (Net System Production [NSP] of -1384 $t \cdot km^{-2} \cdot yr^{-1}$). The transfer efficiency was highest at trophic level II (TL, with many invertebrates and demersal fishes) and the contribution of energy transformations by top predators (groups at TL >3.5) was low, suggesting that the transfer and recycling of energy is retained and accumulated in the lower levels of the food web (groups with TL <2.5). Recycling of organic matter and detritivory are important elements in enrichment and nutrient cycling in this food web (Finn's Cycling Index [FCI] of 4.9). Nutrient cycling has a major impact on ecosystem dynamics and stability (Ulanowicz, 1969; Theis *et al.*, 2021). Our results provide broader insight into the main mechanisms governing energy flows and processes shaping the trophic structure of the CS ecosystem. The above findings provide an understanding of the processes and interactions within the system that inform plans for conservation and management.

The Ecopath model identified the ecological role of keystone groups defined as structuring species by processes associated with predation (top-down forces) with sharks, bottlenose dolphin, Australian sea lion, and cormorants as functionally important species in the system. Identifying these keystone groups can help to develop effective conservation strategies for species-level prioritization in CS. Also, the modelling indicated that declines in benthic fishes (i.e. western foxfish, western blue groper, little gurnard perch, sea mullet) have the potential to reduce the production of higher trophic levels consumers.

The ecological indicators generated in this study provide baseline information on the trophic structure, energetics, and function of the CS ecosystem. The 36 indicators presented in this study can be used to inform scientist and managers of changing conditions in the CS food web and how this food web responds to stressors and disturbances (e.g. infrastructure development and climate change) through evaluating different scenarios for the Sound.

There were many factors that might affect the performance of the model in describing the structure and trophic interactions of CS. For example, the model was used to estimate the biomass of those functional groups without some types of biomass data from CS , such as PS adults, pre-spawners, juveniles, small pelagic fishes, plankton groups and benthic primary producers. A second factor is that time constraints prevented recent estimates of recreational fishing catch and effort for key species in CS (e.g. Australian Herring, King George Whiting, Mulloway, Australian Salmon, Blue Sprat, Butterfishes, and other whiting species) being included in the model. These data have been provided to the project team and can be incorporated in a new Ecopath model, funding permitting. A third key factor lies in the diet composition of the functional groups, where the contribution of detritus as a food source for detritivorous fishes and invertebrates is a partially determined component of this food web. These uncertainties could introduce inaccuracies in the predicted outputs of the model. Hence, information on the biology and abundance of these species should be targeted for further research. Some of this information is being collected as part of ongoing WWMSP projects in CS. The predictions from the water quality model on detritus and primary production, being developed in the WWMSP Project 1.2 "*Pathways to productivity: Development of a water response model for Cockburn Sound*", are likely to reduce some of the uncertainties in the model.

Implications for stakeholders

In this study, the integral and cooperative participation of direct stakeholders from Westport, WAMSI, DPIRD, and DBCA in the building of our conceptual, qualitative, and quantitative ecosystem models played a vital role in linking social, economic, and ecological factors to understand potential ecosystem change in CS. Overall, the conceptual and qualitative models developed in this project display current knowledge of the five species selected (PS, BSC, SM, little penguin, and seagrass), which can be considered important tools for communication with stakeholders. This helps a inform a wide audience of how CS is likely to respond to current and future development and environmental pressures and encourages two-way knowledge transfer between researchers and different interest groups.

The Ecopath ecosystem modelling provided a framework for identifying key research questions, pressures, and keystone species in CS and assigning priorities for ecosystem approaches to management. Results from this study provided a useful suite of ecosystem-level performance indicators for CS for the period of 2020-2022 that could inform on how the system may respond in the future to ecological perturbations and infrastructure development.

Recommendations

1. Revise the Ecopath model to incorporate data currently being gathered by other projects of the WWMSP, and the latest recreational fishing data from DPIRD.
2. Develop conceptual and qualitative models for components of the CS system that were seen as important during the current project or that are identified as priorities from current WWMSP projects e.g. blue sprat, zooplankton, detritus and detritivory. These serve as important communication and knowledge transfer mechanisms on the functioning of CS to diverse groups of people.
3. Develop a temporal-dynamic ecosystem model (Ecosim) using the structure and outputs of Ecopath model presented in this study. The Ecosim model will have the capacity to run scenarios, developed with CS stakeholders, to explore changes in CS associated with climate change and dredging. This research was not an objective of the current study.
4. Develop scenarios to be evaluated for the system in consultation with stakeholders.
5. Develop a spatial dynamic ecosystem model (Ecospace) for CS to better assess the importance of seagrasses and other habitat-forming groups (i.e. sponges, corals, and macroalgae) for the CS food web. This model would also allow the spatial footprint of the proposed new port to be assessed with greater certainty.
6. During the final project workshop, it was suggested that a reconstruction of past states of CS (i.e. periods 1970s, 1990s, and 2010s) would be very valuable, along with developing temporal and spatial scenarios of the whole system, to assess the historical impacts of dredging and cumulative impacts of development on the Sound. Furthermore, the development of past states of CS, using Ecopath with Ecosim, would provide the basis for hindcasting the present-day conditions of the model. The development of dynamic scenarios for evaluation in Ecosim was not part of the current study.
7. Link the top-down quantitative food-web model (Ecopath) with the bottom-up water quality model under construction in WWMSP Project 1.2 (Matt Hipsey) for a better understanding of the performance of both models and management trade-offs associated with management strategies.
8. Develop a compiled version of the software that allows a diverse range of users to run different scenarios of change in the CS ecosystem. This would serve to enhance understanding of potential future states of CS in response to different pressures.

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The WAMSI Westport Marine Science Program is a $13.5 million body of research that is designed to fill knowledge gaps relating to the Cockburn Sound region. It was developed with the objectives of improving the capacity to avoid, mitigate and offset environmental impacts of the proposed Westport container port development and increase the WA Government's ability to manage other pressures acting on Cockburn Sound into the future. Funding for the program has been provided by Westport (through the Department of Transport) and the science projects are being delivered by the Western Australian Marine Science Institution.

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List of Abbreviations

BSC:	Blue swimmer crab
CC:	Climate change
CS:	Cockburn Sound
CPUE:	Catch per unit of effort
CSIRO:	Commonwealth Scientific and Industrial Research Organisation
DPIRD:	Department of Primary Industries and Regional Development
DBCA:	Department of Biodiversity, Conservation, and Attractions
ECU:	Edith Cowan University
EE:	Ecotrophic Efficiency
EwE:	Ecopath with Ecosim software
FCI:	Finn's Cycling Index
GNU:	General Public Licence
IUCN:	International Union for Conservation of Nature
KS:	Keystone species index
LC:	Leeuwin Current
MTI:	Mixed Trophic Impacts
MTL:	Mean Trophic Level
MU:	Murdoch University
P/B:	Production / Biomass ratio
PS:	Pink snapper
PP:	Primary production
PREBAL:	Pre-balancing diagnostics
Q/B:	Consumption / Biomass ratio
QM:	Qualitative modelling
RTI:	Relative total impacts
SM:	Scaly Mackerel
SOI:	System Omnivory Index
SS:	Weighted sum of square deviations
SST:	Sea surface temperature
TE:	Mean Transfer Efficiency
TL:	Trophic Level
TST:	Total System Throughput
UWA:	University of Western Australia
WAMSI:	Western Australian Marine Science Institution
WWMSP:	WAMSI Westport Marine Science Program

Chapter 1: Introduction

Cockburn Sound (CS) is highly valued by the community for its ecological, economic, and recreational attributes. This ecosystem is home to a vital part of Western Australia's economy by incorporating the Kwinana industrial area, international shipping, port facilities, national defence, and an important metropolitan desalination plant. The diversity of activities in CS places it under increasing environmental pressure from industrial, urban, and recreational use. CS is one of the most intensively used marine areas in Western Australia and has had a history of major industrial development and nutrient pollution. This has contributed to significant losses of seagrass meadows (~80%) between the 1950s and early 2000s and declines in exploited fish and invertebrate species such as pink snapper (PS; *Chrysophrys auratus*) and blue swimmer crab (BSC; *Portunus armatus*).

Biological communities in CS are organized in food webs and the nature of key ecosystem linkages (who eats who) and other trophic processes (how and when material flows between populations) is still far from being fully understood. Resolving this knowledge gap is a fundamental step required for environmental and biodiversity management. By bringing together historical fishery datasets and new data from the WAMSI Westport research program, this project quantified the nature of the CS food web through the development of conceptual, qualitative, and quantitative ecosystem models. The project developed an ecosystem model of the CS that provided the quantitative basis needed to explore solutions to manage current and future risks, including a better understanding of ecological flow-on effects from impacts associated with development. These models provided a baseline understanding of key ecosystem processes, drivers, and pressures in CS.

Ecosystem models attempt to represent ecological systems by quantifying interactions among their components, from individual populations to communities and even entire biomes. In this study, we decided to use Ecopath with Ecosim (EwE) software (Polovina, 1984; www.Ecopath.org), an energy balance model that has been widely applied to inform ecosystem-based management (e.g. Plaganyi *et al*., 2004); climate change impacts (e.g. Brown, *et al*., 2010); fishing impacts (e.g. Lozano-Montes *et al.,* 2013), spatial closures (e.g. Lozano-Montes *et al*., 2012); artificial reefs (e.g. Wu *et al*., 2016), and aquaculture impacts (e.g. Han *et al.,* 2017). The EwE software is the most applied tool for modelling marine and aquatic systems globally, with over 600 models published (Colléter *et al.,* 2015). The EwE package has three main components: (1) Ecopath - a static, mass-balanced food web model; (2) Ecosim – a time dynamic simulation module primary designed for scenarios development; and (3) Ecospace – a spatial and temporal dynamic module for exploring impact and placement of protected areas. In this study, Ecopath allowed us to characterize trophic structure, ecosystem attributes, and functioning of CS. Ecosim was only used for fitting of the food web model and quantification of uncertainty of Ecopath input parameters. The development of environmental and management scenarios using Ecosim is not part of this project, nor is the simulation of dynamic change in CS in response to pressures part of the project.

The development of the Ecopath model (food web) in this study included two work packages: (1) conceptual and qualitative modelling, and (2) quantitative ecosystem modelling using Ecopath. The conceptual and qualitative modelling helped us to clarify how drivers and pressures interact with communities in the CS, in a structured way, identify system response pathways, feedback loops and other system features of interest. The Ecopath model provided a static description of energy and mass flow in the food web for the current state of CS (2020-2022). The Ecopath model developed in this study assessed interactions between 73 functional groups (~134 species), including fished species (i.e. PS, BSC, scaly mackerel (SM; *Sardinella lemuru*) and species of conservation significance (i.e. Australian sea lions [*Neophoca cinerea*], dolphins, sea birds, and little penguin [*Eudyptula minor*]). The process for developing the conceptual, qualitative, and quantitative food-web models included a series of three workshop designed to establish an understanding of key processes in CS, define the biological structure of the Ecopath model, discuss data gaps, data uncertainties and present results and findings from qualitative and quantitative ecosystem models to key stakeholders.

In this study, we used biological information from other projects in the WAMSI Westport Marine Science Program (WWMSP; i.e. fish and invertebrate trawls from projects 4.2.1 "*Spatial distribution and temporal variability in life stages of key fish species in Cockburn Sound*", and project 2.4 "*Benthic communities in soft-sediment and hard substrates: baseline data, pressure-response relationships of key biota for EIA, and mitigation strategies for artificial reefs*") to develop a series of conceptual, qualitative and ecosystem models (using Ecopath with Ecosim software) to gain knowledge of how the communities of CS are organized in food webs, and other key ecosystem process that are still far from comprehensive.

1.1 Objectives

1. Develop conceptual and qualitative models based on potential impacts of the port (including ecological and socio-economic inputs), including a historical conceptual model for the pre-industrialization period (1950s) if reasonable information is available*****.
2. Develop a quantitative ecosystem model that characterises the trophic structure, key ecosystem attributes and overall functioning of CS using Ecopath software.
3. Integrate data from other themes into a quantitative ecosystem model to support a synthesis of current knowledge of ecological and ecosystem processes.

*****Note: These objectives do not match the original objectives included in the Science Plan submitted to WWMSP in December 2021. As the Science Plan was revised and approved in January 2022, the above original Science Plan objectives evolved, but the three objectives presented in this study encompasses the six original objectives of the Science Plan. In addition to the six objectives of the Science Plan, we have completed qualitative modelling to complement the conceptual models and inform the quantitative Ecopath model.

The Report is structured in two major technical Sections: Chapter 2 focusses on the Conceptual and Qualitative Modelling and Chapter 3 focusses on the Ecopath quantitative ecosystem model. Each of these Chapters has an Introduction to the approach, followed by Methods, Results and Discussion. The General Conclusions, Recommendations and Future Directions are presented following these Chapters.

Chapter 2: Conceptual and Qualitative modelling of Cockburn Sound

2.1 Introduction to Conceptual and Qualitative Modelling

Models are simplifications of real systems. They can be used as tools to better understand a system and to make predictions of what will happen to all the system components following a disturbance or a change in any one of them. Conceptual and qualitative models are descriptors of the general functional relationships among essential components of an ecosystem. They tell the story of "how the system works" and can be used as tools to better understand a system and to make predictions of what will happen to all the system components following a disturbance or a change in any one of them.

2.2. Conceptual modelling

In this project, conceptual models were developed to provide an understanding of the main structures and pathways of CS, and they were used to inform and complement the quantitative ecosystem models (section 3.2 of this report). We developed sixteen conceptual models that include a wide range of environmental, biological, and anthropogenic factors that may influence the health of CS. Nine of these models describe key pressures (e.g. climate change, dredging, ground water quality, desalination) and threats for species of conservation interest (e.g. little penguin, seagrass). They were presented in the first workshop of the project (12th May 2022) and feedback received from these models provided the basis for the development of additional four conceptual models for seagrass (roles of seagrass in ecosystem services, and seagrass vulnerability for periods of 1960s, 1980s and 2020) and three models describing the life cycle of fished species (pink snapper [PS], blue swimmer crabs [BSC], scaly mackerel [SM]) in CS. The life cycle models of SM and seagrass were presented during the third project workshop (15th March 2023). A total of five life cycle conceptual models and 16 conceptual models were developed during this study (Table **2.1**). These are summarised in the report and more details are provided in Appendix 1.

The fished species included two that are of great recreational significance (BSC and PS) and one (SM, *Sardinella lemuru*) that is likely to have a significant influence of the food web, connecting the lower trophic levels of phytoplankton and zooplankton to the higher trophic levels such as piscivorous fish, dolphins, and Australian sea lions. They also represent a range of life-cycles and species with different habitat requirements e.g. the BSC are closely associated with the substrate and complete their short life-cycle of <3 years within CS, while SM are a tropical species, living in the water column to about 6-7 years of age and are only found in CS as larger juveniles (recruits) and adults i.e. the eggs, larval and juvenile stages are found in more northern waters outside the Sound.

Table 2.1. Conceptual models developed in this study. These models are presented in Appendix 1.

Category	Model	Workshop
Target fished species	Life Cycle Blue Swimmer Crab	Presented in Workshop 2
	Life Cycle Pink Snapper	Presented in Workshop 2
	Life Cycle Blue Swimmer Crab	Presented in Workshop 2
	Life Cycle Scaly Mackerel	Presented in Workshop 3
Species of conservation interest	Seagrass 2020	Presented in Workshop 3
	Seagrass 1980s	Presented in Workshop 2
	Seagrass 1960s	Presented in Workshop 2
	Seagrass contributions to ecosystem services	Presented in Workshop 2
	Little Penguin	Presented in Workshop 1
Interacting pressures	Climate Change	Presented in Workshop 1
	Dredging	Presented in Workshop 1
	Desalination	Presented in Workshop 1
	Ground water quality	Presented in Workshop 1
Ecosystem processes	Cockburn Sound food web	Presented in Workshop 1
	Cultural ecosystem of Cockburn Sound	Presented in Workshop 1
	Coupled Socio-Ecological System	Presented in Workshop 1

2.3. Qualitative modelling

A qualitative model is a representation of the relationships between system variables i.e. components in the ecosystem and flows between components in diagrams. These models are useful for drawing together large amounts of diverse information from physical, ecological, and social fields and for communicating understanding across disciplines. This kind of model has become an important tool in the study and management of ecological systems as ecosystem process often cannot be directly manipulated in a field test. In this study, we adopted signed digraphs (or loop analysis), a type of qualitative model, to describe the relationships between species, the environment and influencing factors – shown by circles (Dambacher *et al*. 2002a; 2015). The influences of one component on another are shown by the sign of the interactions: positive effects are denoted by an arrow; negative effects denoted by a line terminating in a filled circle; and effects of the factor on itself, such as density-dependent effects, by a circle at the base of a semi-circle. The signed digraph represents the ecosystem as a set of 'components' shown by the circles and positive or negative 'links' between the components.

2.3.1. Purpose of qualitative models

The qualitative models of this study are used to assimilate, simplify, and communicate information to convey our understanding of ecosystem structure and functioning. They increased our understanding of ecosystem function by visualizing how species are influenced by each other and by abiotic factors. These qualitative models allowed us to make predictions on how CS might change in response to potential stressors on the marine environment such as port development, and climate change. They also informed and complemented the quantitative Ecopath model being developed for CS because the qualitative models allow a wide array of alternative model structures to be explored. The development of conceptual models in combination with qualitative models provides an effective communication and knowledge transfer mechanism for a wide range of people with diverse backgrounds.

2.3.2. General methods for qualitative modelling

Model construction

Five main stages are involved in the construction of qualitative models to make predictions about the response of the model system to changes in state or pressures on the system. These are: 1. Constructing signed digraphs of the model system; 2. Constructing the community matrix from the signed digraph and examining its stability; 3. Calculating the inverse matrix; 4. Calculating the prediction matrix; and 5. Calculating the absolute feedback and weighted prediction matrix. Each of these stages is described briefly below.

Step 1: Signed digraphs

The first stage in model development is to provide a schematic of the system – this is typically done using the familiar and intuitive "signed digraphs" – diagrams that describe the relationship of community species using nodes or elements (boxes or circles) and positive or negative links as described above. Links are symbols representing interactions occurring among components in the model system. These can represent a flow of material or energy within the system or can be used to indicate a causal effect of one component on another (Dambacher *et al*., 2002a). Our signed digraphs qualitative models have been developed using *PowerPlay* software. Powerplay is a Java-based program providing a friendly graphical interface, so it is easy develop models of ecological communities and factors affecting them. For more details of Powerplay see Dambacher *et al*., (2002b).

Step 2: Community matrix [A]

The next stage in qualitative model development is the construction of the "community matrix" which summarises the Interactions between nodes or elements (+, -, 0) in a signed digraph to represent the ecological interactions and pressures within the ecosystem. A perturbation (increase) in the community matrix is shown down a column for a component in the system, while the responses (predictions) of components to perturbations are read across rows (Dambacher *et al*., 2002a) as shown in Figure 2.1.

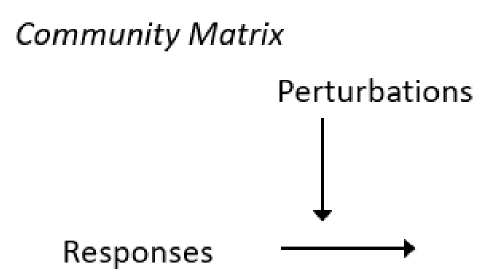


Figure 2.1. Representation of perturbations and responses interactions in the community matrix

We used matrix algebra to generate the adjoint matrix to analyse the stability of the model following Dambacher *et al*., 2002a (criterion I and ii) and how positive influences in a model with different life-history stages can lead to an ambiguous response. In some cases, the positive net feedbacks could result in a false ambiguity (Dambacher *et al*., 2015). This is discussed in more detail when it is relevant to a particular model below.

Step 3: The inverse matrix [A^{-1}]

Step 3 in model development is construction of the inverse matrix [A^{-1}] of the Community matrix [A], which is an intermediate step in calculating the adjoint or prediction matrix ([-A], (i.e. the predicted results from the interactions in the signed digraphs). The Community matrix generated from the signed digraph is represented as [A]. Each of the community matrices in this study was inverted using the method of Gaussian elimination in Maple Software (https://www.maplesoft.com). Figure 2.2 displays an example of how a community matrix of 3x3 is inverted using the method of Gaussian elimination.

$$\mathsf{A} \equiv \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix},$$

the matrix inverse is

$$\mathsf{A}^{-1} = \frac{1}{|\mathsf{A}|} \begin{bmatrix} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} & \begin{vmatrix} a_{13} & a_{12} \\ a_{33} & a_{32} \end{vmatrix} & \begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} \\ \begin{vmatrix} a_{23} & a_{21} \\ a_{33} & a_{31} \end{vmatrix} & \begin{vmatrix} a_{11} & a_{13} \\ a_{31} & a_{33} \end{vmatrix} & \begin{vmatrix} a_{13} & a_{11} \\ a_{23} & a_{21} \end{vmatrix} \\ \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} & \begin{vmatrix} a_{12} & a_{11} \\ a_{32} & a_{31} \end{vmatrix} & \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \end{bmatrix}.$$

Figure 2.2. Example of calculating an 3x3 inverse matrix [A] following the method of Gaussian elimination. [A] is the starting community matrix generated from the signed digraph.

Step 4: The adjoint matrix ("prediction matrix")

The community matrix [A] represents the components and the direct positive or negative interactions between components within the system; however, the indirect impact of a perturbation is more complex to determine. Responses to a perturbation are calculated using both the direct and indirect effects of change in community elements (Dambacher *et al*., 2002a). The prediction matrix is designated as the adjoint matrix Adj [-A]. The adjoint of the Community matrix predicts the sensitivity of any variable in the model system to the change of system parameters. Mathematically, the elements of the adjoint matrix are the cofactors of the transpose matrix (Dambacher *et al*., 2002a). Thus, a change in the abundance of a species in the community matrix is determined by the net effect of complementary feedback loops. The adjoint matrix can be viewed as a prediction that provides an estimate of the change in equilibrium abundance of each system element resulting from a negative or positive impact (Dambacher *et al*., 2002a). A positive number in the adjoint matrix represents a positive response, a zero represents no response, and a negative number represents a negative response. Because the adjoint is the sum of positive and negative loops, it is not possible to know the numbers of positive and negative loops in the subsystem. This can be estimated by constructing an Absolute Feedback matrix. This is done using the same calculation method as used to construct the adjoint matrix, except taking the absolute value for all elements in the calculation – this allows the total number of complementary feedback loops for each community response to be calculated (Dambacher *et al*., 2002a). The adjoint matrices developed in this study were calculated using Maple software (https://www.maplesoft.com/).

Step5: Absolute Feedback and the Weighted-Prediction Matrix

Feedback in qualitative models is a term used to describe the process in which an increment in one variable produces a change in other variables in the system (positive or negative; Puccia and Levins 1985). Any value from the adjoint matrix is difficult to interpret because it is derived from the sum of both positive and negative cycles. Each element of the adjoint matrix can be weighted by the total number of both positive and negative cycles. This is the called "Absolute Feedback" matrix [T]. Each element of [T] represents the total number of cycles (negatives and positives) in a response (Dambacher *et al*., 2002a). Dividing the absolute value (||) of each element of the adjoint matrix by each element of Matrix [T], produces a matrix of ratios, or the "Weighted-prediction" matrix [W]. Possible values of W range from 0 to 1, where values of W near zero are predictions that are highly indeterminate or uncertain (Dambacher *et al*., 2002a). The reliability of predictions in the adjoint matrix increases as the values of [W] become closer to 1. A value of W=1 shows a response that is completely reliable in terms of their response sign or direction of change (Dambacher *et al*., 2002a). We follow Dambacher *et al*. (2015) in choosing a value of W>0.80 to indicate a reliable predicted response.

During the first project workshop (12^{th} May 2022), we introduced qualitative modelling using signed-digraphs and social network diagrams. Participants highlighted the need to use the models to explore the early impact of the port development on the fished species, including the recruitment of PS, BSC, , and SM, as well as some species of conservation interest such as little penguin, and seagrass. We have developed qualitative models in consultation with experts of DPIRD, UWA, ECU and DBCA as well as feedback received during the first two workshops of the project and the process of model development is summarised in Figure 2.3.

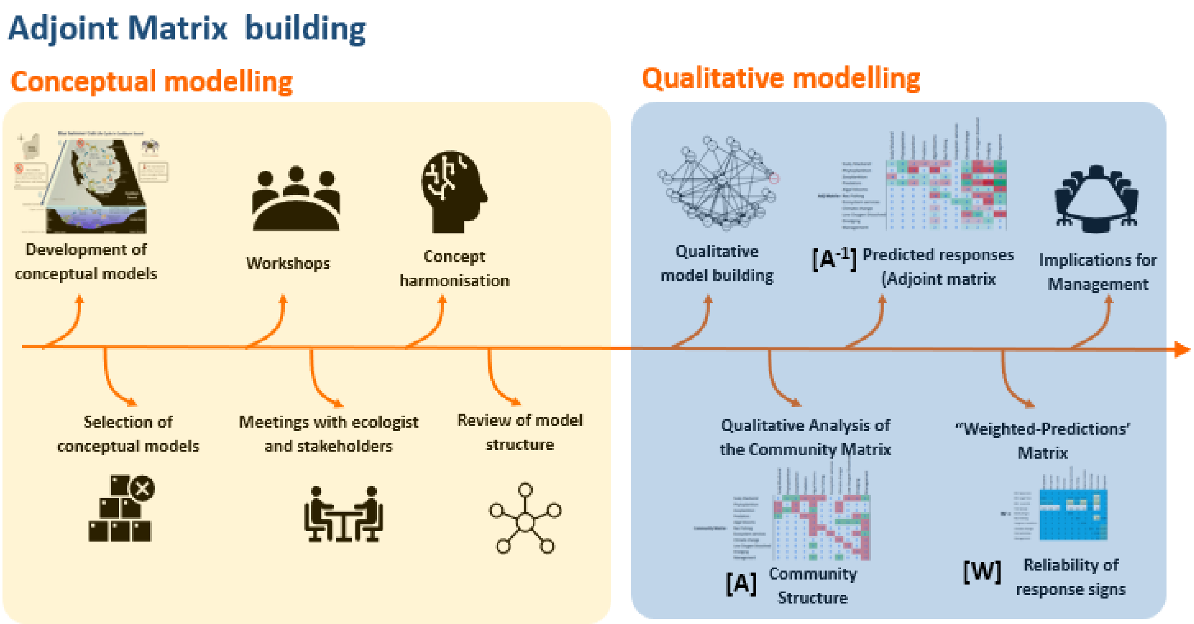


Figure 2.3. Process of building qualitative models for CS to predict responses of components (species and processes) in the system to perturbations.

2.3.3. Case studies

In this study, we built 14 qualitative models for five key species in CS to explore the effects of climate change and infrastructure development (Figure 2.4).

2.3.3.1. Blue swimmer crab (BSC), Portunus armatus (formerly Portunus pelagicus)

The reproductive cycle of BBSC populations along the WA coast is strongly influenced by water temperature (de Lestang et al., 2010). The waters of the lower west coast are at the southern extreme of this species temperature tolerance and reproduction is restricted to the warmer months, with mating occurring in late summer when females are soft-shelled and a peak of spawning in spring (Kangas 2000; de Lestang et al., 2010). In comparison, the warmer, tropical waters of Shark Bay induce spawning all year round, with most of the contribution from spawning coming from the winter period (July – September) (de Lestang et al., 2003a; Harris et al., 2012; Chandrapavan et al., 2017).

Movement and habitat in Cockburn Sound

In contrast to the emigration and immigration of BSC in estuaries and rivers (e.g. the Peel-Harvey and Swan-Canning estuaries), the population in CS is self-recruiting with little immigration into, or emigration out of the Sound, the fishery from neighbouring bodies of water. Juveniles congregate in southern inshore waters around Mangles Bay, Jervoise Bay, and James Point, before moving into central deeper waters (Potter *et al*., 2001).

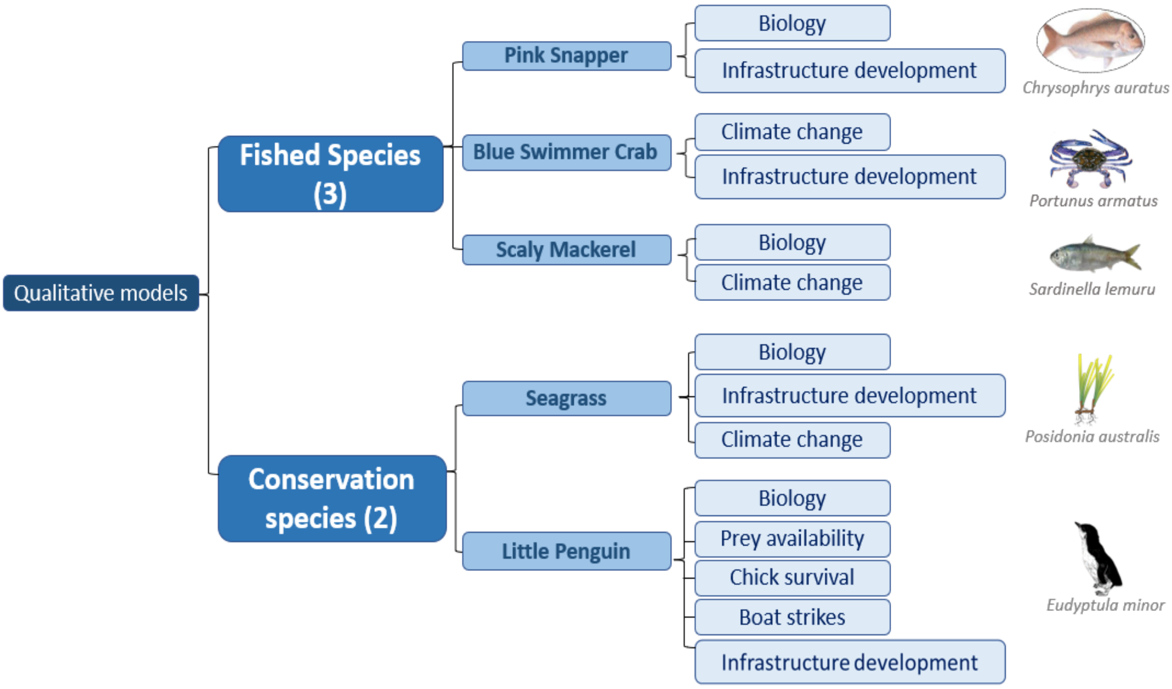


Figure 2.4. Qualitative models developed for CS to explore the effects of climate change and infrastructure development for five key species: PS, BSC, SM, little penguin, and seagrass.

Conceptual life cycle model

Understanding the life history of the BSC, *Portunus armatus*, – or how it forages, ages, grows, and reproduces throughout its life - is key to sustainably managing its fishery and supporting a healthy population. It is a short-lived species, reaching a maximum age of about 3 years (maximum size of ~225 mm carapace width; Marks *et al*., 2020; Johnston *et al*., 2021) and matures at ~12 months of age (~100 mm CW; Johnston *et al*., 2021). The reproductive cycle of this species in Western Australia is strongly influenced by water temperature. Seagrass plays an important role in the development of this crab and in CS, juveniles are mostly found in seagrass habitats in the shallow waters of Mangles Bay, Jervois Bay, and James Point. BSC are fished by commercial and recreational fishers in Western Australia, though the commercial fishery in CS has been closed since 2014. The recreational fishery of this species remains open north off Woodman Point. The 2020 levels of recruitment and breeding stock biomass of *P. armatus* in CS were low and the decline in abundance is believed to be substantially attributable to environmental changes in CS, rather than fishing (Johnston *et al*, 2020). The life history information of this species (Figure 2.5. Summary of the life cycle of the BSC (*Portunus armatus*) in CS and some of the key processes that influence it. Derived from workshop discussions, discussions with researchers and Johnston *et al*., 2020.

has helped managers to implement some regulations (e.g. seasonal closures, commercial minimum legal size of 130 mm CW and recreational legal size of 127mm CW; and closing the commercial fishery). These regulations help ensure that BSC remains sustainable for future generations.

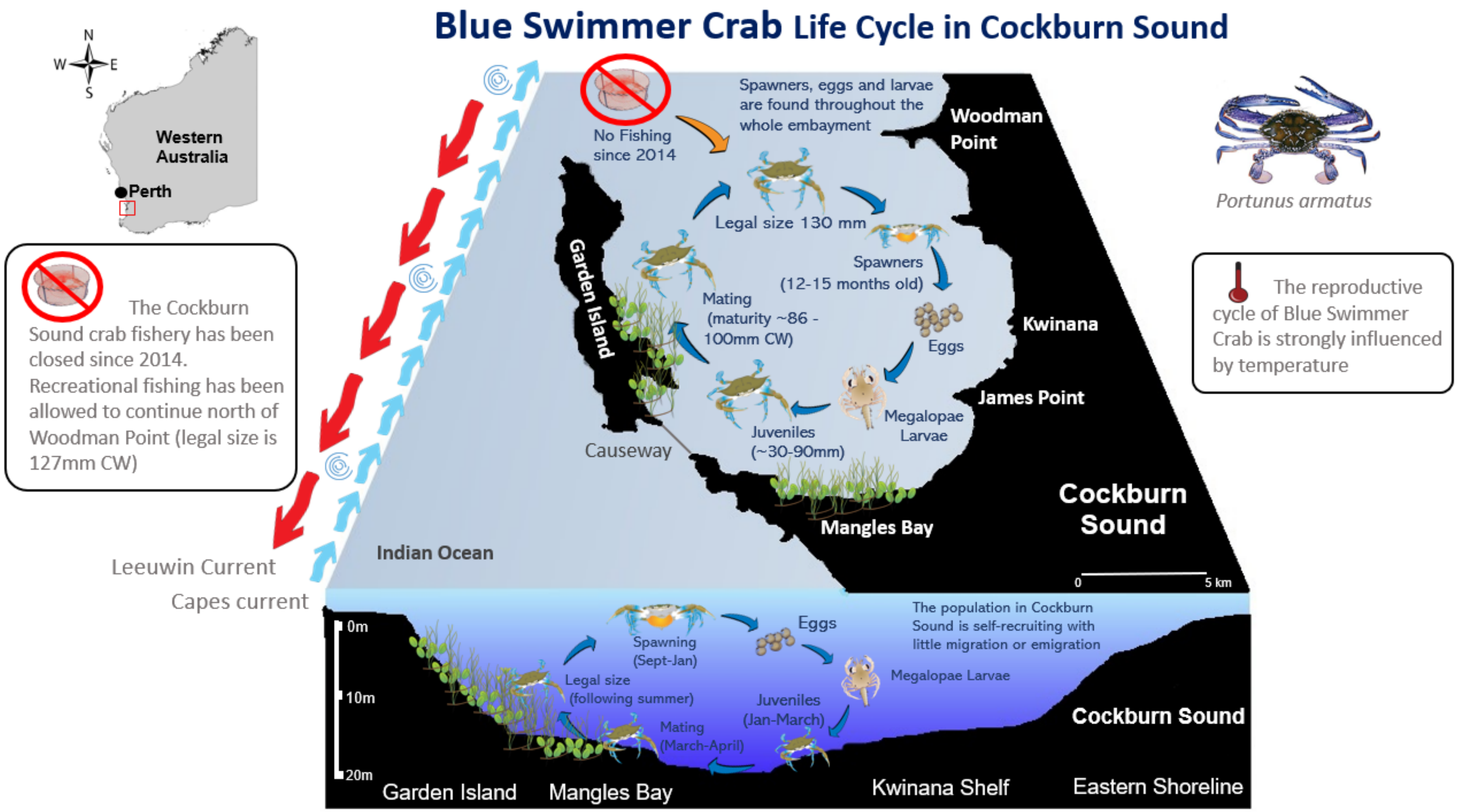


Figure 2.5. Summary of the life cycle of the BSC (*Portunus armatus*) in CS and some of the key processes that influence it. Derived from workshop discussions, discussions with researchers and Johnston *et al*., 2020.

BSC qualitative model

The preliminary signed digraph model of the BSC life cycle was designed to explore specific relationships between ecosystem components, and pressures in CS. The model includes 10 nodes representing five life stages of BSC (spawners, legal size, mating, juveniles and larvae), and key ecological processes and drivers such as the influence of the biofouling community associated with new hard structures from port development, seagrass meadows, recreational fishing, climate change, and port activities (Table 2.2). Port activities includes dredging and ship traffic. One general management node was included in the model to address both fisheries and environmental management in general (Figure 2.6). Climate change in this case refers not only the warming effect on the waters of CS, but also other effects associated with climate change such as acidification, and deoxygenation.

Table 2.2. The ten nodes (species and processes) included in the BSC life cycle qualitative model.

Node	Group
BSC Leg	BSC Legal Size
BSC Spw	BSC spawners
BSC Juv	BSC Juvenile
BSC L	BSC larvae
BioF	Biofouling community
Rec F	Rec Fishing
Seags	Seagrass meadows
CC	Climate change
Port A	Port activities
Mang	Management

The signed digraph shows the relationships between the nodes of the BSC life cycle and their interactions with seagrass and stressors such as climate change, recreational fishing, and port activities (i.e. dredging, shipping) (Figure 2.6).

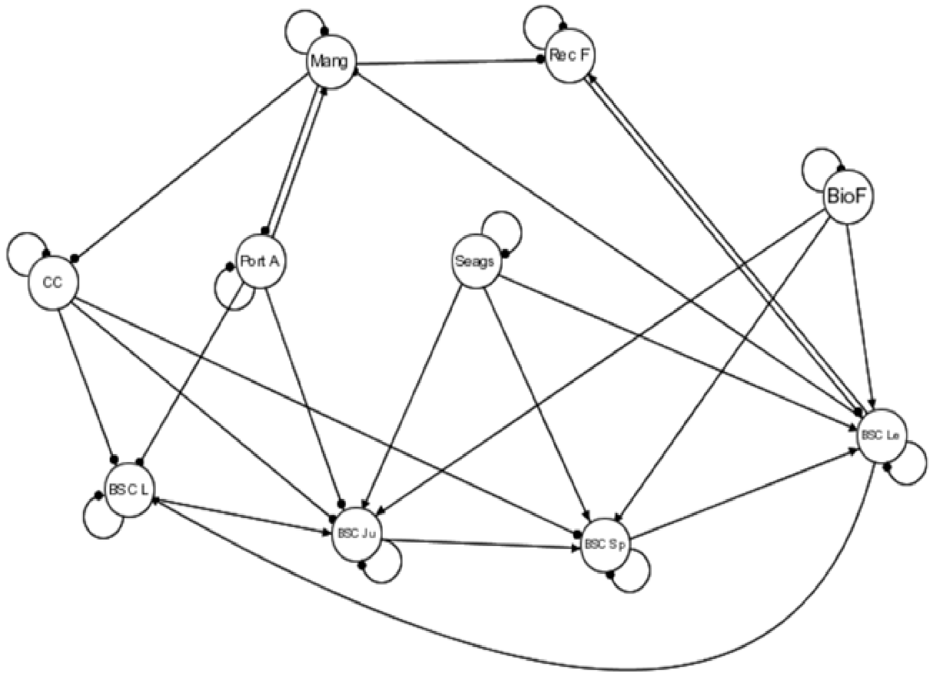


Figure 2.6. Signed digraph for BSC biology qualitative model showing the direct links for different stages in the life cycle with main stressors (i.e. climate change, recreational fishing, and port activities) in CS.

Community matrix and stability of the model

Positive relationships between nodes in the community matrix of the BSC with seagrass and stressors (climate change, recreational fishing, and port activities) are shown by a 1 and highlighted in green, negative relationships by -1 and red highlight, with no relationship shown by a 0 and no highlight (Table 2.3). PowerPlay generates the specifications for the community matrix [A] which is read in Maple software (see details in methods of this section), where the community matrix is determined, its stability investigated and the adjoint matrix [-A] is calculated (see below).

The stability of the community matrix (Table 2.3) for BSC life cycle was examined using the Hurwitz criterion i and ii (C≥1). The negative sign of all coefficients (Fn) (Appendix 2) of the adjoint matrix suggest a very stable model. Also, the value of C was 7.2×10^5, which indicates that the model is stable (see Dambacher *et al.* 2002a).

Columns in the community matrix (Table 2.3) shows the influence of one node on all others; for example, BSC Spawners have a positive effect on larvae and the biofouling community has a positive influence on BSC legal size, spawners, and juveniles through an increment in prey availability. Looking across a row of the Community Matrix in Table 2.3 shows how one node is influence by all other nodes in the model e.g. BSC legal size and juveniles are positively influenced by the biofouling community and seagrass meadows and negatively influenced by recreational fishing.

Table 2.3. Community matrix [A] of the BSC with 11 nodes with positive impacts (1, green cells), and negative impacts (-1, red cells) highlighted. No impact is shown by 0 and no highlight.

	BSC Spawners	BSC Legal Size	BSC Juvenile	BSC larvae	Biofouling Community	Rec. Fishing	Seagrass meadows	Climate change	Port activities	Management
BSC Legal size	-1	1	0	0	1	-1	1	0	0	0
BSC Spawners	0	-1	1	0	1	0	1	-1	0	0
BSC Juvenile	0	0	-1	1	1	0	1	-1	-1	0
BSC larvae	1	0	0	-1	0	0	0	-1	-1	0
Biofouling C.	0	0	0	0	-1	0	0	0	0	0
Rec Fishing	0	0	0	0	0	-1	0	0	0	-1
Seagrass meadows	0	0	0	0	0	0	-1	0	0	0
Climate change	0	0	0	0	0	0	0	-1	0	-1
Port activities	0	0	0	0	0	0	0	0	-1	-1
Management	-1	0	0	0	0	0	0	0	1	-1

Adjoint matrix or prediction matrix [-A] and uncertainty

The adjoint matrix [-A] for the BSC Community matrix [A] was derived following the method described in Dambacher *et al.* (2002a). The adjoint shows the responses of each component of the community matrix to an increase or press of each component in the model. The probability of sign matrix was used to colour code the adjoint matrix – green and red show high certainty (>0.80) of the predicted positive and negative responses respectively, while 0 with no highlight shows high certainty of no predicted model response. A "?" and no highlight shows low certainty (≤0.8) of the predicted response.

The adjoint matrix for assessing infrastructure development and recreational fishing, and climate change on the life cycle of BSC shows that increase in recreational fishing will negatively affect all life stages of BSC through the direct extraction of legal-size crabs (Table **2.4**). An increase in climate change (warmer waters, acidification, and deoxygenation) is predicted to negatively impact all life history stages of BSC (Table 2.4). When port activities are increased, the direction of BSC responses were negative, but their probability of correct sign ranged between 0.5-0.8 (Appendix 2) so they are considered ambiguous, as suggested by Dambacher *et al.*, (2002a). Increased Management (a fisheries management control focused on reducing fishing pressure) was predicted to increase the reproductive stages of BSC (spawners and legal-size crabs; Table 2.4).

Table 2.4. The Adjoint Matrix [-A] derived from the Community matrix [A] for the BSC. Green cells are positive responses with high probability of signed response (P=1); red cells are negative responses with high probability (P=1), 0 = no predicted response with high probability (P=1); and "?" represents uncertain responses (probability of signed response P<0.85).

	Blue swimmer crab - Spawners	Blue swimmer crab - Legal size	Blue swimmer crab - Juvenile	Blue swimmer crab - Larvae	Biofouling community	Rec. Fishing	Seagrass meadows	Climate change	Port activities	Management
Blue swimmer crab - Spawners	2	0	2	2	4	-2	4	-4	?	5
Blue swimmer crab - Legal size	2	?	2	2	6	-2	6	-6	?	6
Blue swimmer crab - Juvenile	2	0	4	4	6	-2	6	-8	?	9
Blue swimmer crab - Larvae	2	0	2	4	4	-2	4	-6	?	7
Biofouling community	0	0	0	0	?	0	0	0	0	0
Recreational fishing	2	0	2	2	4	?	4	-4	?	4
Seagrass meadows	0	0	0	0	0	0	?	0	0	0
Climate change	0	0	0	0	0	0	0	2	?	?
Port activities	0	0	0	0	0	0	0	0	?	?
Management	0	0	0	0	0	0	0	0	?	?

2.3.3.2. Pink snapper (PS), Chrysophyrs auratus (formerly Pagrus auratus)

Conceptual model

CS supports one of the largest spawning aggregations of PS (*Chrysophrys auratus*) in Western Australia (Wakefield 2010). Snapper in CS contribute to stocks of this relatively long-lived species (maximum age ~40 years, length of 130cm and weight of ~20kg) across the lower West Coast (Bertram *et al*., 2022), where it reaches maturity at about 5 years of age (Wakefield *et al*., 2015, 2016). Snapper has a complex population structure (Figure 2.7) and understanding how it grows, reproduces, and matures is essential for the sustainable management of the fishery. The life history information of this species has been incorporated in age-based stock assessment models by DPIRD to determine the status of PS in Western Australia. Currently, stocks of PS in the DPIRD management bioregion of Western Australia are classified as inadequate (Fairclough *et al.,* 2021). The CS 4-month annual spawning closure to fishing for snapper (1 Sept - 31 Jan) provides targeted protection for spawning Snapper and it has been a key management measure for protecting these aggregations in the West Coast Bioregion since 2000. Recently (1st February 2023), this closure was extended to 6 months; 1 February to 31 March (inclusive); 1 August to the beginning of the September/October school holidays; and end of the September/October school holidays to 15 December (inclusive) (https://www.fish.wa.gov.au/fishing-and-aquaculture/demersal/Pages/default.aspx#:~:text= Catching%20demersal%20scalefish%20will%20be,to%2015%20December%20).

During the workshops, discussions identified that there was some uncertainty about the role of seagrass in the early juvenile stages of PS, as previous surveys had not detected them in that habitat (Wakefield *et al*., 2013). During the seagrass seed restoration program (Seeds for Snapper), divers observed significant numbers of small snapper in the seagrass beds when collecting seagrass seeds (Prof. Gary Kendrick, UWA, *pers. comm*.). For this reason, we have shown seagrass as an important habitat for the small juvenile snapper, recognising that they live around low profile reef structures as they increase in size (Wakefield *et al*., 2013).

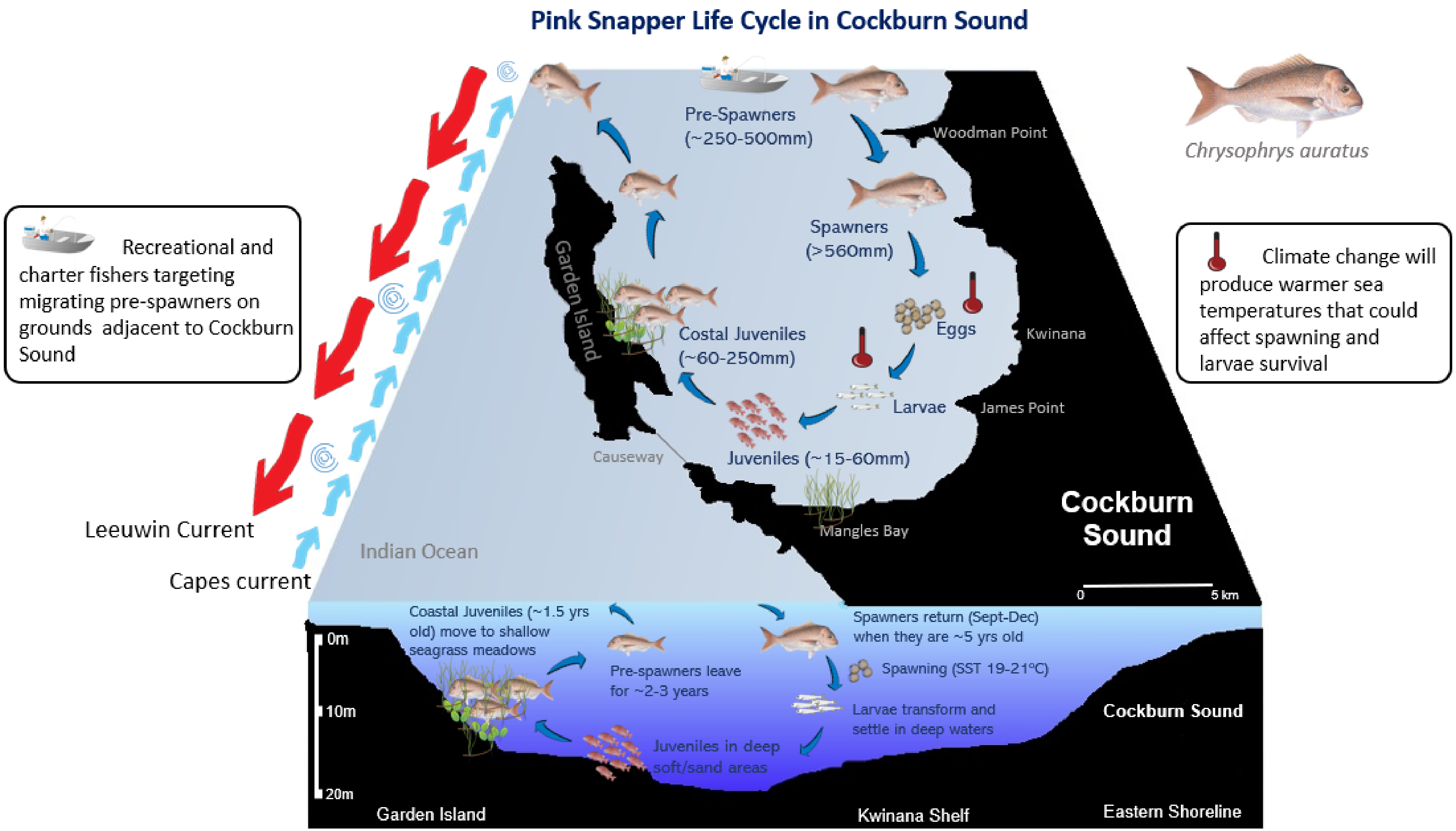
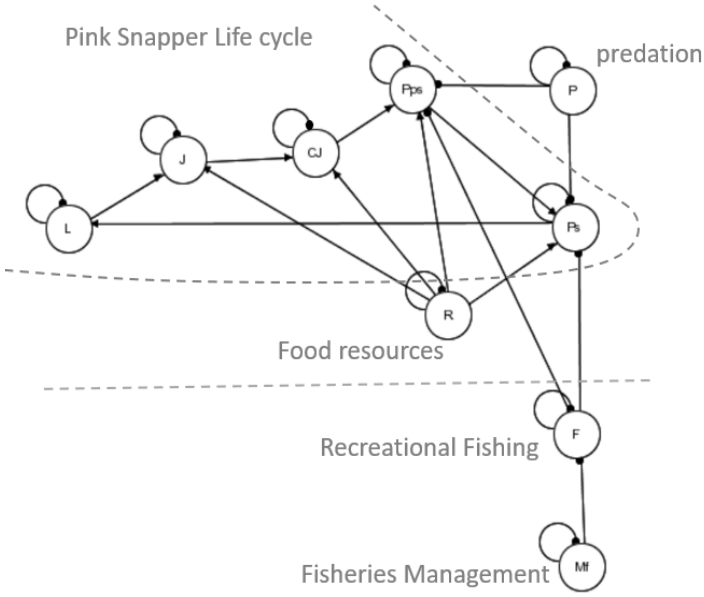


Figure 2.7. Life cycle of PS (*Chrysophyrs auratus*) in CS and the main processes affecting its biology. Conceptual diagram developed from workshop discussions and Wakefield *et al*., 2010.

Qualitative biology model

Signed digraph

Nine nodes were included in the qualitative biology model for PS which includes four life stages (spawners, pre-spawners, coastal juveniles, and larvae), food resources, predators (e.g. large sharks), recreational fishing, and fisheries management (Figure 2.8). This model was created to evaluate the impacts of biotic factors (i.e. predation and prey availability), recreational fishing and fisheries management in CS.



#	Node	Functional Group
1	Ps	Pink Snapper spawner
2	Pps	Pink Snapper pre-spawner
3	CJ	Coastal juvenile
4	J	Juvenile
5	L	Larvae
6	R	Food resources
7	P	Predators (e.g. large sharks)
8	F	Recreational fishing
9	Mf	Fisheries Management

Figure 2.8. Qualitative biology model of PS which includes nine nodes to represent main life stages of PS, predation, recreational fishing, and fisheries management.

Community matrix [A] and model stability

The community matrix for signed digraph of the PS biology model shows that PS spawners have a positive direct effect on the abundance of larvae, while recreational fishing and predators were associated with negative effects on PS spawners and pre-spawners (**Table 2.5**). Food resources have a positive influence on the larval to spawning stages of snapper. In this qualitative model, the link between the fisheries management node (Mf) and the recreational fishing node (F) is negative because Mf represents the process and tools that prevents potential overfishing and keep stocks of PS above target levels by reducing fishing effort.

Under stability criterion ii, the signs of all nine polynomial coefficients were negative (Appendix 2), and the value of C was 1.8 x 10^5 (Appendix 2), which indicates that the PS Biology model is very stable (see Dambacher *et al.* 2002a).

Table 2.5. Community matrix for the 9-node biology model of PS derived from the signed digraph in PowerPlay. Positive interactions are shown by a 1 and green highlight, negative by a -1 and red highlight and no interaction by a 0 with no highlight.

	PS spawner	PS pre-spawner	PS coastal juvenile	PS juvenile	PS larvae	Food resources	Predators	Recreational fishing	Fisheries Management
PS spawner	-1	1	0	0	0	1	-1	-1	0
PS pre-spawner	0	-1	0	0	0	1	-1	-1	0
PS coastal juvenile	0	0	-1	1	0	1	0	0	0
PS juvenile	0	0	1	-1	1	1	0	0	0
PF larvae	1	0	0	0	-1	0	0	0	0
Food resources	0	0	0	0	0	-1	0	0	0
Predators	0	0	0	0	0	0	-1	0	0
Recreational fishing	0	0	0	0	0	0	0	-1	-1
Fisheries Management	0	0	0	0	0	0	0	0	-1

The adjoint [-A] for PS biology

The adjoint or prediction matrix shows that predation and recreational fishing produced both direct negative effects on PS spawners and pre-spawners, and indirect negative effects on coastal juvenile, juveniles, and larvae (by reduction in abundance of spawners) (Table 2.6).

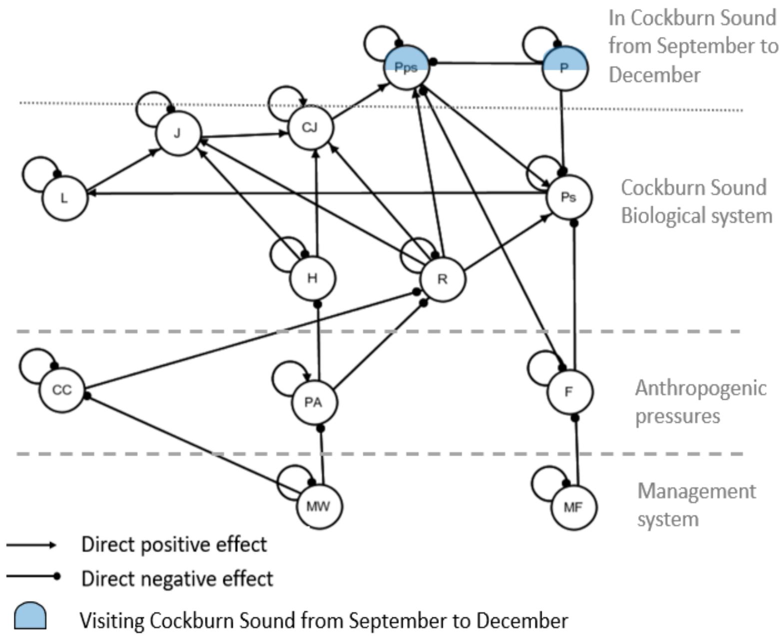
Table 2.6. The adjoint matrix (prediction matrix) [-A] for the biology model of PS showing the results of a press on the system and the direction and certainty of the response sign. Green cells = positive response with high probability (P=1); red = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1); "?" = low certainty of the direction of the response (P<0.80).

	PS spawner	PS pre-spawner	PS coastal juvenile	PS juvenile	PS larvae	Food resources	Predators	Recreational fishing	Fisheries Management
PS spawner	1	1	1	1	1	4	-2	-2	2
PS pre-spawner	1	1	1	1	1	4	-2	-2	2
PS coastal juvenile	1	1	1	1	1	4	-2	-2	2
PS juvenile	1	1	1	1	1	4	-2	-2	2
PF larvae	1	1	1	1	1	4	-2	-2	2
Food resources	0	0	0	0	0	?	0	0	0
Predators	0	0	0	0	0	0	?	0	0
Recreational fishing	0	0	0	0	0	0	0	?	?
Fisheries Management	0	0	0	0	0	0	0	0	?

Pink snapper port activities qualitative model

Signed digraph

Three nodes were added to the biology qualitative model for PS to create a model for evaluating the potential impacts of port activities (i.e. dredging, increase in shipping traffic) and climate change (increasing sea surface temperature [SST]) on PS (Figure 2.9). These nodes were: port activities (PA; including dredging shipping traffic, port maintenance), Global warming (CC), and Water Management (Mw) (Figure 2.9).



#	Node	Functional Group
1	Ps	Pink Snapper spawner
2	Pps	Pink Snapper pre-spawner
3	CJ	Coastal juvenile
4	J	Juvenile
5	L	Larvae
6	R	Food resources
7	P	Predators (e.g. large sharks)
8	H	Nursery habitats (e.g. reefs, sandy bottoms, seagrass)
9	F	Recreational fishing
10	CC	Global warming
11	PA	Port Activities (Dredging, shipping traffic, port maintenance)
12	Mf	Fisheries Management
13	Mw	Water Management

Figure 2.9. Port activities model of PS which includes 13 nodes to represent main life stages of PS, port activities (i.e. dredging, shipping traffic, port maintenance) and global warming.

Community matrix [A] and model stability

The community matrix formed from the signed digraph for the Port activities model shows that nursery habitats (reefs, sandy areas, seagrass) of PS are negatively impacted by global warming and port activities (i.e. dredging, port maintenance, shipping traffic) (Table 2.7). In the model, Water Management has a negative effect on port activities due to regulating and reducing activities such as dredging in the system. In a similar way, the fisheries management node has a negative link to recreational fishing (Table 2.7).

Under stability criterion ii, the signs of 13 polynomial coefficients were negative (Appendix 2), and the value of C was 1.8 x 10^5 (Appendix 2), which indicates that the PS Biology model is very stable (see Dambacher *et al.* 2002a).

Table 2.7. Community matrix for the 13-node infrastructure development model of PS from the signed digraph in PowerPlay. Positive interactions are shown by a 1 and green highlight, negative by a -1 and red highlight and no interaction by a 0 with no highlight.

	PS spawner	PS pre-spawner	PS coastal juvenile	PS juvenile	PS larvae	Food resources	Predators	Nursery habitats	Recreational fishing	Global warming	Port Activities	Fisheries Management	Water Managements
PS spawner	-1	1	0	0	0	1	-1	0	-1	0	0	0	0
PS pre-spawner	0	-1	1	0	0	1	-1	0	-1	0	0	0	0
PS coastal juvenile	0	0	1	1	0	1	0	1	0	0	0	0	0
PS juvenile	0	0	0	-1	1	1	0	1	0	0	0	0	0
PS larvae	1	0	0	0	-1	0	0	0	0	0	0	0	0
Food resources	0	0	0	0	0	-1	0	0	0	-1	-1	0	0
Predators	0	0	0	0	0	0	-1	0	0	0	0	0	0
Nursery habitats	0	0	0	0	0	0	0	-1	0	0	-1	0	0
Recreational fishing	0	0	0	0	0	0	0	0	-1	0	0	-1	0
Global warming	0	0	0	0	0	0	0	0	0	-1	0	0	0
Port Activities	0	0	0	0	0	0	0	0	0	0	-1	0	-1
Fisheries Management	0	0	0	0	0	0	0	0	0	0	0	-1	0
Water Managements	0	0	0	0	0	0	0	0	0	0	0	0	-1

The adjoint matrix [-A]

The prediction matrix shows that global warming and port activities both produced direct negative effects on PS spawners and pre-spawners, and indirect negative effects on coastal juveniles, juveniles, and larvae (by a reduction in abundance of spawners) (Table 2.8). The model predicts that Fisheries Management and Water Management have positive effects on all life stages of PS (Table 2.8).

Table 2.8. The adjoint matrix (prediction matrix) [-A] for infrastructure development model of PS showing the results of a press on the system and the direction and certainty of the response sign. Green cells = positive response with high probability (P=1); red = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1); "?" = low certainty of the direction of the response (P<0.80).

	PS spawner	PS pre-spawner	PS coastal juvenile	PS juvenile	PS larvae	Food resources	Predators	Nursery habitats	Recreational fishing	Global warming	Port Activities	Fisheries Management	Water Managements
PS spawner	1	1	1	1	1	4	-2	-2	-2	-4	-6	2	10
PS pre-spawner	1	1	1	1	1	4	-2	-2	-2	-4	-6	2	10
PS coastal juvenile	1	1	1	1	1	4	-2	-2	-2	-4	-6	2	10
PS juvenile	1	1	1	1	1	4	-2	-2	-2	-4	-6	2	10
PS larvae	1	1	1	1	1	4	-2	-2	-2	-4	-6	2	10
Food resources	0	0	0	0	0	?	0	0	0	?	?	0	?
Predators	0	0	0	0	0	0	?	0	0	0	0	0	0
Nursery habitats	0	0	0	0	0	0	0	?	0	0	0	0	0
Recreational fishing	0	0	0	0	0	0	0	0	?	0	0	0	0
Global warming	0	0	0	0	0	0	0	0	0	?	0	0	?
Port Activities	0	0	0	0	0	0	0	0	0	0	?	0	?
Fisheries Management	0	0	0	0	0	0	0	0	0	0	0	?	0
Water Managements	0	0	0	0	0	0	0	0	0	0	0	0	?

2.3.3.3. Scaly mackerel (SM), Sardinella lemuru

Conceptual model

SM is a tropical species in the genus *Sardinella* found in the Eastern Indian Ocean and in the Western Pacific Ocean, in an area extending from southern Japan through the Malay Archipelago to Western Australia (https:fishesofaustralia.net.au/home/species/3988). It is a coastal, pelagic, schooling, and strongly migratory fish. This species feeds on phytoplankton, also zooplankton (mainly copepods). In Western Australia the spawning probably occurs between December to March, but the spawning grounds are not known. SM is a resource accessed by the commercial and recreational fishing sectors in Western Australia. SM are taken by purse seiners operating between Geraldton and Geographe Bay, and they are highly mobile with a patchy distribution (Figure 2.10). Otolith microchemistry showed no evidence for the existence of separate stocks between Carnarvon and Fremantle (Gaughan and Mitchell 2000). A risk-based weight of evidence assessment, using all available lines of evidence, showed that in 2021, the current level of risk to this stock is low (Blazeski *et al*., 2021). SM is a short-lived fish (up to seven years, attaining sexual maturity at about age two) that can reach up to 22 cm fork length and that feed by filtering plankton. They are an important food for seabirds. Australian sardines (*Sardinops sagax*) and SM are two of at least 25 recorded prey species taken by little penguin (*Eudyptula minor*) colonies on Penguin and Garden Islands in CS (Murray *et al*., 2011). However, the trophic relevance of SM in the CS marine ecosystem is less clear.

SM were chosen for study as they are the most abundant small pelagic or baitfish recorded in the commercial fishing statistics in CS. However, during the workshops, it was pointed out that several other species of small pelagic, temperate fish are also abundant in CS (e.g. Pilchards *Sardinops sagax,* Blue Sprat *Spratelloides robustus, and* Australian Anchovies *Engraulis australis*). These species are likely to spend more of their life cycle in the Sound than SM and be important in the food web in CS. They would need to be considered in more detail in any future work the trophic pathways in the ecosystem.

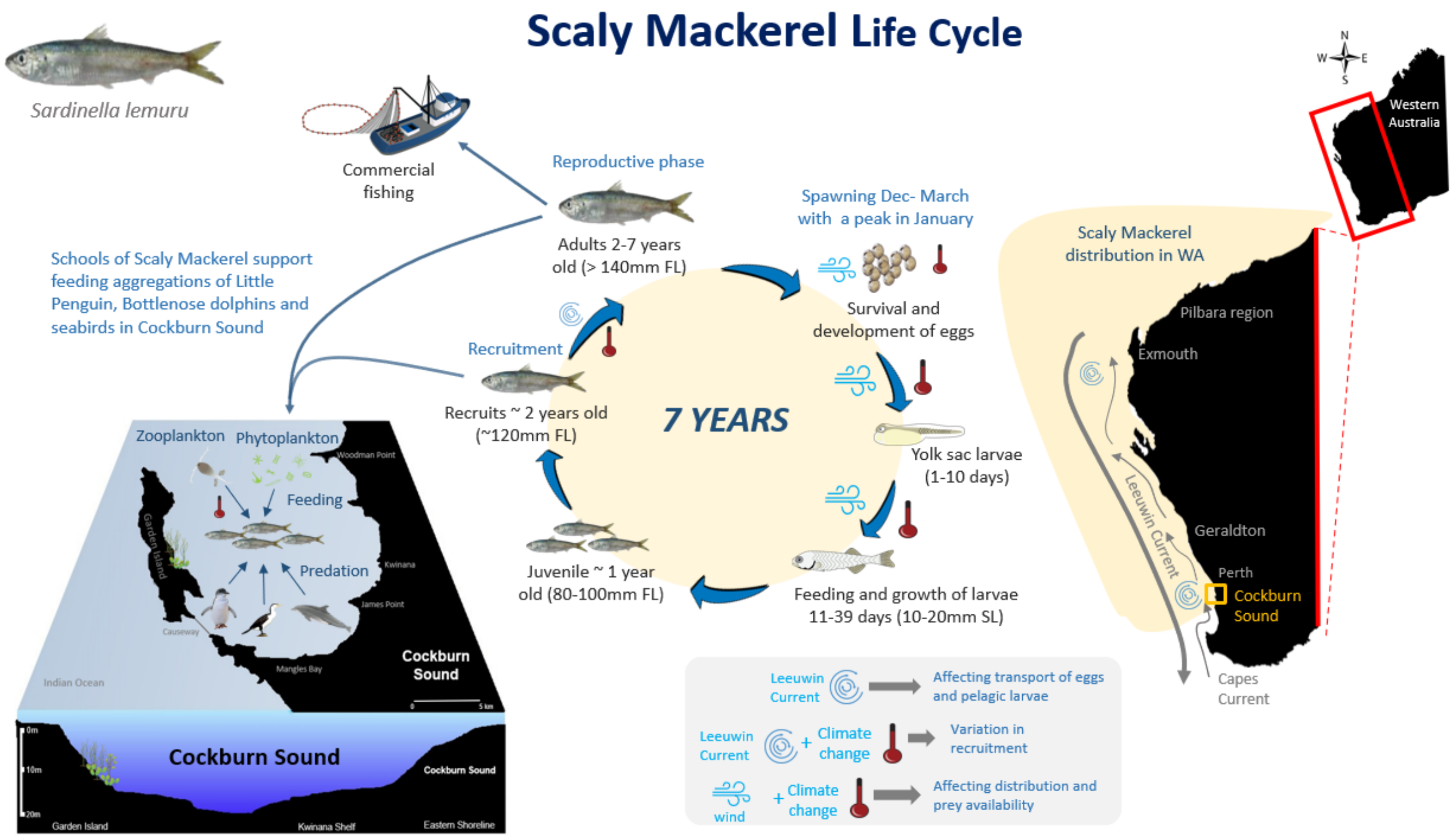


Figure 2.10. Life cycle of SM (*Sardinella lemuru*) in CS and main processes influencing the life cycle. Life cycle summarised from discussions with DPIRD staff, particularly Jeffrey Norris.

SM qualitative biology model

The signed digraph biology model of SM life cycle was designed to explore specific biotic relationships between prey and predators at different life stages of SM in CS. The model includes eight nodes representing five life stages of SM (adults, recruits, juveniles, feeding larvae, and yolk-sac larvae) as shown in Table 2.9.

Table 2.9. Eight nodes representing five life stages of scaly mackerel *SM* (adults, recruits, juveniles, feeding larvae, yolk-sac larvae), prey (phytoplankton and zooplankton), and predators (i.e. seabirds, dolphins).

#	Node	Component / Process
1	*A*	Scaly Mackerel adults
2	*R*	Scaly Mackerel recruits
3	*J*	Scaly Mackerel juveniles
4	*FL*	Scaly Mackerel feeding larvae
5	*YL*	Scaly Mackerel yolk sac larvae
6	*Ph*	Phytoplankton
7	*Z*	Zooplankton
8	*P*	Predators (seabirds, dolphins)

Signed digraph, community matrix [A]

The signed digraph for SM highlights that only two life-history stages, the adults (A) and recruits (R) are found in CS (blue shading in Figure 2.11), with spawning and larval to juvenile stages occurring in more northern waters where they are under the influence of the prevailing currents and wind conditions (Figure 2.11). Elevated temperatures can truncate spawning (Pankhurst and Munday, 2010). Larval fishes are usually more sensitive than adults to environmental fluctuations and might be especially vulnerable to climate change (Pankhurst and Munday, 2010). In this qualitative model, we assumed that elevated temperature would negatively influence development rates, survival, and duration of pelagic larval and juveniles of SM. The signs of all eight polynomial coefficients in the signed digraph for the SM biology model were negative (Appendix 2), and the value of C was 1×10^4 (Appendix 2), which indicates that the SM biology model is very stable (see Dambacher *et al.* 2002a).

The community matrix shows that an increase in any life-history stage of the SM, results in an increase in the next stage. SM adults and recruits are positively affected by phytoplankton and zooplankton in CS (Figure 2.11; Table 2.10). Predators in the Sound, such as bottlenose dolphins, Australian sea lions, and little penguins have a negative effect on the adults and recruits.

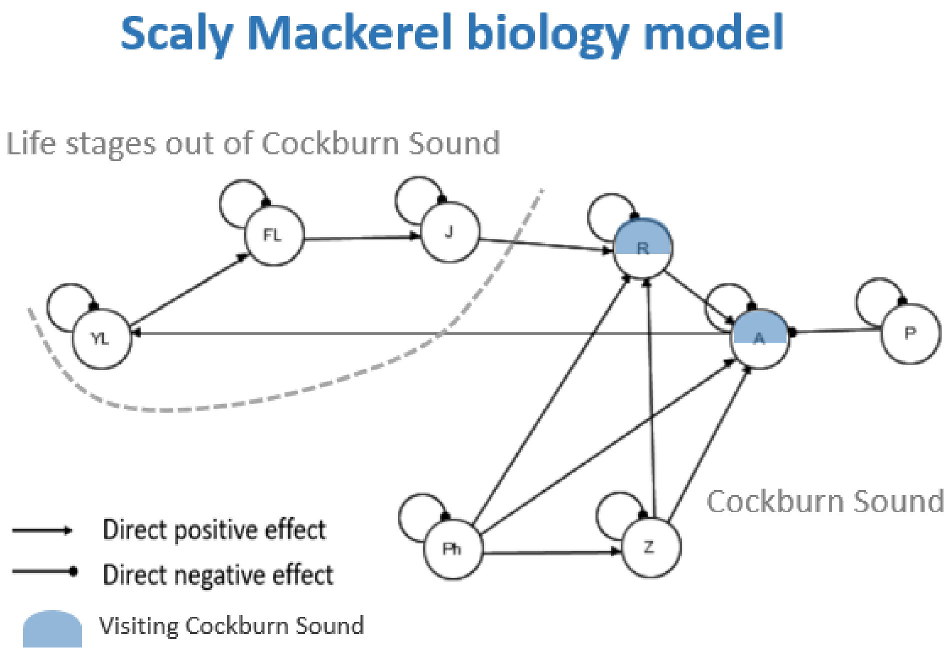


Figure 2.11. Signed digraph of the eight functional nodes included in the SM biology model.

Table 2.10. The specification of the community matrix for the eight-node SM biology model with positive impacts among nodes (1, green cells) and negative impacts (-1, orange) highlighted. No impact is shown by 0 and no highlight.

	SM adults	SM recruits	SM juveniles	SM feeding larvae	SM yolk-sac larvae	Phytoplankton	Zooplankton	Predators
SM adults	-1	1	0	0	0	1	1	-1
SM recruits	0	-1	1	0	0	1	1	0
SM juveniles	0	0	-1	1	0	0	1	0
SM feeding larvae	0	0	0	-1	1	0	0	0
SM yolk-sac larvae	1	0	0	0	-1	0	0	0
Phytoplankton	0	0	0	0	0	-1	0	0
Zooplankton	0	0	0	0	0	1	-1	0
Predators	0	0	0	0	0	0	0	-1

The adjoint [-A] and uncertainty

The prediction matrix (or adjoint) shows that predation on SM adults had a negative indirect impact on the production of larvae and juveniles (Table 2.11). Meanwhile, plankton groups (phytoplankton and zooplankton) in CS had a positive effect on SM adults that resulted in an indirect predicted increase in all other life history stages i.e. Larvae (feeding larvae and yolk-sac larvae), juveniles and recruits (Table 2.11).

Table 2.11. The adjoint matrix [-A] derived from the community matrix [A] for the SM biology model. Green cells = positive response with high probability of signed response (P=1); red = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1); "?" = uncertain response i.e. probability of signed response P<0.8.

	SM adults	SM recruits	SM juveniles	SM feeding larvae	SM yolk-sac larvae	Phytoplankton	Zooplankton	Predators
SM adults	1	1	1	1	1	5	3	-1
SM recruits	1	1	1	1	1	5	3	-1
SM juveniles	1	1	1	1	1	5	3	-1
SM feeding larvae	1	1	1	1	1	5	3	-1
SM yolk-sac larvae	1	1	1	1	1	5	3	-1
Phytoplankton	0	0	0	0	0	?	0	0
Zooplankton	0	0	0	0	0	?	?	0
Predators	0	0	0	0	0	0	0	?

Scaly mackerel qualitative climate change model

Signed digraph

Three nodes were added to the biology qualitative model for SM to create a model for evaluating the potential impacts of climate change (increasing SST and changes in Leeuwin Current) on SM (Figure 2.12). These nodes were: increase in Leeuwin Current (LC), Increases in SST, and Climate change as a driver (CC) of both the LC and SST changes. These three nodes are associated with changes in ocean temperature and acidification that could have profound effects on reproduction in fish, including SM.

The direct relationships between these nodes and their link to the SM biology components are shown on the signed digraph in Figure 2.12.

Community matrix [A] and model stability

The community matrix formed from the signed digraph for the biology model shows that SM adults (A) and recruits (R) are positively impacted by phytoplankton in CS (Table 2.12). SM juveniles (J), feeding larvae (FL) and SM yolk sac larvae (YL) are not feeding in CS and are not directly connected to plankton food sources (Figure 2.12). Climate change (CC) increases in the model the extent of changes in Leeuwin Current (LC) and increases SST (SST) (Table **2.12**).

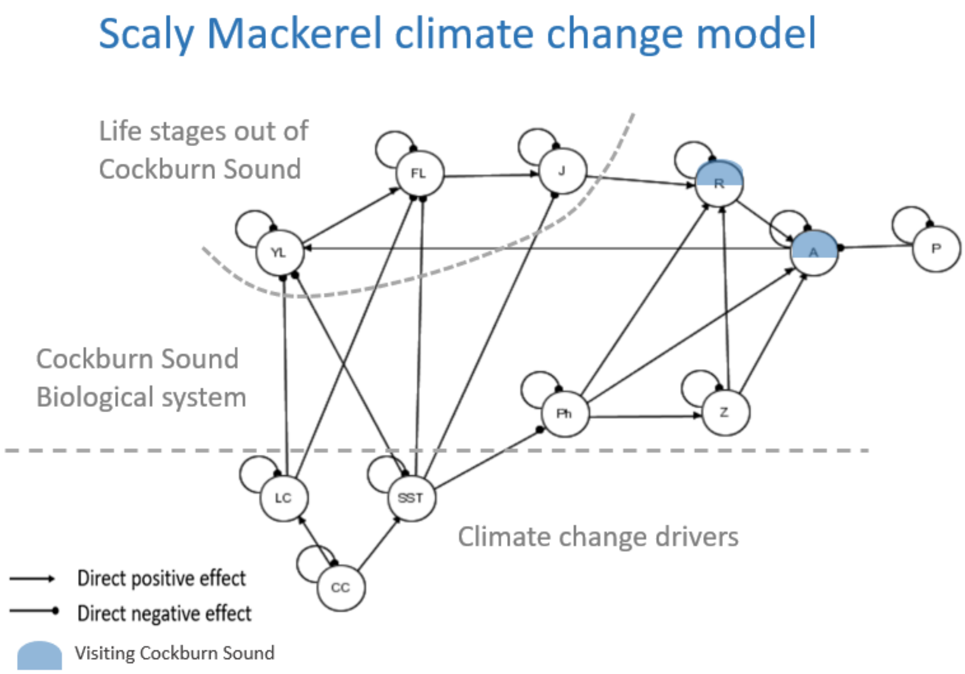


Figure 2.12. Signed digraph of the 11 functional groups and processes included in the climate change SM model.

Table 2.12. Community matrix for the 11-node climate change model of SM derived from the signed digraph in PowerPlay. Positive interactions are shown by a 1 and green highlight, negative by a -1 and red highlight and no interaction by a 0 with no highlight.

	SM adults	SM recruits	SM juveniles	SM feeding larvae	SM yolk sac larvae	Phytoplankton	Zooplankton	Predators	Leeuwin Current	Increases in SST	Climate Change driver
SM adults	-1	1	0	0	0	1	1	-1	0	0	0
SM recruits	0	-1	1	0	0	1	1	0	0	0	0
SM juveniles	0	0	-1	1	0	0	1	0		-1	0
SM feeding larvae	0	0	0	-1	1	0	0	0	-1	-1	0
SM yolk-sac larvae	1	0	0	0	-1	0	0	0	-1	-1	0
Phytoplankton	0	0	0	0	0	-1	0	0	0	-1	0
Zooplankton	0	0	0	0	0	1	-1	0	0	0	0
Predators	0	0	0	0	0	0	0	-1	0	0	0
Leeuwin Current	0	0	0	0	0	0	0	0	-1	0	1
Increases in SST	0	0	0	0	0	0	0	0	0	-1	1
Climate Change driver	0	0	0	0	0	0	0	0	0	0	-1

The adjoint or prediction matrix [-A]

The prediction matrix shows that predation on SM adults (A) produced indirect negative effects on early stages of the life cycle (Table 2.13). Increases in phytoplankton and zooplankton are predicted to have a positive effect on SM adults (A) that indirectly resulted in predicted increases in larvae stages (YL, FL), juvenile (J), and recruits (R) (3). Increases in the Leeuwin Current (LC) and increases in SST (SST) resulted in negative effects for all stages in the life cycle of SM (Table 2.13).

Table 2.13. The adjoint matrix (prediction matrix) [-A] for the climate change model of SM showing the results of a press on the system and the direction and certainty of the response sign. Green cells = positive response with high probability (P=1); red = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1); "?" = low certainty of the direction of the response (P<0.80).

	SM adults	SM recruits	SM juveniles	SM feeding larvae	SM yolk sac larvae	Phytoplankton	Zooplankton	Predators	Leeuwin Current	Increases in SST	Climate Change driver
SM adults	1	1	1	1	1	5	3	-1	-2	-8	-10
SM recruits	1	1	1	1	1	5	3	-1	-2	-8	-10
SM juveniles	1	1	1	1	1	5	3	-1	-2	-8	-10
SM feeding larvae	1	1	1	1	1	5	3	-1	-2	-8	-10
SM yolk-sac larvae	1	1	1	1	1	5	3	-1	-2	-8	-10
Phytoplankton	0	0	0	0	0	?	0	0	0	?	?
Zooplankton	0	0	0	0	0	?	?	0	0	?	?
Predators	0	0	0	0	0	0	0	?	0	0	0
Leeuwin Current	0	0	0	0	0	0	0	0	?	0	?
Increases in SST	0	0	0	0	0	0	0	0	0	?	?
Climate Change driver	0	0	0	0	0	0	0	0	0	0	?

2.3.3.4. Seagrass, Posidonia sinuosa

Conceptual model

Seagrasses are iconic species, valued for their ecological and economic importance (Mohring & Rule, 2013; McMahon *et al.,* 2018; McMahon *et al*., 2022). Seagrass meadows sustain a high diversity of fauna, by providing habitat for numerous fish and invertebrates, including commercially and recreationally fish species such as snapper, mullet, and BSC (Mohring & Rule, 2013). Seagrasses are thus highly regarded for their contribution to fisheries productivity as well as other ecosystem services including sediment stabilisation and the storage of carbon (Loneragan *et al*. 2013; Wu *et al*., 2017; Statton *et al*., 2018; Kendrick *et al*., 2019).

Seagrasses can increase in extent through flowering and the production of seeds, settlement of seeds and development of new shoots from the seeds, or from the lateral growth of existing shoots in the established bed and production of new shoots from the same plant (i.e. vegetative expansion, Sherman *et al*., 2018, Figure 2.13). *Posidonia sinuosa* is the dominant seagrass species found in CS (Kendrick *et* al., 2002). It is a large, meadow-forming seagrass, with shoots extending up to 650 mm in length and 8 mm in width (Collier *et al*., 2007).

Posidonia sinuosa flowers between May and August, fruits are produced in October-November, and the shedding of fruit occurs mainly in November (sometimes extending into December) when seeds are found on the sea floor (Figure 2.13). This knowledge of the life cycle and time of seed production has been used to initiate the "Seeds for Snapper" citizen science seagrass restoration program. In this program, floating seagrass fruits, or mature fruits still attached to the plants, are collected for germination on shore and the germinated seeds re-introduced to designated restoration sites around the Sound. The program facilitates increased seedling establishment in a cost-effective and efficient way (Sinclair *et al*., 2021). Such management interventions have been introduced following the historic widespread loss and limited recovery of seagrass meadows in CS since the 1960s (Fraser & Kendrick, 2017).

Historically, seagrass meadows covered approximately 4,200 ha of CS, at depths of up to 10 m (Kendrick, 2002). The seagrass coverage in the sound has declined by 77% since 1967 (Kendrick *et al*., 2022). Between 1967 and 1981, approximately 2,189 ha of seagrass were lost in CS, mostly from shallow subtidal banks on the eastern and southern shores (Kendrick *et al*., 2002). Since 1981, further seagrass losses (79 ha) have been associated with port maintenance and a sea urchin outbreak on inshore northern Garden Island (Kendrick *et al.,* 2002). Due to its relatively deep and protected waters, CS provided an ideal anchorage, and in 1954 it was designated as an industrial harbour for the Perth-Fremantle region (Kendrick, *et al*. 2002). Seagrasses are susceptible to changes in the water column environment, such as increases in nutrients and turbidity, and changes in the sediments (nutrients, low oxygen levels). The growth of algal epiphytes, stimulated by nutrients reduces the light environment for the host seagrass and has led to reductions in seagrass cover (Statton *et al*., 2018). Significant turnover of the sediments caused by fauna such as polychaetes, shrimps, bivalves or by major wind and wave events associated with storms, may also lead to the loss of seagrass and destabilisation of the sediments (Figure 2.13).

Anthropogenic activities that increase sediment load and reduce the light environment, e.g. dredging, increased boat traffic in shallow waters, movement of boat anchors or mooring chains, will also reduce the extent of seagrass (Figure 2.13, Fraser and Kendrick, 2017; Statton *et al*., 2018).

Currently, the main perennial seagrass beds in CS are found in the waters near Garden Island on the western side of the Sound, extending into the south-western part of Mangles Bay, and at Woodman Point (Figure 2.13). Ephemeral beds of seagrass are also found south of Woodman Point.

The conceptual model of the life cycle for *P. sinuosa* and three qualitative models of the biological interactions, anthropogenic influences and a combined model for this species were constructed following discussions in the second project workshop and with two seagrass researchers (Prof. Gary Kendrick, UWA and Assoc. Prof. Kathryn McMahon, ECU) with extensive knowledge of their biology and ecology and response to changes in their environment and anthropogenic stressors.

Seagrass qualitative models

Seagrass biology qualitative model

We developed a qualitative model representing the life cycle of seagrass in CS including both the sexual cycle and vegetative spread of seagrass as mechanisms for increasing the extent of established seagrass beds shown in the signed digraph in Figure 2.14. These beds consist of shoots derived from the production of new seeds (sexual reproduction) and shoots derived by the vegetative lateral expansion of existing shoots (vegetative growth). This model includes 10 nodes representing four life stages in the sexual reproduction of seagrass: established seagrass meadow; seagrass flowering; seagrass seeds and seagrass recruits; and three stages in the vegetative expansion of seagrass – established seagrass meadow; vegetative propagules (extension of new lateral shoots) and vegetative recruits (i.e. new vegetative shoots) (Figure 2.14). Some key ecological processes such as bioturbation of the sediments, herbivory, and the influence of fish species associated with seagrass meadows are represented in this model.

Community matrix [A] and model stability

The influence of one node on the other nodes is read down a column. For example, an increase in the established seagrass meadow (ESM) has a positive influence on seagrass flowering (SF), vegetative propagules (VP) and fish species (FS), while an increase in bioturbators (B) and herbivory (H) both have negative influences on seagrass recruits (SR) and vegetative propagules (VP). The response of one node in the model to all other nodes is read across rows e.g. Seagrass recruits (SR) and positively influenced by an increase in seagrass seeds (SS) and negatively influenced by bioturbators (B) and herbivory (H) (Table 2.14).

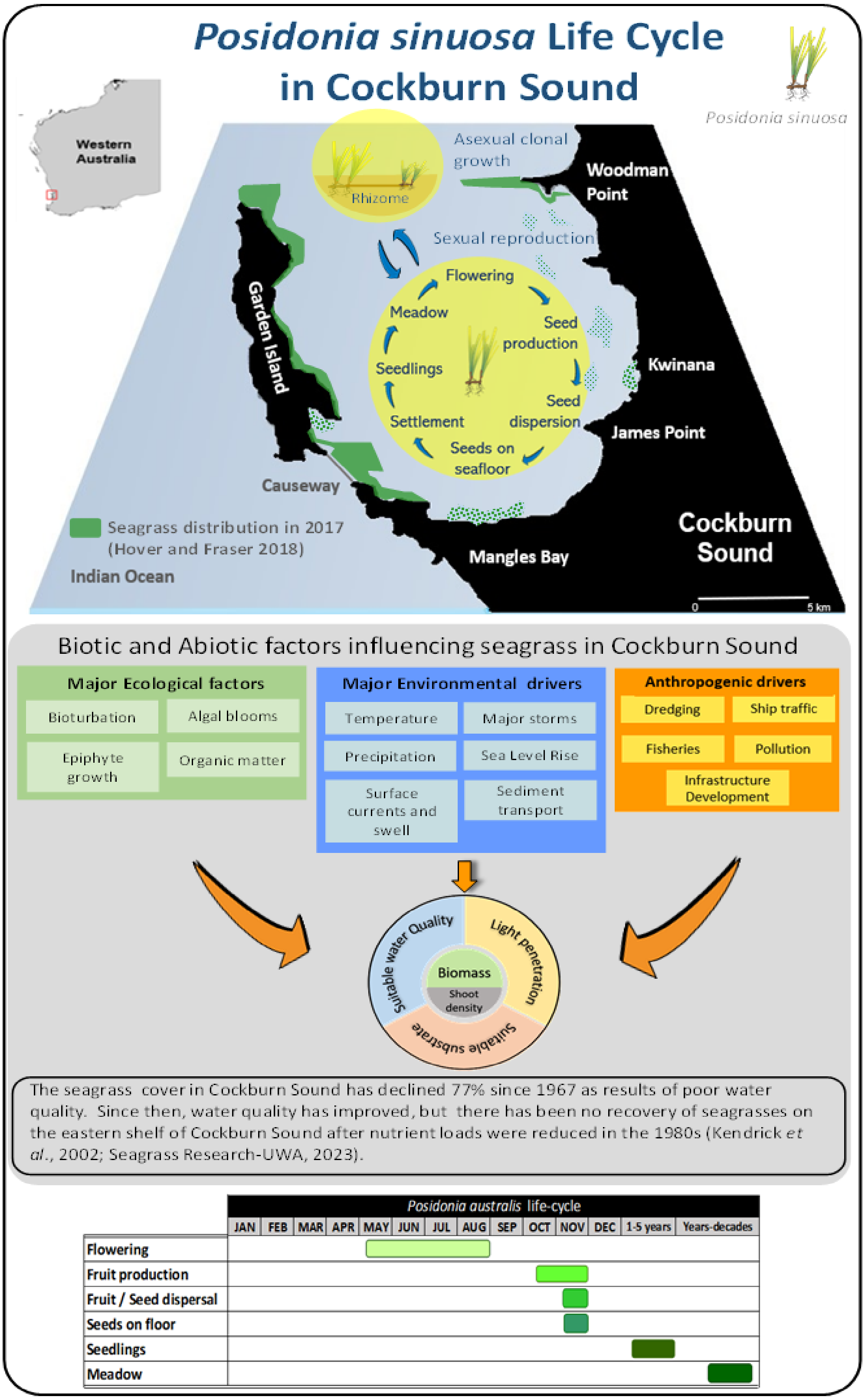


Figure 2.13. Conceptual model for biology, environmental and anthropogenic influences on seagrass, *Posidonia sinuosa*, in CS. Model developed during a multi-disciplinary workshop (September 2022) and follow up discussions with seagrass experts (November to December 2022).

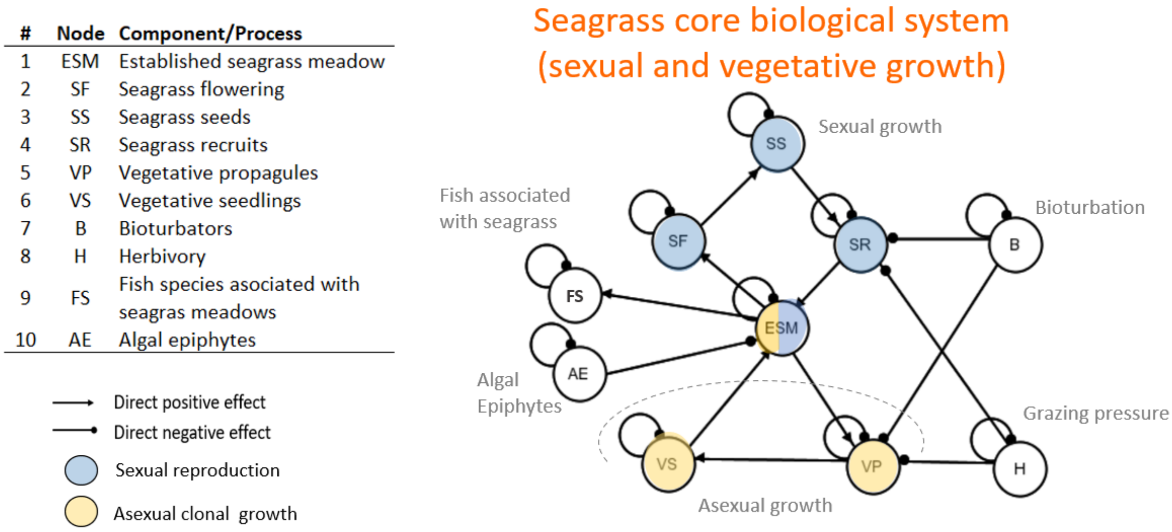


Figure 2.14. Signed digraph of the 10 functional groups or nodes included in the seagrass biology model. Model developed during project workshops and discussions with seagrass researchers.

Table 2.14. The specification of the community matrix for the 10-node seagrass biology model with positive impacts among nodes (1, green cells) and negative impacts (-1, red) highlighted. No impact is shown by 0 and no highlight.

	Established seagrass meadow	Seagrass flowering	Seagrass seeds	Seagrass recruits	Vegetative propagules	Vegetative seedlings	Bioturbators	Herbivory	Fish in seagras meadows	Algal epiphytes
Established seagrass meadow	-1	0	0	1	0	1	0	0	0	-1
Seagrass flowering	1	-1	0	0	0	0	0	0	0	0
Seagrass seeds	0	1	-1	0	0	0	0	0	0	0
Seagrass recruits	0	0	1	-1	0	0	-1	-1	0	0
Vegetative propagules	1	0	0	0	-1	0	-1	-1	0	0
Vegetative seedlings	0	0	0	0	1	-1	0	0	0	0
Bioturbators	0	0	0	0	0	0	-1	0	0	0
Herbivory	0	0	0	0	0	0	0	-1	0	0
Fish species associated with seagrass meadows	1	0	0	0	0	0	0	0	-1	0
Algal epiphytes	0	0	0	0	0	0	0	0	0	-1

The stability of the community matrix for seagrass biology was examined using the Hurwitz criterion ii (C≥1). The value of C was 2.7 x 10^5, which indicates that the seagrass model is very stable (see Dambacher *et al*. 2002a).

The adjoint matrix ([-A]) and uncertainty

The adjoint matrix for the seagrass biology model shows that an increase in the extent of established seagrass (ESM) is predicted to increase all components of both the sexual and asexual cycle of seagrass and the fish species (Table 2.15,). Increases in the vegetative propagules and shoots were also predicted to increase the extent of the established seagrass meadow, fruits, seeds, and seagrass recruits (SR i.e. new shoots from sexual reproduction) and an increase in VS was also predicted to increase the vegetative propagules (Table 2.15). An increase in Algal epiphytes had the greatest number of predicted negative impacts on nodes in the system, with predicted declines in all components of seagrass and fish species associated with seagrass meadows. An increase in bioturbation (B) and herbivory (H) both had predicted negative impacts on the ESM, SF and SS, with very uncertain predictions on other seagrass nodes (Table 2.15).

Table 2.15. The adjoint matrix (prediction matrix) [-A] derived from the community matrix [A] for the seagrass model. Green cells = positive response with high probability of signed response (P=1); red = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1); "?" = uncertain response i.e. probability of signed response P<0.80.

	Established seagrass meadow	Seagrass flowering	Seagrass seeds	Seagrass recruits	Vegetative propagules	Vegetative seedlings	Bioturbators	Herbivory	Fish in seagras meadows	Algal epiphytes
Established seagrass meadow	1	1	1	1	1	1	-2	-2	0	-1
Seagrass flowering	1	?	1	1	1	1	-2	-2	0	-1
Seagrass seeds	1	?	?	1	1	1	-2	-2	0	-1
Seagrass recruits	1	?	?	?	1	1	?	?	0	-1
Vegetative propagules	1	1	1	1	?	1	?	?	0	-1
Vegetative seedlings	1	1	1	1	?	?	?	?	0	-1
Bioturbators	0	0	0	0	0	0	?	0	0	0
Herbivory	0	0	0	0	0	0	0	?	0	0
Fish species associated with seagrass meadows	1	1	1	1	1	1	-2	-2	?	-1
Algal epiphytes	0	0	0	0	0	0	0	0	0	?

Seagrass qualitative infrastructure development model

Signed digraph

Five nodes were added to the qualitative model for seagrass biology to create a model for evaluating the potential impacts of infrastructure development on seagrass (Figure 2.15). These nodes were: dredging, light reduction, physical removal of seagrass, port activities (i.e. operation of vessels as well as the development and maintenance of supporting infrastructure) and management (i.e. includes port management + environmental management), and the direct relationships between these nodes and their link to the seagrass biology components are shown on the right-hand side of the signed digraph in Figure 2.15.

#	Node	Component/Process
1	ESM	Established seagrass meadow
2	SF	Seagrass flowering
3	SS	Seagrass seeds
4	SR	Seagrass recruits
5	VP	Vegetative propagules
6	VS	Vegetative seedlings
7	B	Bioturbators
8	H	Herbivory
9	FS	Fish associated with seagrass meadows
10	AE	Algal epiphytes
11	Dr	Dredging
12	LR	Light Reduction
13	PR	Physical Removal
14	PA	Port activities
15	Ma	Management

Sexual reproduction

Asexual clonal growth

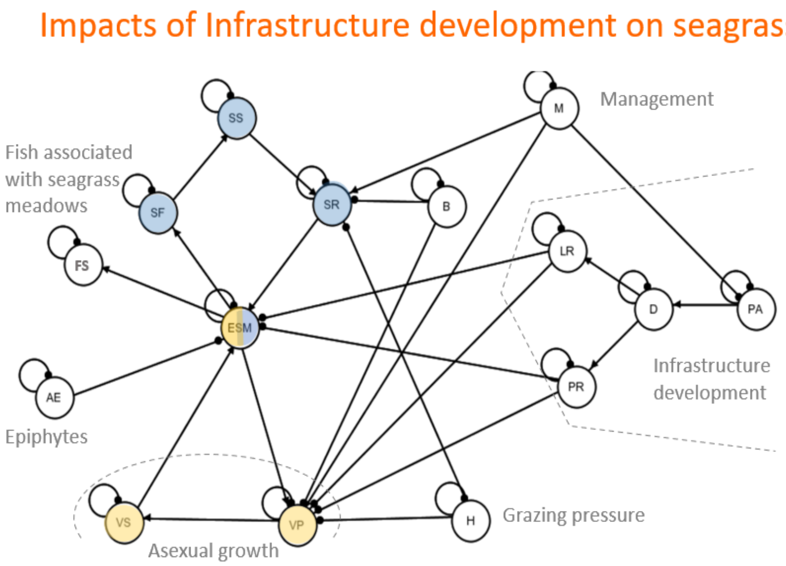


Figure 2.15. Signed digraph of the 15 functional groups or nodes included in the infrastructure development seagrass model for CS.

Community matrix [A] and stability of the seagrass infrastructure development model

The community matrix formed from the signed digraph for the infrastructure model shows that dredging has a direct effect on light reduction (increases light reduction) and increases the physical removal of seagrass (Table 2.16). Light reduction and the physical removal of seagrass both reduce the extent of seagrass meadows and the vegetative propagules). Port activities increase Dredging and Management increases seagrass recruits and vegetative propagules (Table 2.16).

Table 2.16. The specification of the community matrix for the 15-node Infrastructure Development seagrass model for CS derived from the signed digraph in PowerPlay (Figure 2.15). Positive interactions are shown by a 1 and green highlight, negative by a -1 and red highlight and no interaction by a 0 with no highlight.

	Node	1 ESM	2 SF	3 SS	4 SR	5 VP	6 VS	7 B	8 H	9 FS	10 AE	11 Dr	12 LR	13 PR	14 PA	15 Ma
1	**ESM**	-1	0	0	1	0	1	0	0	0	-1	0	-1	-1	0	0
2	**SF**	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
3	**SS**	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
4	**SR**	0	0	1	-1	0	0	-1	-1	0	0	0	0	0	0	1
5	**VP**	1	0	0	0	-1	0	-1	-1	0	0	0	-1	-1	0	1
6	**VS**	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0
7	**B**	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0
8	**H**	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
9	**FS**	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
10	**AE**	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
11	**Dr**	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0
12	**LR**	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0
13	**PR**	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0
14	**PA**	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1
15	**Ma**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

The adjoint matrix [-A] for the seagrass infrastructure development model

The adjoint matrix for assessing infrastructure development on seagrass shows that an increase in dredging (D, column 11) is predicted to negatively affect all components of seagrass biology – both the sexual and vegetative growth phases (Table 2.17). An increase in light reduction (LR), physical removal and port activities (PA) are predicted to decrease the established seagrass bed (ESM) and the sexual reproductive cycle (SF, SS and SR), but the direction of the response of seagrass vegetative growth was uncertain (VP and VS) (Table 2.17). This is a false ambiguity in the prediction matrix as the positive feedback loops on the components of the vegetative nodes to ESM are providing this uncertainty (J. Dambacher, CSIRO, pers. comm., see also Dambacher *et al*. (2015)). Increases in LR and PR were also predicted to decrease fish species. Increased management was predicted to increase the ESM and reproductive components of the seagrass life cycle with uncertain responses for the vegetative growth. Management was also predicted to have a positive effect on fish species associated with seagrass meadows (Table 2.17).

Table 2.17. The adjoint matrix (prediction matrix) [-A] for the infrastructure development seagrass model showing the results of a press on the system and the direction and certainty of the response sign. Green cells = positive response with high probability (P=1); red and orange = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1). "?"n = low certainty of the direction of the response (P<0.80). (a) conditioned to stability of the vegetative subsystem (EMS→ VP→ VS→ EMS).

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Node	**ESM**	**SF**	**SS**	**SR**	**VP**	**VS**	**B**	**H**	**FS**	**AE**	**Dr**	**LR**	**PR**	**PA**	**Ma**
1	**ESM**	1	1	1	1	1	1	-2	-2	0	-1	-4	-2	-2	-4	6
2	**SF**	1	?0	1	1	1	1	-2	-2	0	-1	-4	-2	-2	-4	6
3	**SS**	1	?0	?0	1	1	1	-2	-2	0	-1	-4	-2	-2	-4	6
4	**SR**	1	?0	?0	?0	1	1	?-1	?-1	0	-1	-4	-2	-2	-4	5
5	**VP**	1	1	1	1	?0	1	?-1	?-1	0	?-1	-2	?-1a	?-1a	?-2	?3
6	**VS**	1	1	1	1	?0	?0	?-1	?-1	0	?-1	-2	?-1a	?-1a	?-2	?3
7	**B**	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0
8	**H**	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
9	**FS**	1	1	1	1	1	1	-2	?-2	?-1	0	-4	-2	-2	-4	6
10	**AE**	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
11	**Dr**	0	0	0	0	0	0	0	0	0	?-1	-1	0	0	?-1	?1
12	**LR**	0	0	0	0	0	0	0	0	0	?0	-1	?-1	0	?-1	?1
13	**PR**	0	0	0	0	0	0	0	0	0	?0	-1	0	?-1	?-1	?1
14	**PA**	0	0	0	0	0	0	0	0	0	0	0	0	0	?-1	?1
15	**Ma**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	?-1

Seagrass qualitative climate change model

Signed digraph

The signed digraph for the climate change qualitative model (Figure 2.16) adds two nodes on the left-hand side of the seagrass infrastructure development digraph (Figure 2.15) – these nodes are climate change (water warming) leading to low oxygen levels in the water column and their effects on the seagrass system. The climate change model does not include other predicted effects of climate change such as an increased frequency of storm events, leading to the physical disruption of the sediments and loss of seagrass cover.

Community matrix [A] and seagrass climate change model stability

The community matrix of the climate change model shows that climate change is predicted to have a direct negative effect on vegetative shoots and a direct positive effect on low oxygen (Table 2.18). Climate change is also shown as having a direct positive effect on low oxygen i.e. frequency of low oxygen events increases. The community matrix for the climate change model shows that both climate change (CC, column 16) and low oxygen (LO, column 17) are predicted to have negative effects on the established seagrass meadows and vegetative propagules (Table 2.18). Climate change has a positive effect on low oxygen levels – the frequency of these events increases with climate change. Stability analysis indicated that the climate change model is stable (full details in Appendix 2).

#	Node	Component/Process
1	ESM	Established seagrass meadow
2	SF	Seagrass flowering
3	SS	Seagrass seeds
4	SR	Seagrass recruits
5	VP	Vegetative propagules
6	VS	Vegetative seedlings
7	B	Bioturbators
8	H	Herbivory
9	FS	Fished species
10	AE	Algal epiphytes
11	D	Dredging
12	LR	Light reduction
13	PR	Physical removal
14	PA	Port activities
15	M	Management
16	CC	Climate change
17	LO	Low oxygen
18	RB	Recreational boating

Sexual reproduction

Asexual clonal growth

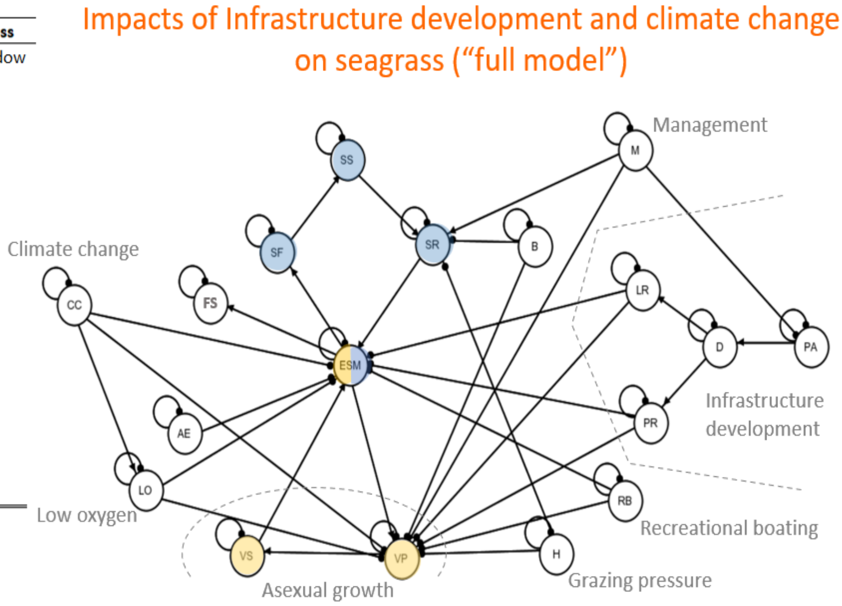


Figure 2.16. Signed digraph of the 17 functional group or nodes included in the impacts of climate change seagrass model.

Table 2.18. The specification of the Community Matrix for the 17-node seagrass climate change model, including infrastructure development and seagrass biology, from the signed digraph in PowerPlay (Figure 8). Positive interactions are shown by a 1 and green highlight, negative by a -1 and red highlight and no interaction by a 0 with no highlight.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Node	**ESM**	**SF**	**SS**	**SR**	**VP**	**VS**	**B**	**H**	**FS**	**AE**	**Dr**	**LR**	**PR**	**PA**	**Ma**	**CC**	**LO**
1	**ESM**	-1	0	0	1	0	1	0	0	0	-1	0	-1	-1	0	0	-1	-1
2	**SF**	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	**SS**	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	**SR**	0	0	1	-1	0	0	-1	-1	0	0	0	0	0	0	1	0	0
5	**VP**	1	0	0	0	-1	0	-1	-1	0	0	0	-1	-1	0	1	-1	-1
6	**VS**	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0
7	**B**	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
8	**H**	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
9	**FS**	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0
10	**AE**	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
11	**Dr**	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0
12	**LR**	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0
13	**PR**	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0
14	**PA**	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0
15	**Ma**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
16	**CC**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
17	**LO**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1

The adjoint matrix [-A] for the seagrass climate change model

The adjoint matrix for assessing climate change impacts on seagrass shows that an increase in climate change (CC, column 16) and low oxygen (LO, column 17) are both predicted to negatively affect the established seagrass meadows and the reproductive cycle of seagrass, with uncertain effects on seagrass vegetative propagules and vegetative shoots (Table 2.19). Both CC and LO also had a predicted negative impact on fish species associated with seagrass meadows. Increased climate change has a positive predicted effect on low oxygen. An increase in light reduction (LR), physical removal and port activities (PA) are predicted to decrease the established seagrass bed (ESM) and the sexual reproductive cycle (SF, SS and SR), but the direction of the response of seagrass vegetative growth was uncertain (VP and VS) (Table 2.19).This uncertainty, like that in the seagrass infrastructure adjoint matrix is a false ambiguity. We can be confident that the model predicts negative responses on vegetative growth. Increases in LR and PR were also predicted to decrease fish species. Increased management was predicted to increase the ESM and reproductive components of the seagrass life cycle with uncertain responses for the vegetative growth. Management was also predicted to have a positive effect on fish in seagrass meadows (Table 2.19).

Table 2.19. The adjoint matrix (prediction matrix) for the 17-node climate change seagrass model, including infrastructure development and seagrass biology, showing the results of a press on the system and the direction and certainty of the response sign. Green cells = positive response with high probability (P=1); red and orange = negative response with high probability (P=1), 0 = no predicted response with high probability (P=1); ?n = low certainty of the direction of the response (P<0.80). (a) Conditioned to stability of the vegetative subsystem (EMS→ VP→ VS→ EMS) as shown in Figure 2.16.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Node	ESM	SF	SS	SR	VP	VS	B	H	FS	AE	Dr	LR	PR	PA	Ma	CC	LO
1	ESM	1	1	1	1	1	1	-2	-2	0	-1	-4	-2	-2	-4	6	-4	-2
2	SF	1	?0	1	1	1	1	-2	-2	0	-1	-4	-2	-2	-4	6	-4	-2
3	SS	1	?0	?0	1	1	1	-2	-2	0	-1	-4	-2	-2	-4	6	-4	-2
4	SR	1	?0	?0	?0	1	1	?-1	?-1	0	-1	-4	-2	-2	-4	?5	-4	-2
5	VP	1	1	1	1	?0	1	?-1	?-1	0	-1	?-2	?-1a	?-1a	?-2	?3	?-2	?-1
6	VS	1	1	1	1	?0	?0	?-1	?-1	0	-1	?-2	?-1a	?-1a	?-2	?3	?-2	?-1
7	B	0	0	0	0	0	0	?-1	0	0	0	0	0	0	0	0	0	0
8	H	0	0	0	0	0	0	0	?-1	0	0	0	0	0	0	0	0	0
9	FS	1	1	1	1	1	1	-2	-2	?-1	0	-4	-2	-2	-4	6	-4	-2
10	AE	0	0	0	0	0	0	0	0	0	?-1	0	0	0	0	0	0	0
11	Dr	0	0	0	0	0	0	0	0	0	-1	-1	0	0	?-1	?1	0	0
12	LR	0	0	0	0	0	0	0	0	0	0	?-1	?-1	0	?-1	?1	0	0
13	PR	0	0	0	0	0	0	0	0	0	0	?-1	0	?-1	?-1	?1	0	0
14	PA	0	0	0	0	0	0	0	0	0	0	?0	0	0	?-1	?1	0	0
15	Ma	0	0	0	0	0	0	0	0	0	0	0	0	0	0	?-1	0	0
16	CC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	?-1	0
17	LO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	?-1	?-1

Seagrass summary of qualitative modelling results

A summary of results of the three qualitative seagrass models developed in this study are presented in a simple tabular format in Table 2.20. They provided key information of the qualitative responses of the processes examined.

Table 2.20. Summary of the predicted responses from the adjoint matrices for three seagrass models – biology, infrastructure development and climate change – in CS, Western Australia. (n) = number of nodes in the model. Node may be a species or process.

Model (n) and sign of effect	Impacting node	Impacted node(s)	Possible mechanism
Biology (10)			
+	Established seagrass meadow (ESM)	Seagrass fruits (SF), Seagrass seeds (SS), Seagrass recruits (SR), Vegetative propagules (VP), Vegetative shoots (VS), Fish species (FS)	Greater extent of established seagrass meadows increases the plant material for seagrass reproduction and also asexual propagation. The greater extent provides greater habitat for fish species.
+	Seagrass fruits (SF)	ESM, VP, VS, FS	Increased fruiting leading to an increase in the established seagrass bed and greater vegetative spread. Also, greater habitat for fish species.
+	Seagrass seeds (SS)	ESM, SF, VP, VS, FS	As for SF, and a positive influence on seagrass fruits
+	Seagrass recruits (SR)	ESM, SF, SS, VP, VS, FS	As for SS and a positive influence on seagrass seeds
+	Vegetative propagules (VP)	ESM, SF, SS, SR	Leads to an increase in the established seagrass meadow and all components of the seagrass sexual reproduction and fish species.
+	Vegetative shoots (VS)	ESM, SF, SS, SR	As for vegetative propagules.
-	Bioturbators (B)	ESM, SF, SS, FS	
-	Herbivores (H)	ESM, SF, SS, FS	
-	Algae epiphytes (AE)	ESM, SF, SS, SR, VP, VS, FS	

Table 2.20. Continued.

Model (n) and sign of effect	Impacting node	Impacted node(s)	Possible mechanism
Infrastructure development (15)			
+	Management (Ma)	ESM, SF, SS, SR, FS	Management of port activities and seagrass recruits leads to an increase in the established seagrass meadow, fruiting, seeds and recruits. This is also positive for fish species
-	Port activities (PA)	ESM, SF, SS, SR, FS	Increased port activities increase dredging which in turn reduces the light environment and can physically remove seagrass. Reduced seagrass leads to negative influence on fish species
-	Dredging (D)	ESM, SF, SS, SR, VP, VS, FS	Dredging has negative influences on all components of the seagrass life cycle and fished species. It acts by physically removing habitat and reducing the light environment.
	Light reduction (LR)	ESM, SF, SS, SR, FS	Light reduction affects photosynthesis and reproductive cycle of seagrass. Uncertain effects on vegetative propagules and shorts. Reduction in habitat negatively influences fish species
	Physical removal (PR)	ESM, SF, SS, SR, FS	Physical removal is predicted to impact the same nodes as light reduction.
Climate change (17)			
_	Climate Change (CC)	ESM, SF, SS, SR, FS	Increased temperatures reduce the level of dissolved oxygen in the water column available for photosynthesis. This negatively impacts the seagrass physiology and reproduction. Predicted impacts on vegetative stages are uncertain. Reduced extent of seagrass meadows negatively influences fish species.
_	Low oxygen (LO)	ESM, SF, SS, SR, FS	Extended periods of high temperatures and still conditions, also algal blooms lead low oxygen conditions and the build-up of hydrogen sulphide in the sediments. This adversely effects seagrass and fish species.

2.3.3.5. Little penguin, Eudyptula minor

Conceptual model

A detailed conceptual model for little penguin is used to illustrate the linkages among management actions, environmental stressors, and ecological effects in CS (Figure 2.17). This conceptual model was presented during the first workshop of the project (May 2022) and revised following feedback from Dr Belinda Cannell (UWA) in the 2nd project workshop (Figure 2.17).

The little penguin biology model

To increase our understanding of how little penguin is influenced in Garden Island by biotic factors (i.e. decline in prey availability, survival of chicks) and some potential stressors to the marine environment of CS (e.g. port development, motorised vessels) we developed a 10-node model (Table 2.21) which includes little penguin adults and chicks, food resources for little penguins, predators (e.g. sharks), boat strikes, climate change (global warming, marine heat waves, La Nina – excessive rainfall) and management (land and water).

Signed digraph model

The signed digraph Figure 2.18) shows the relationships between the nodes of the little penguin model and interactions between the nodes. The signed digraph model for little penguins (Figure 2.19 A-D; Table 2.22) was used to test the following hypotheses using models A-D involving prey availability, chick survival, boat strikes and increases in port activities as described below. The community and adjoint matrices, stability analyses and probabilities of correct signs are presented in Appendix 2.

Hypotheses:

Feeding ecology:

1. ***Model A: Prey availability decreased***: A decrease of accessibility and abundance of prey species (associated by increments of SST by global warming) would have a negative effect on little penguins.
2. ***Model B: Chick survival decreased***: little penguin colony in Garden Island would be negatively impacted by a simulated decline in survival rate (e.g. starvation) of little penguin chicks.

Anthropogenic factors

3. ***Model C: Boat strikes increased***: Feeding/swimming behaviours of little penguin would be negatively impacted by vessel impacts.
4. ***Model D: Port activities increased***: Impacts from port development and maintenance (construction, dredging, noise) would produce physical disturbances affecting feeding/swimming behaviours of little penguin that would result in negative impacts.

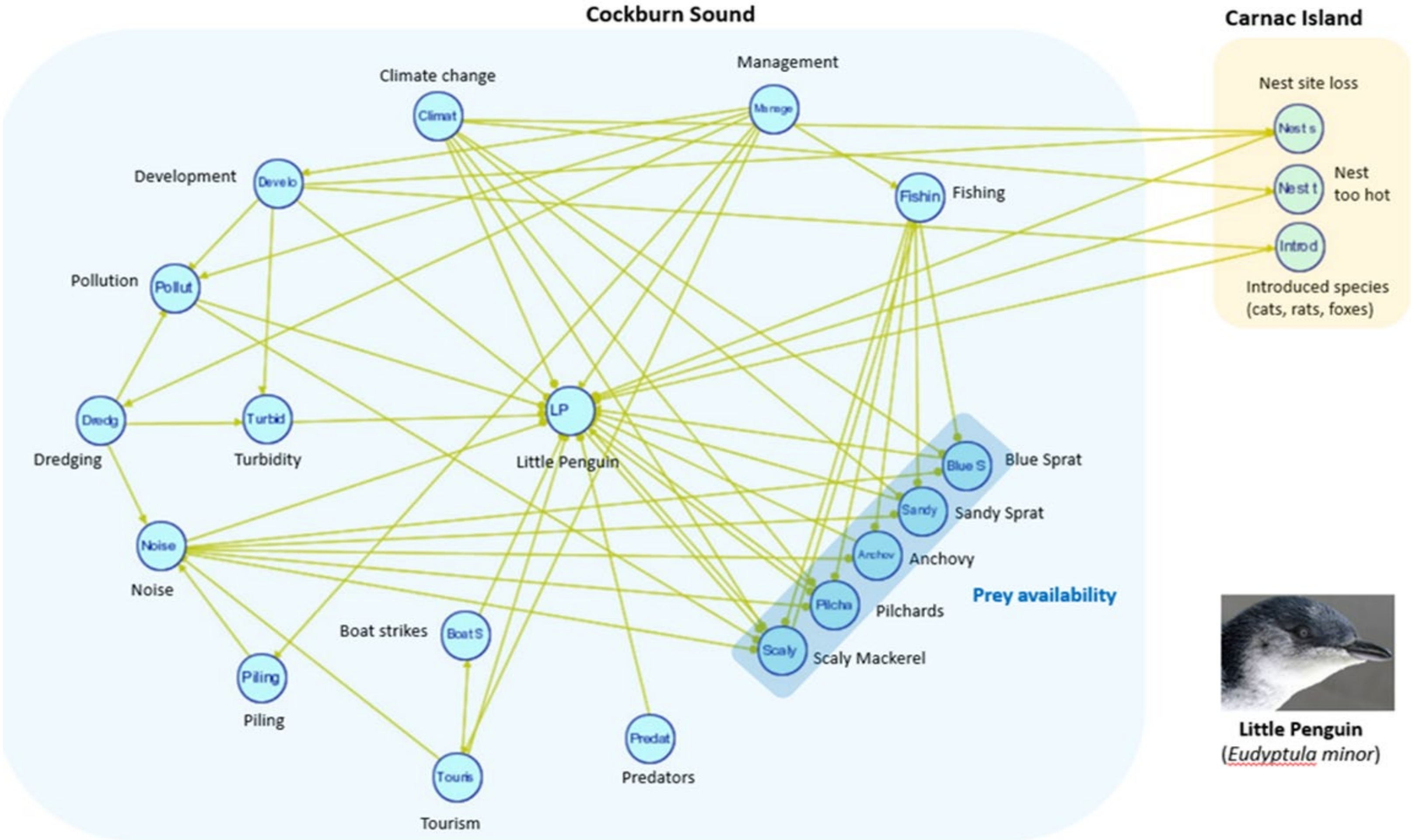


***Figure 2.17**. Conceptual* model for little penguin (*Eudyptula minor*) in CS. Developed through project workshops and in discussions with Dr Belinda Cannell (UWA).

Table 2.21. Functional groups and processes of the 10-node qualitative model for little penguin

#	Node	Group/ process
1	***LP***	Little Penguin
2	***Ch***	Little Penguin chicks
3	***R***	Food resource
4	***P***	Predators
5	***BS***	Boat strike
6	***T***	Turbidity
7	***PA***	Port activities (e.g. dredging, ship traffic)
8	***F***	Fishing
9	***CC***	Climate change (global warming, MHW, La Niña - excesive rainfall-)
10	***M***	Management (land and water)

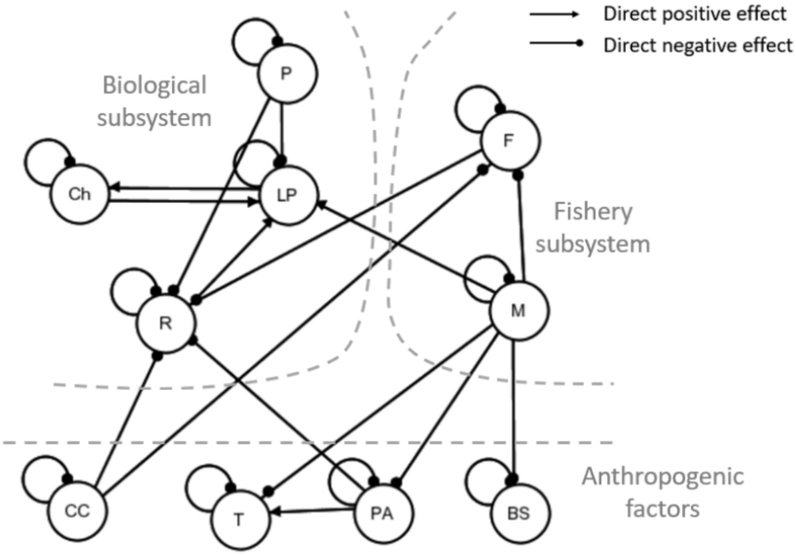


Figure 2.18. Core 10-node model for the little penguin in CS. Model developed through workshop discussions and with little penguin researchers from University of Western Australia (Dr Belinda Cannell), and Murdoch University (Dr Erin Clitheroe).

Table 22. Sign of direct effects between anthropogenic and biological variables in the core little penguin model and description of mechanisms explaining the interaction.

Direct effect			
Sign	to	from	Mechanism
+	1	2	Little Penguins adults provide food/nurturing to chicks
+	2	1	Chicks survival impacts the growth of the colony at Garden Island
+	3	1	Food source (prey) provides energy to Little Penguins
+	7	6	Turbidity is increased by port activities (shipping trafic, dreging, construction)
+	10	1	Land Management (in Garden Island) improves breeding success and climate adaptation for Little Penguins
-	8	3	Commercial fishing targeting prey fish of Little Penguin (e.g. Scaly Mackerel)
-	4	3	Predators consume some of the Little Penguin prey (e.g. small pelagic fish)
-	9	2	Global warming impacting negatevely survival of chicks in Garden Island
-	9	3	Global warming impacting negatevely distribution/abundnace of small pelagics fishes, resulting in changes in prey accesability for Little Penguin
-	9	8	Global warming impacting negatively distribution and/or abundnace of target species
-	10	9	Management reducing port activities (e.g. dredging, polllution, noise)

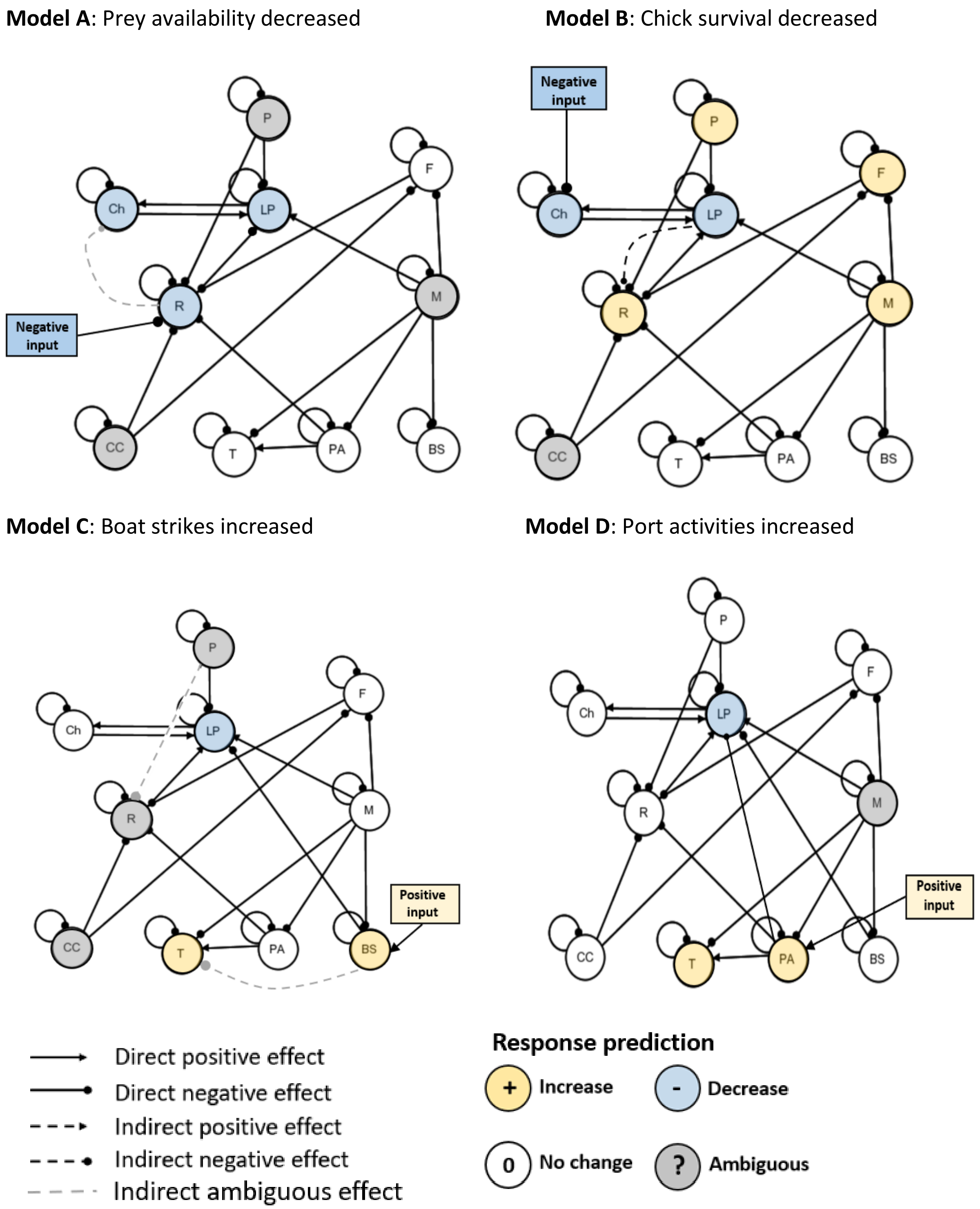


Figure 2.19. Qualitative response predictions (from the adjoint matrices presented in Appendix 2) of little penguin to positive and negative inputs to prey availability (Model A), chick survival (Model B), boat strikes (Model C), and port activities (Model D).

Little penguin - Summary of qualitative modelling results

We used the adjoint matrices of the four little penguin sub-models (A to D in Figure 2.19) to assess the predicted qualitative responses of little penguin to changes in prey availability, chick survival, boat strikes and port activities, summarised in Table 2.23. These models showed that little penguins (adults and chicks) were negatively impacted by both biotic factors (i.e. predation and chick survival) and anthropogenic variables, such as boat strikes and port activities (i.e. dredging, noise pollution) (Table 2.23). Increases in port activities resulted in predicted increases in turbidity by activities such as dredging that physically removes sediments. Also, port activities negatively impacted little penguins (adults) by possible negative effects of turbidity on prey capture for visual oriented hunting. Land management regulations to conserve the quality of little penguin nests on Garden Island were predicted to lead to an increase in adults and chicks (Table 2.23).

Table 2.23. Summary of responses of little penguin to reductions in prey availability, chick survival; increments in boat strikes, and port activities (i.e. dredging and shipping traffic)

Model (n) and sign of effect	Impacting node	Impacted node(s)	Possible mechanism
Prey availability decreased (10)			
+	Food resources (R)	LP, Ch	Positive effect associated with an increase in food availability
-	Predation (P)	LP, Ch	Predation had a negative effect on Little Penguin adults and chicks by an increased mortality
-	Fishing (F)	LP, Ch	Negative effects of fishing on Little Penguin adults and chicks by a possible depletion of prey (i.e. scaly mackerel, Blue Sprat, bait fishes) by fishing.
+	Management (M)	LP, Ch	Land management regulations to keep/improve quality of nest on Garden Island, These actions would lead an increase in Little Penguin adults and chicks.
Chick survival decreased (10)			
+	Little Penguin Chicks (Ch)	LP, Ch	A simulated increase in Little Penguin chicks had a positive effect on Little Penguin adults and chocks through recruitment that leads a population increase of adults in Garden Island. The predicted increase of Chicks could be associated with low-intraspecific competition for space (nesting sites) in Garden Island
Boat strikes increased (10)			
-	Boat strikes (BS)	LP, Ch	An increase in boat strikes had a negative effect on Little Penguin adults and chicks that could be explained by a possible increase in mortality on penguins by collisions with motorised water vehicles.
Port activities increased (10)			
+	Port activities (PA)	T	Decreased habitat quality. Sediment movements by dredging would reduce light penetration affecting visual hunting of Little Penguins
-	Port activities (PA)	LP, Ch	Increased port activities has negative influences on Little Penguin adults and chicks. This could be associated with increments in noise pollution (affecting prey availability and/or increasing stress levels); and by decreased quality of feeding grounds for Little Penguin by dredging

2.4 Discussion and Conclusions

The 16 conceptual models (Table 2.1) developed in the project, and presented during the first two workshops, allowed us to gain understanding of key groups, pressures, and interactions in the CS ecosystem. This understanding was used to further develop 14 qualitative models (Table 2.4) to assimilate and simplify information on how species in CS are influenced directly and indirectly by biotic and abiotic factors. In developing the conceptual models, the important life-history stages for including in the qualitative and quantitative models were also identified for the five selected species: three fished species (BSC, PS, and SM) and two species of conservation significance (seagrasses and little penguins). Fourteen qualitative models were developed for these five species during the three project workshops, and they focused on: 1) the importance of predation and food resources on different stages in the life cycles; 2) the interactions of the species with port activities, including dredging, shipping traffic and port maintenance; 3) the influence of climate change, including increments of SST, and changes in dissolved oxygen; and 4) anthropogenic activities, including boat strikes.

The adjoint (prediction) matrix was estimated from community matrix and used to explore changes in state at the equilibrium level for populations of the five modelled groups after a press (positive or negative change) was added to a specific node (group or process) in the qualitative model. In evaluating the predicted response to a press, we considered the weighted prediction values from the adjoint matrix: those values of >80% were considered as having a high certainty; while those from 30% to 80% were uncertain (following Dambacher *et al*., 2002; 2015). Some elements of the prediction matrices of the Seagrass infrastructure and Seagrass climate change models did not match the sign or direction in the qualitative community matrix resulting in qualitative responses ambiguous. In both models, this instability was presented in the vegetative state (asexual growth) of seagrass, and it probably is explained by a positive loop between establish meadows with vegetive propagules and vegetive recruits (J. Dambacher, personal communication, March 2nd, 2023). Further research on the ecology of vegetative reproduction of seagrass could provide basis for the resolution of ambiguity. Ecosystem interactions with vegetative seagrass growth in CS are relatively uncertain (K. McMahon, personal communication, December 19th, 2022).

2.4.1 Biology, human activities, and port development

The biology models for BSC, PS, SM and little penguins suggested that interactions between food resources (plankton, small fish pelagics and benthic invertebrates) could be significantly affected by port activities such as dredging, shipping traffic and port maintenance, e.g. high levels of dredging leading to increased siltation and nutrient release could result in changes in primary production, habitat loss and degradation, high levels of turbidity and even changes in seabed morphology, that would impact plankton and benthic fauna negatively. Further research on the feeding ecology of BSC, PS, and SM would be valuable for understanding the relationships between these groups and their prey.

Cockburn and Warnbro Sounds support the largest known spawning schools or 'aggregations' of PS in the DPIRD management bioregion and are critical for sustaining adequate breeding stocks of this species across the bioregion (DPIRD, 2019). The biology model of PS predicts increased recreational fishing pressure will have a negative effect on PS spawners and pre-spawners. This result is consistent with the extension of the demersal fishing closure from three to four months to six months in February 2023. There is also evidence that recreational fishers (including the charter sector) target migrating pre-spawning PS on grounds adjacent to CS (DPIRD, 2019). The impact of these activities could disrupt the spawning success and reduce the number of fish that can spawn (DPIRD, 2019).

The prediction matrices showed that PS, seagrass, and little penguin responded negatively to infrastructure development and port activities. These findings are consistent with previous qualitative modelling of seagrass and fish in CS, where increases in sediment loads were predicted to be detrimental to seagrass and fish (Metcalf *et al*., 2009). For the BSC model in our study, the responses to these activities were considered ambiguous (P<0.8) and this is probably explained by the positive interactions and positive feedbacks of the biofouling community node (e.g. algae, worms, mussels, barnacles, bryozoans) as food resource for juveniles, legal size, and spawner crabs. The biofouling community in this model increases with the increase in hard structure (settlement surfaces) provided by the port facility. Further research on the impacts of establish biofouling species on the marine environment is recommended.

2.4.2 Climate change

In the Seagrass model, climate change has a predicted positive effect on low oxygen leading to negatively effects on established seagrass meadows and its reproductive cycle, but the direction of the responses of seagrass vegetative propagules and vegetative shoots were uncertain. The responses of CS ecosystem to climate change projections (i.e. increasing water temperature and low dissolved oxygen) are highly uncertain, and further research to quantify these responses in the short-term is needed. In 2020, the City of Cockburn undertook a risk assessment on the impacts of climate change to develop a strategy for 2020-2030 (City of Cockburn, 2020), and in 2020 another WWMSP project 4.3 (Climate change and aquatic resources of CS) is conducting assessments of climate change impacts on aquatic resources in the system. Seagrass has been used as a key indicator of ecosystem health in CS. Seagrass meadows are recognised for both their ecological and economic relevance in supporting diversity and productivity of coastal systems, stabilising sediments, and protecting shorelines and they are considered the dominant ecosystem engineers in many soft-bottom ecosystems (Conolly, 2012).

Despite improvements in water quality within CS, no signs of any large-scale recovery of seagrasses have been seen and seagrass decline has continued in some areas within CS and Warnbro Sound (Kendrick *et al*., 2002; 2019). The ecological role of seagrass is analysed more closely using the quantitative ecosystem model (Ecopath), presented in section 4 “Ecosystem modelling” of this report.

Generalised management of fisheries and the environment were predicted to have positive influences on the life-cycle of the five modelled species. The importance of management in CS and its potential positive influence on aquatic resources and seagrass was also identified in the previous qualitative model of fish, seagrass and fisheries and development impacts in the Sound (Metcalf *et al*., 2009). This previous study also identified that with multiple management authorities in the Sound (e.g. DPIRD, DBCA, Department of Water and Environmental Regulation, Department of Transport, Department of Defence, CS Management Council) and multiple potential impacting factors, strong ecosystem-based management with a coordinated and integrated approach is likely to enhance the likelihood of sustaining the structure and function of the CS marine ecosystem. The significance of coordinated management for maintaining aquatic ecosystems was also identified in a qualitative modelling study of the Peel-Harvey estuary, ~30 km south of Cockburn Sound (Metcalf *et al.,* 2014).

2.4.3 Conclusions

Some of the more novel conclusions of our qualitative modelling work relate to the three fished species. Overall, the models for PS, BSC and SM behaved similarly to one another. The reciprocal feedbacks between the biological and infrastructure subsystems in these fished species models produced conditions for stability. Analysis of these models showed strong negative reactions of adults and many life stages to an increase in port activities such as dredging and shipping traffic. Weighted analysis of these predictions generally indicates a high level of predictability of these model results (i.e., P > 0.8, Appendix 2).

Increased management was predicted in all models to have a positive effect on the fished species and conservation significance groups in the system. In the PS infrastructure model, management was split into water management and fisheries management and both nodes were predicted to positively impact PS spawners and pre-spawners. These result highlights the vital role of management agencies and the need for cooperation among agencies and the industry to implement management strategies focused on both the marine environment and the food webs it supports. Similar conclusions on the importance of coordinated, cooperative management have been drawn in the previous qualitative modelling for seagrass, fish, fisheries, and development in CS and the governance of the Peel-Harvey Estuary to maintain water quality and ecosystem health (Metcalf *et al*., 2009; 2014).

The process of developing these qualitative models involved different steps of collecting knowledge and building social capacity such as: the building of relationships with key stakeholders, knowledge development through three project workshops, expert meetings, and collaboration with scientists from government agencies (i.e. DPIRD, DBCA, CSIRO), universities (i.e. ECU, UWA, MU) and independent researchers, to integrate ecological knowledge of this ecosystem. The qualitative models synthetized knowledge of key species, processes, and pressures in the region, and were used to guide the development of the Ecopath quantitative model (Chapter 3).

In this study, the integral and cooperative participation of direct stakeholders from Westport, WAMSI, DPIRD, and DBCA in the building of our conceptual and qualitative models played a vital role in linking social, economic, and ecological factors in relation to understanding potential ecosystem change. Important knowledge gaps of unknown responses in our qualitative models were highlighted during the final project workshop (March 15, 2023). For example, in the SM Climate Change model, uncertainty in the response of phytoplankton and zooplankton to changes in Leeuwin Current and increasing SST were identified – a level of warming leads to increased growth rates and production of plankton but greater levels of increases are likely to lead to a collapse. Overall, the qualitative models display current knowledge of the five species selected, which can be considered important tools for communication with stakeholders helping to increase understanding of how CS would respond to current and future pressures.

Chapter 3: Quantitative Ecopath Ecosystem Modelling

3.1. Ecopath modelling

Ecosystem models attempt to represent ecological systems by quantifying interactions among the ecosystem components, from individual populations to communities and even entire biomes. Since its development in the 1980s (Polovina, 1984), Ecopath with Ecosim (EwE), an energy balance ecosystem model, has been widely applied: to inform ecosystem-based management (e.g. Plaganyi and Butterworth 2008); climate change impacts (e.g. Brown, *et al*., 2010); fishing impacts (e.g. Lozano-Montes *et al.,* 2013), spatial closures (e.g. Lozano-Montes *et al*., 2012); artificial reefs (e.g. Wu *et al*., 2016; Wang *et al*., 2022), and aquaculture impacts (e.g. Han *et al.,* 2017). Ecopath models have been developed for a diverse range of ecosystems around the Australian coastline – e.g. eastern Gulf of Carpentaria (Bustamante *et al*., 2011), Great Barrier Reef (Gribble *et al*. 2005), south-eastern Australia (Bulman *et al*., 2006), Tasmanian waters (Watson *et al*., 2012) and for four major regions along the Western Australian coastline: the Kimberley (Boschetti *et al*., 2017); Northwest Shelf (Lozano-Montes and Keesing., 2019); Ningaloo reef (Fulton *et al*., 2011); and Jurien Bay (Loneragan *et al.,* 2010; Lozano-Montes *et al*., 2012; Table 3.4). The EwE software is the most applied tool for modelling marine and aquatic systems globally, with over 800 models published (www.Ecopath.org). Ecopath focuses on trophic interactions and is used more for understanding of whole food webs than individual components of the system. Ecosim is the dynamic component of Ecopath with Ecosim software and it has been used to explore environmental and anthropogenic drivers of ecosystem change (e.g. Loneragan *et al*., 2010; Fulton *et al*., 2011; Lozano-Montes *et al*., 2019; Subramaniam *et al*., 2020). Here, Ecosim was used to calibrate the run the sensitivity analysis of the Ecopath food web model. Note that the exploration of different management options or environmental scenarios through dynamic simulations of Ecosim were not part of this project (see details in Figure 3.10).

In this study, the Ecopath model was used to assess interactions between different functional groups, including intra- and inter-specific competition and predation of fish (including target fished species) and other species of high conservation and community interest (e.g. Australian sea lion, bottlenose dolphin, sharks, little penguin, and migratory sea birds). We used biological information from other Westport-WAMSI projects to gain knowledge of how the communities of CS are organized in food webs and key aspects of ecosystem functions and other trophic processes that are still far from comprehensive. The Ecopath model developed in this 12-month project aimed to quantify:

1. the ecosystem attributes and trophic structures;
2. the ecological role of top predators and keystone species;
3. the ecological indicators of ecosystem biodiversity and ecosystem functioning.

3.2. Objectives

1. Characterise the trophic structure, key ecosystem attributes and overall functioning of the CS ecosystem; and
2. Integrate data from other themes into a quantitative ecosystem model to support a synthesis of current knowledge of ecological and ecosystem processes in CS.

3.3. Methods

3.3.1. Study area

Following feedback from Workshop 1, the model domain was extended from CS to include Owen Anchorage to Fremantle and the Stragglers Rocks, covering a total area of about 260 km^2 (Figure 3.1). The model represents the food web of the key commercial species, key recreational species, key conservation species, demersal and pelagic fish assembles, invertebrates and primary producers of the embayment of CS ecosystem in the depth range from 0 and 20 m.

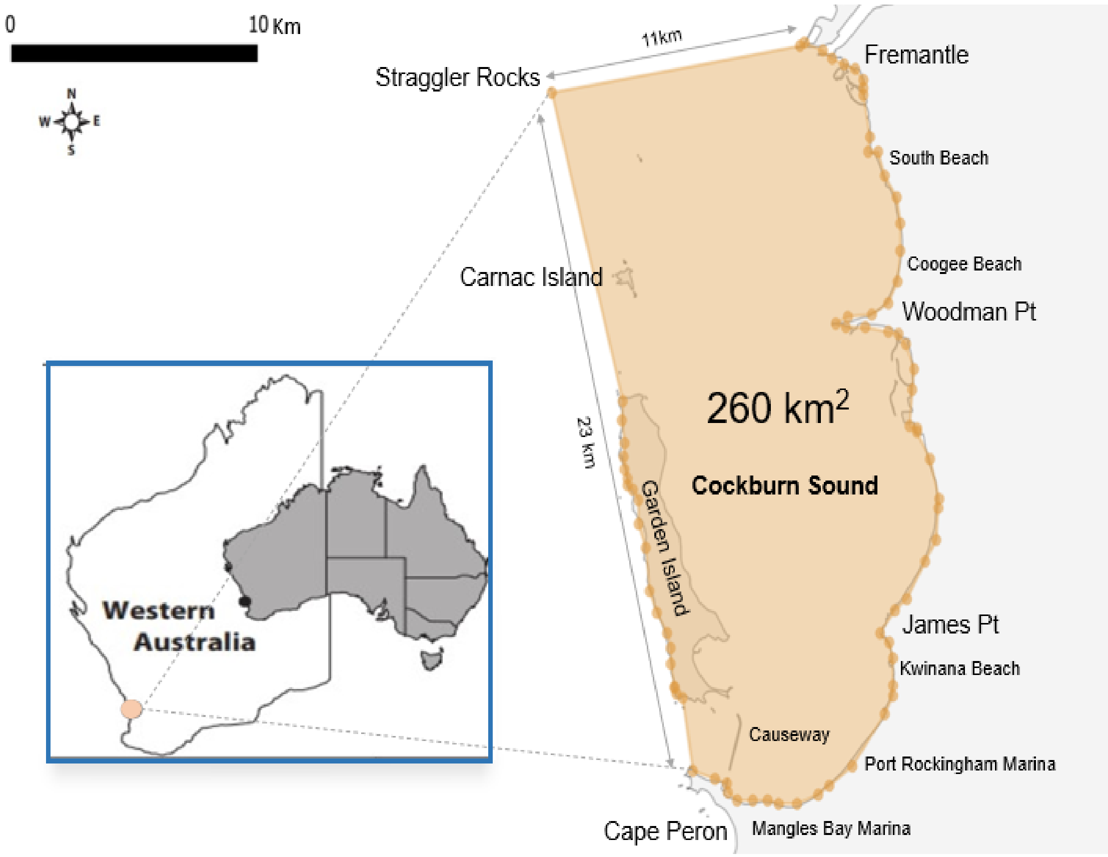


Figure 3.1. Model domain for the Cockburn Sound Ecopath model is south-western Australia. The model extends from Cockburn Sound to Fremantle and covers an area of 260 km^2.

3.3.2. The model

The EwE modelling software is a free software (under the terms of the GNU General Public Licence), and downloadable online (www.ecopath.org) with more than 800 EwE models for aquatic systems (and a few terrestrial systems) published worldwide (Colléter *et al.,* 2015). The EwE package has three main components: (1) Ecopath - a static, mass-balanced food web model; (2) Ecosim – a time dynamic simulation module primary designed for scenarios development; and (3) Ecospace – a spatial and temporal dynamic module for exploring impact and placement of protected areas. In this study, we developed a food web model of CS to characterise the trophic flows, key ecosystem attributes, and overall function of this system. Ecosim was only used for fitting of the model and quantification of uncertainty of input parameters as explained below. The development of environmental and management scenarios using Ecosim was not part of the current study.

Ecopath creates a static mass-balanced snapshot of the resources and their interactions, including biomass and energy flows. This helped us to elucidate the structure and functioning of the CS system. The Ecopath model is based on a set of linear equations that quantify the trophic flows among the components of the system (living and non-living species or functional groups). Ecopath uses a series of simultaneous linear equations, one for each functional group to quantify the energetic flows among trophic groups according to the law of conservation of mass or energy (Equation 1).

The food web of the Ecopath model is based on two equations describing production and energy balance for each modelled group (in this case 73 functional groups) included in the model:

Eq (1): *Production = catch + predation mortality + biomass accumulation + net migration + other mortality,*

Eq (2): *Consumption = production + respiration + unassimilated food.*

Ecopath also calculates:

production utilized = catch + consumption by predators,

Mathematically the master equation is given by:

$$B_i(PB^{-1})_i EE_i - \sum_{j=1}^{n} B_j (QB^{-1})_j DC_{ij} - Y_i - E_i - BA_i = 0 \qquad 1$$

where:

B_i is the biomass of functional group *i*;

$PB^{-1}{}_i$ is production/biomass ratio and can generally be input as total mortality rate (*Z)*;

EE_i is the ecotrophic efficiency defined as the proportion of production of *i* that is utilized in the system;

B_j is biomass of predator *j*;

$QB^{-1}{}_j$ is consumption rate for predator *j*;

DC_{ij} is the fraction of group *i* in the diet of predator *j*;

Y_i is the total fishery catch of group *i*;

E_i is the net migration of group *i* (emigration-immigration); and

BA_i is the biomass accumulation rate.

EwE uses a set of algorithms (Christensen *et al.*, 2009) to simultaneously solve *n* linear equations of the form in equation 1, where *n* is the number of functional groups. Under the assumption of mass-balance, Ecopath can estimate missing parameters. This allows modellers to select their inputs. EwE uses the constraint of mass-balance to infer qualities of uncertain ecosystem components based on our knowledge of well-understood groups. It places piecemeal information on a framework that allows us to analyse the compatibility of data, and it offers heuristic value by providing scientists a forum to summarize what is known about the ecosystem and to identify gaps in knowledge.

The data needs of EwE can be summarized as follows. Data for four parameters is required for each functional group: biomass (in $t \cdot km^{-2}$), the ratio of production over biomass (P/B; in $year^{-1}$), the ratio of consumption over biomass (Q/B; in $year^{-1}$), and ecotrophic efficiency (EE; a unitless measure of the proportion of production that is utilized by the next trophic level through direct predation of fishing). Each functional group requires three and four of these input parameters and the remaining parameter is estimated using the mass-balance relationship in equation 1. Note EwE also provides an input field representing the ratio of production over consumption (P/Q; unitless), which users may alternatively use to infer either P/B or Q/B based on the other. A biomass accumulation rate may also be entered optionally; the default setting assumes a zero-rate instantaneous biomass change. These EwE data points are referred to collectively in this study as the basic parameters. For further details of EwE data needs and parameter definitions see Christensen and Walters (2009). The period that our model represents is the early 2020s to characterise the current ecosystem state and trophic flows in CS.

Ecosim is the dynamic component of Ecopath with Ecosim software. A key component of Ecosim modelling is its ability to simulate predator-prey interactions on a temporal arena under the foraging arena theory, which splits the availability of a prey group's biomass to each predator group into several vulnerable and invulnerable states (Ahrens *et al.,* 2012). In Ecosim, vulnerabilities (*v*) are assigned to individual predator/prey relationships, indicating whether the biomass of a group is controlled primarily by predators or prey. These vulnerabilities regulate the trophic interactions, and they express the rate at which prey move between being vulnerable and not vulnerable. In Ecosim, vulnerabilities range from 1 to ∞; when *v* takes high values ('top down'), a high proportion of the biomass is vulnerable to predation. If *v* is closer to 1.0 ('bottom up'), prey have the opportunity to find refuge from predators.

3.3.3. Model groups

Determining the structure (or functional groups) of an Ecopath model is largely subjective and is determined on the specific objectives and requirements of a study. The CS ecosystem model contains 73 functional groups, including one non-living group (detritus) (Figure 3.2). The functional groups were identified based on discussions with experts, different interest groups and feedback from Workshop one (12^{th} May 2022). These include species of significance to commercial and recreational fishing (e.g. PS, BSC, "SM" or small commercial pelagic species), those of conservation significance (e.g. little penguins, seagrass) and those likely to be of ecological significance (such as habitat forming species). The model also represents sharks (small, large and juveniles), bottlenose dolphin, seabirds (cormorants, pelicans, gulls, terns, migratory waders), little penguin, pelagic fishes (e.g. skipjack trevally, mulloway, Australian salmon), small pelagic fishes (e.g. southern garfish, sandy sprat, King George whiting, Australian herring), demersal fishes (wrasses, soldiers, mullets, leatherjackets, boxfishes, flounders, pipefishes), invertebrates (Western king prawns, cuttlefish, western octopus, sea cucumbers, black mussels), and plants (e.g. seagrass, macroalgae, macroalgal epiphytes and microphytobenthos). Because of its significance to commercial and recreational fisheries, PS was split into three stanzas: Spawners (>560 mm); pre-spawners (250-560 mm); and coastal juveniles (60-250 mm) to account for specific life history traits that would affect their specific growth, habitat use, predation, and fishing within the Sound. Also, two introduced species of concern for DPIRD are included in the model:” the carpet sea squirt” (*Didemnum vexillum*) and “Dead’s man fingers” (*Codium fragile* subsp. *fragile*). A detailed list of the functional groups and species in the Ecopath model is presented in Appendix 3.

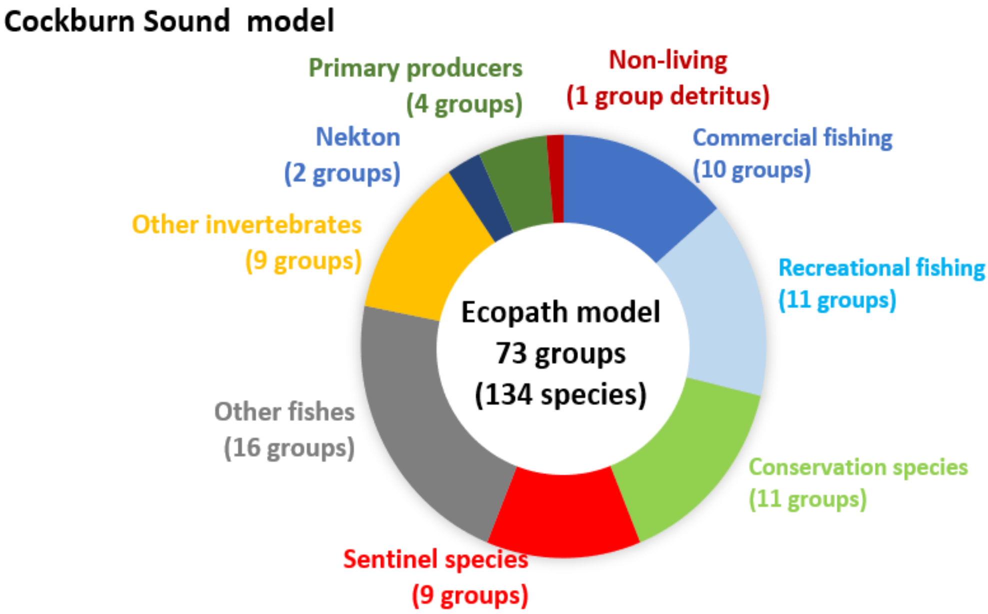


Figure 3.2. Summary of the functional groups contained in the Ecopath model. See Appendix 3 for a detailed list of all species in the model and the different functional groups.

3.3.4. Biological data

Biomasses of fishes and invertebrates estimated from science surveys

Abundance and biomasses of fish and invertebrate communities in CS were obtained from WWMSP sampling in CS (small and large otter trawls, grab sampling, belt transects and rubble collection in 2021 and 2022) by Project 2.4 (Prof. Glenn Hyndes, Dr James Tweedley), and Project 4.2.1 (Dr Danielle Johnston)). Figures 3.3 and 3.4 are examples of seasonal and spatial variation of biomass in fish and invertebrate communities sampled in CS in 2021 and 2022.

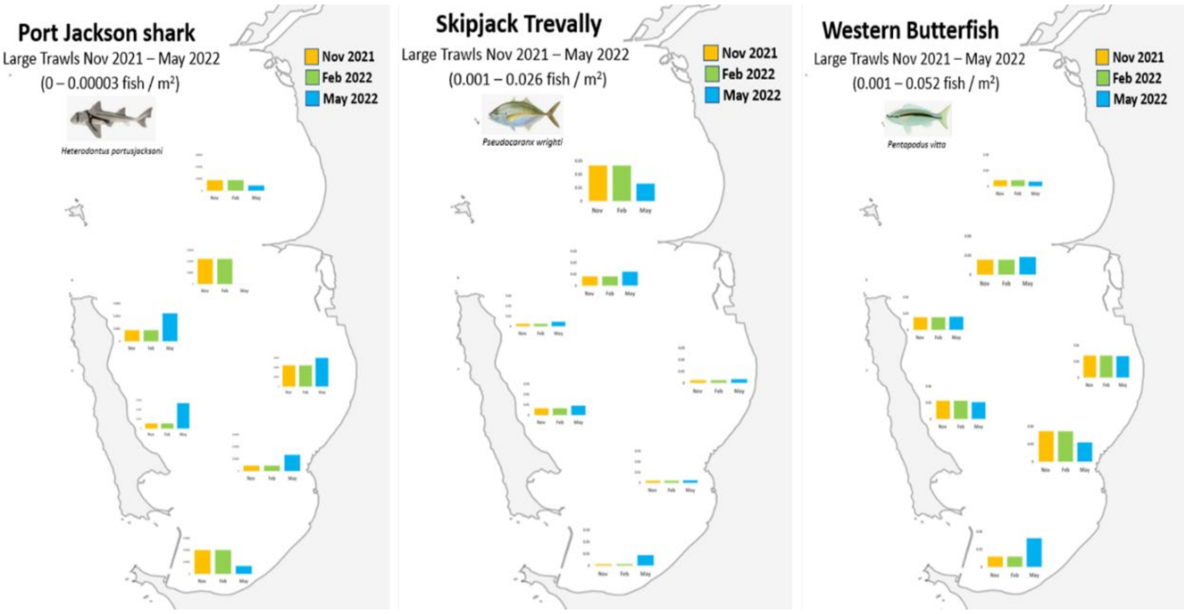


Figure 20. Example of three relative abundances of fishes (#fish/m^2) sampled with large trawl nets in CS in November 2021 and May 2022. Data provided by WAMSI-Westport Project 4.2.1. "Spatial distribution of fish and invertebrates".

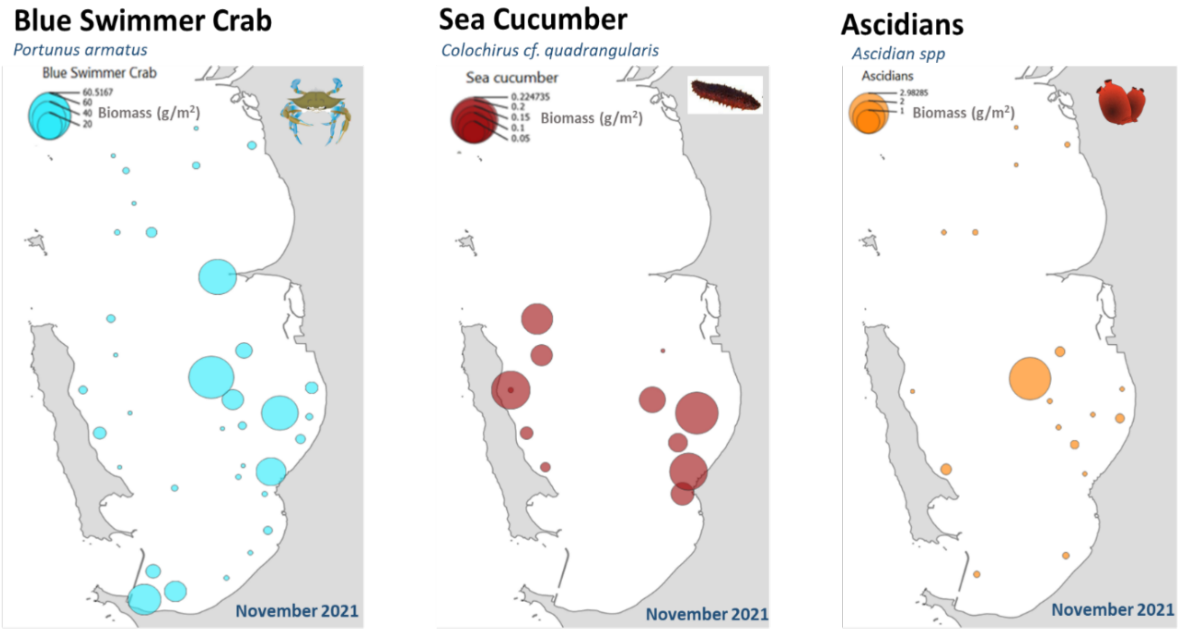


Figure 3.4. Example of biomasses of three species on invertebrates (g/m^2) sampled with small trawl nets in CS during November 2021. Data provided by WAMSI-Westport Project 2.4 Benthic communities in soft-sediment and had substrates.

3.3.5. Production (P/B) and consumption (Q/B) parameters

The production/biomass (*P/B*) and consumption/biomass (*Q/B*) ratios (year^{-1}) are basic input parameters in EwE. In Ecopath, the *P/B* ratio (year $^{-1}$) for non-target species is equivalent to the total mortality rate (Z), made up of fishing mortality (F) and natural mortality rate (*M*). While *F* may be estimated for some exploited species, unfortunately, the natural mortality rate of fish populations is one of the most difficult parameters to estimate. Direct estimates of *M* (e.g. from tagging studies) are usually difficult to obtain for most fish stocks. Numerous methods have been developed to estimate *M* from other, more frequently available life history parameters. We used empirical estimators of natural mortality using the Shiny tool (a package of R) available on the website "Barefoot Ecologist's Toolbox" which employs various empirical estimators of natural mortality (http://barefootecologist.com.au/shiny_m.html). This website was originally developed Prince (2003) and further developed by Adrian Hordyk (Institute for the Oceans and Fisheries, University of British Columbia) and Jeremy Prince (Biospherics, Australia). We selected the estimates of *M* based on the von Bertalanffy growth parameters *K* and its relationships with water temperature as proposed by Jensen (1996, 1997) and recommended by Hasmel (2015). Appendix 4 summarises the natural mortalities estimated for fish groups in the Ecopath model. For fish species in aggregated groups, an overall *P/B* was derived from the median value of the different estimates (Appendix 4). Natural mortality rates for lower trophic invertebrate groups were also obtained from empirical relationships proposed by Optiz (1996). For zooplankton, phytoplankton, macroalgae and seagrass we used parameters of *P/B* ($year^{-1}$) from the temperate food web model of Jurien Bay (Western Australia) (see Loneragan *et al*. 2010, Lozano-Montes *et al*. 2012). The estimates of food consumption rates (*Q/B*, $year^{-1}$) for most fish and invertebrate groups were obtained from empirical equations proposed in Pauly *et al*. (1993); Palomares and Pauly (1998), Optiz (1996), Lasalle *et al*. (2012), and Hill *et al*. (2021).

3.3.6. Diets

The diet composition matrix was assembled as percentage weight or volume of the annual fraction that each prey contributes to the overall diet of the predator (following the methodology recommended by Christensen *et al*., 2004, 2008). Wherever available, dietary information was taken from local studies on CS. As some data from CS were not available, data were taken for the relevant species from adjacent areas (e.g. Perth area, Jurien Bay), assuming that this would provide a reasonable approximation for the diet composition in CS. When no data were available locally, or in adjacent areas, diets were deduced from information in FishBase (Froese and Pauly, 2000). If no specific prey were identified, the aggregated diet group was re-apportioned across possible prey that would be available to the predator according to proportions in the diets of predators in the same functional group. The diet matrix assembled was reviewed by local experts in Western Australia (Table 3.1). The main components of the food web are shown in Appendix 5.

This input data was then used by Ecopath to solve the mass balance equation (Equation 1) for each species. One output of this solution is estimates of trophic interactions and realised predation rates.

Table 3.1. Reviewers of the diet matrix of the Ecopath CS ecosystem model.

Functional Groups	Diet matrix reviewer
Sharks and Rays	Matias Braccini (DPIRD)
Australian Sea Lion	Chandra Salgado-Kent (ECU)
Bottlenose Dolphin	Delphine Chabanne (Murdoch)
Little Penguin	Belinda Cannell (UWA) Erin Clitheroe (CCWA)
Sea birds (Cormorants, pelicans, terns, waders)	Jeffrey Norris (DPIRD) Claire Greenwell (CCWA)
Pink Snapper (adults, pre-spawners, juveniles)	David Fairclough (DPIRD)
Pelagic fish (Mulloway, Skipjack trevally, Sea King fish)	Kurt Krispyn (Murdoch)
Small Pelagic fish (Scaly Mackerel, Blue Sprat, Sandy Sprat)	Jeffrey Norris (DPIRD)
Demersal fish (Mullets, Soldiers, Wrasses, Flounders)	Mitchell Haywood (Murdoch) Kurt Krispyn (Murdoch)
Squid and Cuttlefish	Daniel Yeoh (DPIRD)
Blue Swimmer Crab	Daniel Yeoh (DPIRD)
Invertebrates (crabs, prawns, urchins, seastars)	Daniel Yeoh (DPIRD) Sorcha Cronin-O'Reilly (Murdoch)

3.3.7. Fisheries data

Commercial data

The ecosystem modelling project was introduced to fisheries researchers during a brief seminar at the DPIRD on June 22nd, 2022. The seminar provided information on the background and methods of the study, and the data required to develop the Ecopath model. This served as a basis for subsequent group discussions with fisheries experts to gain an in-depth understanding of commercially and recreationally targeted species and those of conservation significance. All available data specific to CS were discussed and provided in the form of resource assessment reports and total commercial catch and catch per unit effort (CPUE) summaries by fisheries researchers in DPIRD following the discussions.

Data on fishing method and gear type, total catch (kg) and CPUE, where available, were acquired from DPIRD for the main targeted species in CS. Commercial catch data were obtained from the following fisheries that operate in CS: the Cockburn Sound Crab Fishery (BSC *Portunus armatus*), the Cockburn Sound Line and Pot Fishery (Western Rock Octopus, *Octopus djinda*), the Cockburn Sound Fish Net Fishery (Australian herring, *Arripes georgianus,* Southern Garfish *Hyporhampus melanochir*), squid fishery (*Sepioteuthis spp*), and the Cockburn Sound Mussel Fishery (*Mytilus spp.*) Commercial catch values for the Ecopath with Ecosim (EwE) model were calculated using a three-year average annual total catch for species caught between 2019 and 2021, where available (Figure 3.5). The average annual catch value was divided by the area of the model domain (260 km^2) to convert catches to catch in tonnes per area per year – i.e. the standard unit for the Ecopath model ($t/km^2/year$) (Table 3.2). Recent catch statistics were not available for BSC, black mussels, and southern garfish. However, as they are commercially and recreationally important species, the most recent available catch values from 2015-2020 were used. Table 3.2 shows the total commercial catch (kg) of main species in CS in 2019, 2020, and 2021, and the total commercial catch within the Ecopath model domain (t/km^2/year).

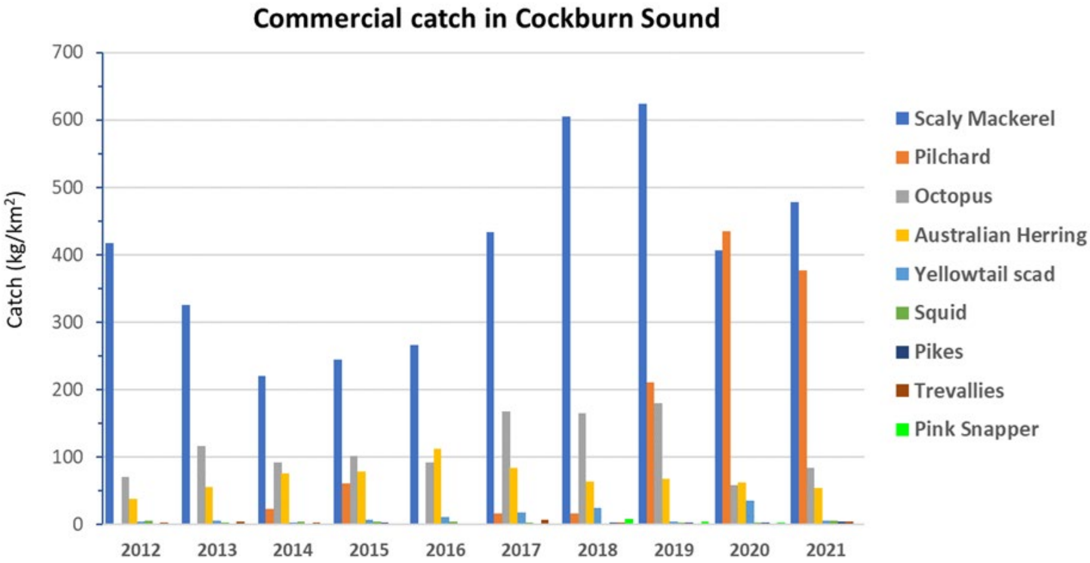


Figure 3.5. Commercial catch (kg/km^2/year) estimated for the CS Ecopath model using a model domain area of 260 km^2. Catch data provided by the Department of Primary Industries and Regional Development.

Recreational Catch

During the second workshop of the project (October 19th, 2022) data gaps for the Ecopath model were discussed, particularly for recreational fishing catch and effort in CS. Experts in recreational fishing were suggested, and additional shore-based reports of recreational fishing were provided by workshop participants. Recent information on recreational catch estimates (2020/2021) for boat-based recreational fishing occurred within the Metropolitan Zone of West Coast Bioregion was provided in February of 2023 by DPIRD. Due to project time constraints, it was not possible to incorporate these data in the Ecopath model. Some of the species of this database that are kept and released in the Metropolitan zone may not have been caught in CS. Further development and discussion of this information is needed for its inclusion in the next version of the CS Ecopath model if funds are available.

Table 3.2. Total commercial catch (kg) of species in CS in 2019, 2020, 2021, and the mean total commercial catch within the Ecopath model domain (t/km²/year). Data provided by DPIRD.

Functional Group	Commercial catch			Mean total catch (t/km²/Year)
	2019	2020	2021	
Squid	984	943.74	1375	0.0042
Australian Herring	17669	16227	14116.24	0.0616
Octopus	46896.2	15044.39	21863.7	0.1074
Pilchard	54920	113150	98100	0.3412
Scaly Mackerel	105690	124160	34150	0.3384
Australian Anchovy	0	300	220	0.0006
Yellowtail Scad	1284	9346	1399	0.0154
Pink Snapper	1079	840	484	0.0030
Yellowfin Whiting	389	100	0	0.0006
Maray	0	3300	0	0.0042
King George whiting	85	78	237	0.0005
Trevallies	393	343	1015.3	0.0022
Rabbitfish	167	185	159	0.0007
Cuttlefish	103	43.51	127	0.0011
Whitings	10	12	6	0.00004
Pikes	754	994	1071	0.0036
Butterfishes	20	10	0	0.00004
Other Garfishes	30	27	0	0.00007

3.3.8. Data quality of the model (Pedigree of the model)

The pedigree of an Ecopath input represents the origin of a given input data. The 'pedigree' routine in Ecopath, functions as a sensitivity analysis by documenting the effect of different quality of data inputs on estimated parameters and their quality. The pedigree index (*P*) measures the amount of local data used in the model among the five basic categories of data: Biomass (*B*), Production to biomass (*P/B*), the ratio of consumption to biomass (*Q/B*), and diets and catches for each of the functional groups. The range of *P* is from 0 for data not rooted locally to 1.0 for data that are fully rooted in local data (Christensen and Walters, 2009). The pedigree Index for the CS Ecopath model was calculated using the expression:

$$P = \sum_{i=1}^{n} \frac{I_{ij}}{n}$$

following Christensen and Walters (2009), where I_{ij} is the pedigree index value for group *I* and parameter *j* for each of the living groups in the ecosystem; *j* can represent either *B*, *P/B*, *Q/B*, catch and diet. When the pedigree table is completed, Ecopath models are then implemented with this "quality footprint' that is unique for the study ecosystem. The model pedigree can be compared between models based on single parameters pedigree, or overall pedigree indices (Christensen and Walters, 2009). For example, the pedigree of the Ecopath Model for Jurien Bay was 0.69 (Table 3.4), which is high compared other similar shelf Ecopath models in Australia and around the world (Loneragan *et al*., 2010; Lozano-Montes *et al*., 2012; Table 3.4).

3.3.9. Pre-balance diagnostics (PREBAL)

In accordance with Heymans *et al*. (2016), we analysed the performance of the CS model by running a set of pre-balanced (PREBAL) diagnostics routine. These diagnostics are based on biological, and fisheries principles and it is recommended that these diagnostics are run before balancing the model (Link, 2010; Heymans *et al*., 2016). These diagnostics, including the slopes of biomass ratios, vital rates, total production, and consumption based on trophic levels, are based on biological and fisheries principles and they are recommended as a means of checking for thermodynamic and ecological principles, as proposed by Heymans *et al*. (2016). The CS model has been evaluated for the quality of the input data through the PREBAL diagnostics presented in Appendix 7. These PREBALs diagnostics are only the first check of the model before beginning the mass-balance process where further parameterization of some groups was conducted. Overall, the performance of the PREBAL diagnostics indicated that our pre-balanced model was, in general, thermodynamically consistent (Appendix 7). Note, the PREBAL diagnostics were also used on the balanced model to check its performance.

3.3.10. Balancing the model

Once the basic EwE parameters had been entered and the PREBAL diagnostic verified, the model was mass-balanced (using equation 1). This assumption is the foundation of Ecopath as it allows for analytical solutions but also means the system maintains the laws of thermodynamics (Christensen *et al*., 2004). As is standard for Ecopath, we used the Ecotrophic Efficiency (EE) as a measure of the proportion of production that is utilized in the system by predation or fishing. In Ecopath, EE cannot exceed 1.0 (it is not possible to consume more than is produced). As a general rule (Heymans *et al*., 2016), EE values near to 1.0 are expected for groups whose production is consumed by predator or removed by the fishery while values near to 0.0 are expected for groups with low predation rates (e.g. top predators like sharks, or blooms of phytoplankton where significant volumes are lost to bacteria and detritus) or not targeted by a fishery. Values of EE were used to highlight groups in the pre-balanced model that need to be adjusted within biologically plausible limits to achieve mass-balance of the flows in the food-web. We manually reduced predation mortality rates of groups with unrealistic EEs >1.0 as suggested by Heymans *et al* (2016). Figure 3.6 summarises the unrealistic EE generated during the first run of the PREBAL model, showing approximately 30% of the groups were out of balance (21 out of 73), where 80% of these groups (17 out of 21) were invertebrate groups. While this result is not unusual for a new Ecopath model, it does highlight the need for more and better information to understand the role of invertebrate groups in the system. The model was balanced manually to ensure that changes to the input parameters were kept within biological reasonable limits. The first step was to reduce the predation on the groups that were out of balance but maintain the original values of biomass for groups with local biomass estimates (this was done primarily via modifying values in the diet matrix). The second step was to adjust consumption rates (Q/B) and production rates (P/B) to achieve mass-balance, where changes of less than 10% were applied to those groups out of balance. Finally, we minimized cannibalism within groups (i.e. sharks) and liberate this energy to other groups (following Christensen *et al*., 2008). The parameters used in the model have been revised and there is a possibility that new estimates from other Westport-WAMSI projects could replace some of the basic input parameters of this version of the model.

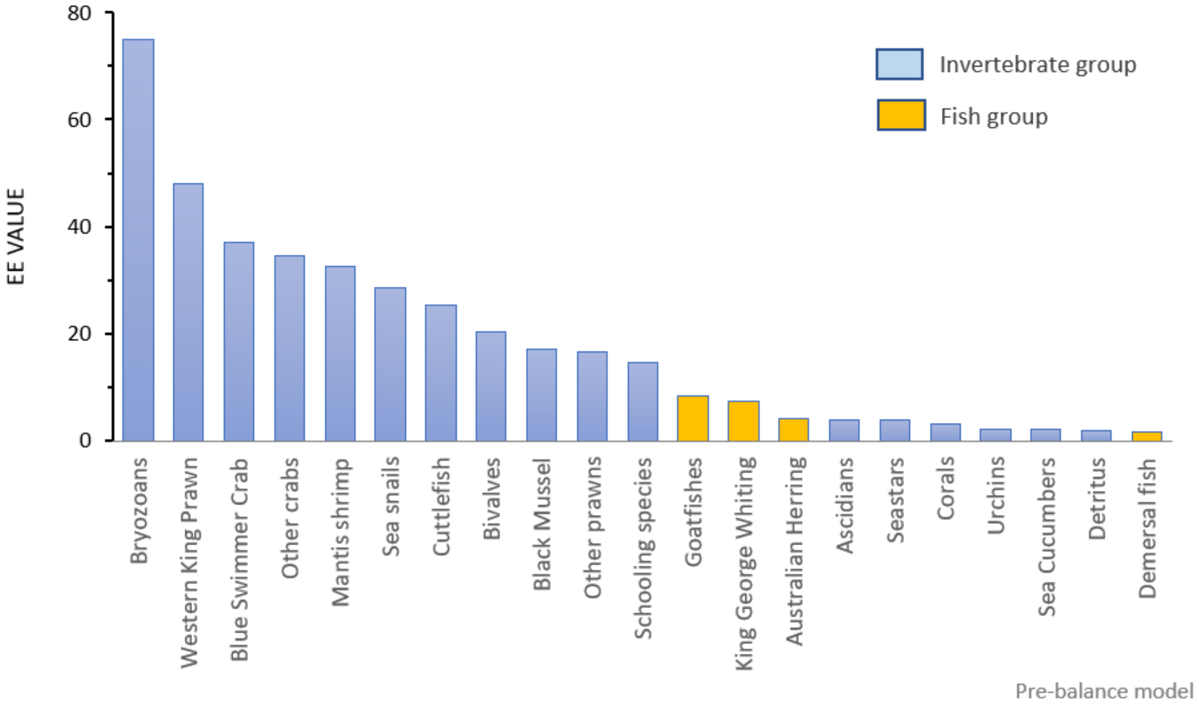


Figure 3.6. Values of Ecotrophy Efficiency (EE) higher than 1 estimated by the CS Ecopath model. Values of EE>1 are unrealistic, and they were adjusted manually by reducing predation rates on the diet matrix of these groups.

3.3.11. Model fitting to time series

We used the Ecosim component of EwE for tunning the Ecopath model. Initially, the vulnerabilities *v*s (see section 3.3.2. for details) for the fitting process in Ecosim were allocated from 1.0 to 10.0 and the final *v*s of each group were set during the tuning of the model with time-series of and catch per effort (CPUE) for the BSC, squids, and octopus (Figure 3.7). Fitting of the Ecopath model was performed using the stepwise fitting procedure in EwE (Christensen *et al*., 2004; Christensen *et al*., 2015). The model tunning procedure seeks the best fit across a range of time series (i.e. relative or absolute biomass, catch, CPUE), modifying the vulnerability to predation (V) parameter in Ecosim. We used series of catch and CPUE from 2010-2022 (provided by DPIRD) for three species; BSC, Squids, and Western Australian Octopus to (see details in Appendix 8). The "vulnerability search" routine in Ecosim allowed us to identify the combination of vulnerabilities which provides the overall best fit. We chose not to assume that changes in primary production or environmental drivers contributed to the fit. This was because we did not have any relevant time series to base drivers upon. If information becomes available, then a primary production anomaly or environmental driver could be included in the estimation of vulnerabilities and fitting.

The sum of squared residuals (SS) of the three species included in the fitting was used as a measure to identify the best runs as suggested by Christensen *et al*. (2004). The fit to time series was judged reasonable for the three groups selected.

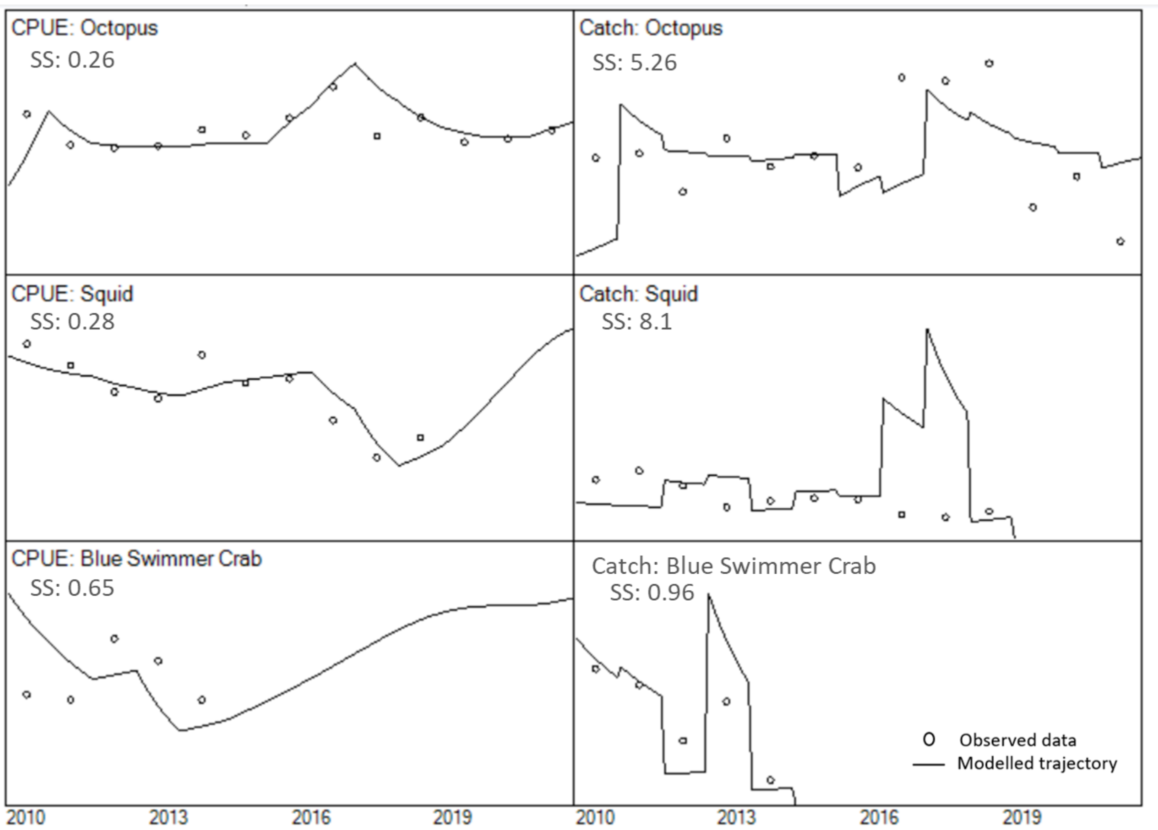


Figure 3.7. Fits of relative CPUE and catch of three commercial species in CS: Octopus (*Octopus djinda*, Squid (*Sepioteuthis spp.*) and BSC (*Portunus armatus*). CPUE modelled trajectories (black line) are compare with time series of observed data (dots). Sum of Squared residuals (SS) are shown as measure of goodness of fit.

3.3.12. Addressing uncertainty: Monte Carlo approach

Ecosim contains a module that allows users to use a Monte Carlo simulation approach to search for Ecopath parameter-combinations that improve the fit of the model to time series data (i.e., reduce the weighted sum of squared deviations, SS). In this study, we used Monte Carlo simulations to reduce the SS of the Ecopath input parameters. We set 500 trials, where each trial represents an Ecosim run with a randomly selected set of Ecopath parameters of B, P/B, Q/B and EE for each group (Christensen *et al*., 2004) and we estimated the percentage change of the main input parameters (B, P/B, Q/B) as shown in Appendix 9. Results from this analysis showed that functional groups with trophic level <2.5 (invertebrates and primary producers) were associated with the highest uncertainty in Biomass and they displayed the biggest changes in Biomass. Further results and methods of this analysis are presented in Appendix 9.

3.3.13. Network Analysis

The Ecopath with Ecosim (EwE) software links concepts developed by theoretical ecologists, especially the network analysis theory of Ulanowicz (1986), with those used by ecologists involved with fisheries, aquaculture, and farming systems research (Christensen *et al*., 2004). The network analysis component of Ecopath is included as a plugin under the *Tools* node, under *Parameterization,* in the main Navigator window of the Ecopath menu. This routine allows users to estimate energy flows between trophic levels within the system (Christensen *et al.,* 2004). The network analysis built in EwE does not produce dynamic results and cannot predict how the biomass would change with time. However, this analysis provides valuable information about the structure of the CS system, by providing a snapshot for one time, that helps identify which parts of this ecosystem play a major role. We compared the network ecosystem attributes estimated for CS with those estimated by other Ecopath models in Western Australia (Figure 3.8).

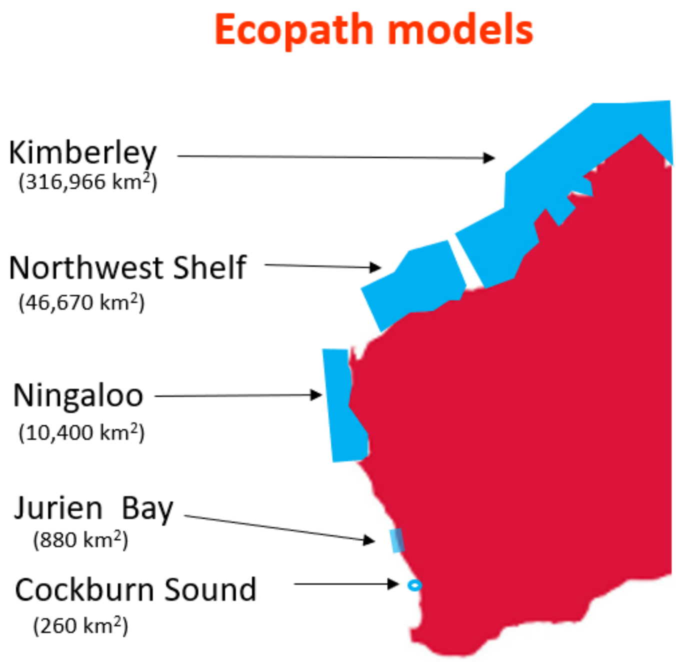


Figure 3.8. Ecopath models of Western Australia used to compare ecosystem attributes with CS Ecopath model. Area of the model domain for each system is shown in parentheses.

3.3.14. Keystone species

Keystone species are defined as species with a structuring role within ecosystems and the food webs that are interconnected despite a relatively low biomass and hence food intake (Power *et al*., 1996). Variations in the keystone species abundance or activity have greater impacts on biodiversity and trophic structure, compared to other coexisting species with similar or higher abundances in the ecosystem (Power *et al.,* 1996). In this study, keystone species were defined using (1) the Keystone Index # 3 (KS) developed by Libralato *et al.* (2006); and (2) the relative total impacts (RTI) based on the mixed trophic impacts analysis (MTI) to account for both direct and indirect effects of trophic interactions, according to Valls *et al*. (2015). The KS is calculated as follows:

$$KS_i = \log[\varepsilon_i * (1\text{-}p_i)]$$

where ε_i = overall effect of group *i* on other groups calculated by the MTI, and p_i represents the contribution of biomass from species *i* or functional group *i* with respect to the total biomass of the CS food web estimated in the Ecopath model.

3.3.15. Ecological Indicators

One of the goals of this study was to characterise the ecosystem properties of CS using a variety of model-based ecological indicators. The Ecopath software is capable of generating a number of outputs for characterising the ecosystem properties and states of maturity from five different analyses: Trophic Pathways analysis, Network analysis, Mixed Trophic Impacts analysis, Lindeman Spine analysis, and Keystone species analysis (Christensen *et al.,* 2004). We used the model outputs from these analyses as ecological indicators to combine information on community energetics, nutrient cycling, ecosystem stability and biodiversity. The 36 chosen Ecopath indicators were divided into five general categories: (1) Ecosystem Level; (2) Use of Energy; (3) Biomass-based; (4) Fisheries; and (5) Conservation and Introduced species (Figure 3.9). The values of these indicators from the CS model can be used to report on the state and condition of the CS food web in a snapshot representing 2020-2022 (Figure 3.9). Linking these ecological indicators to ecosystem changes and pressures on the system requires the development of a temporal dynamic food web of the Sound using the Ecosim component of Ecopath. This beyond the scope of the current project but would be an important component of any future quantitative modelling of CS.

3.3.16. Workflow of model development

A workflow of the main steps in the development of the Ecopath model, analyses completed (section 3.4) is shown in Figure 3.10. The plan is to lodge the Ecopath model in the online "Cockburn Sound Integrated Ecosystem Model (CSIEM)" sharing platform in a GitHub repository under construction by WWSMP Project 1.1 (Figure 3.10).

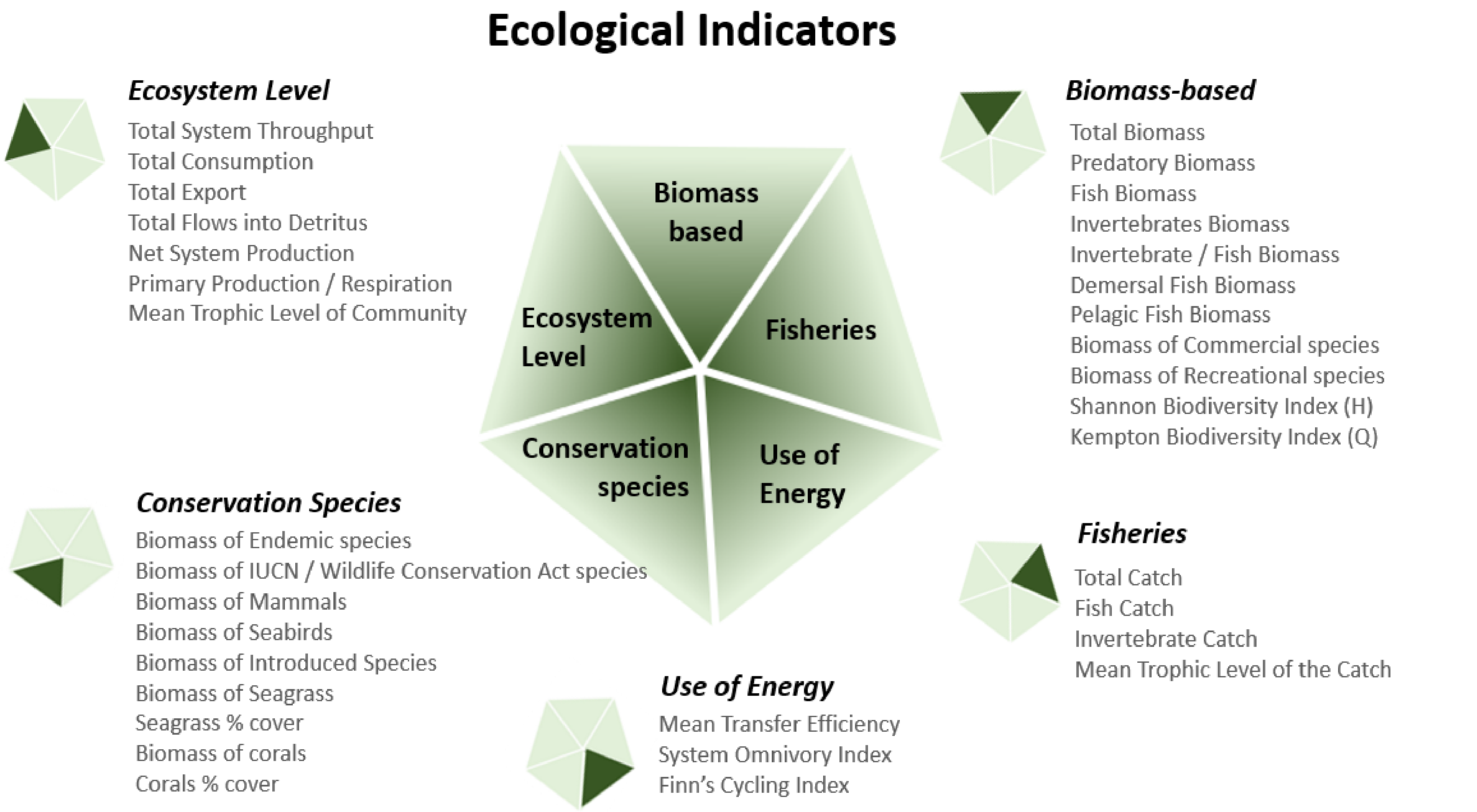


Figure 3.9. The 36 ecological indicators estimated from the Ecopath model used to describe baseline conditions of CS for 2020-2022. These indicators are divided into five categories: (1) Biomass-based, (2) Ecosystem-Level conditions, (3) Use of energy, (4) Conservation of species, and (5) Fisheries.

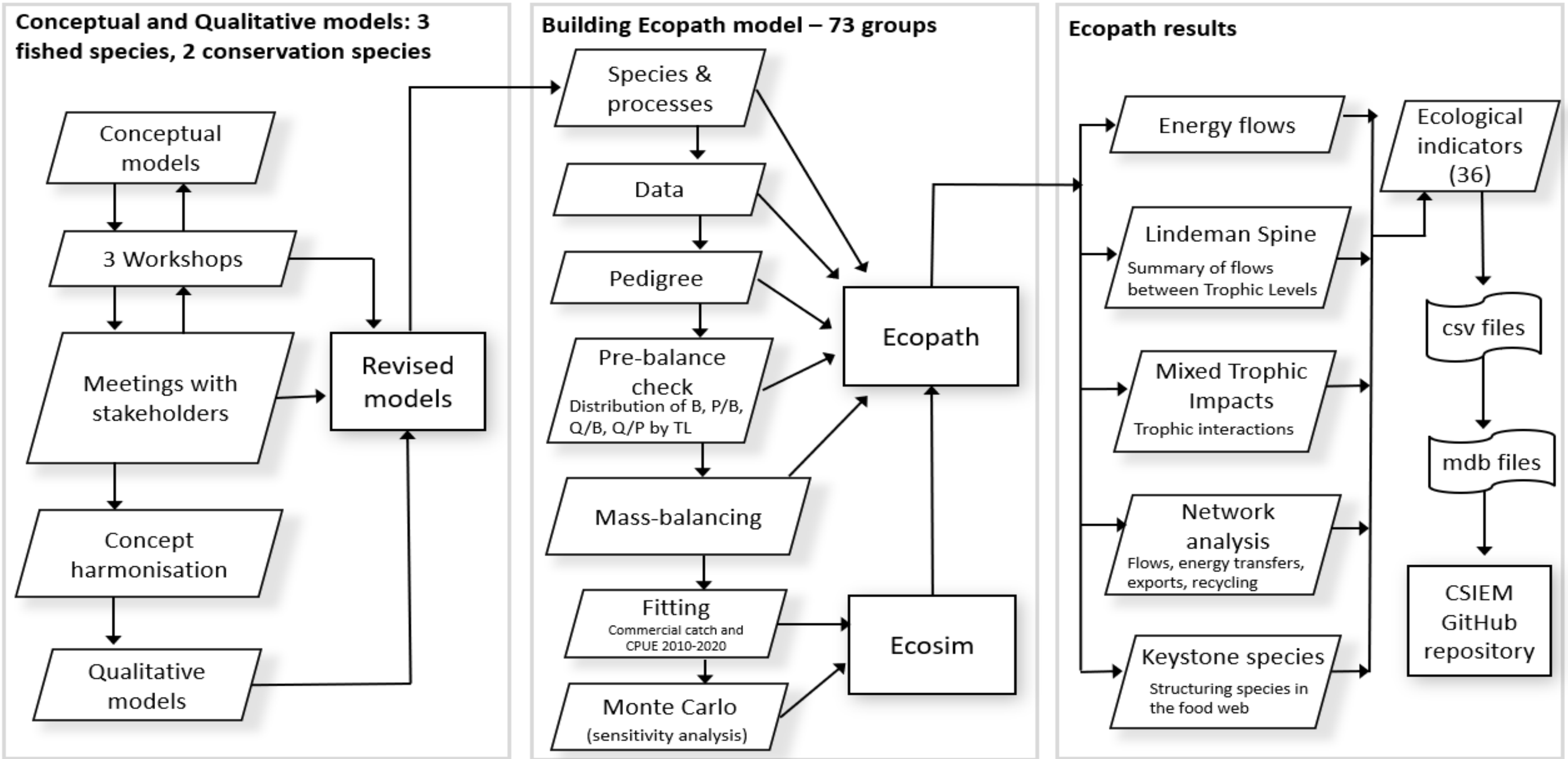


Figure 3.10. Workflow of the steps in the development of the Ecopath model for CS, analyses completed and lodged in the share platform *Cockburn Sound Integrated Ecosystem Model (CSIEM)* in a GitHub repository under construction by WWMSP Project 1.1.

3.4. Results

3.4.1. Biomass distribution per Trophic Level

After the PREBAL analysis and tuning, the CS Ecopath model was used to calculate the trophic level (TL) aggregation for the 72 living groups, showing that the system spans more than four trophic levels (Table 3.3). The food web diagram of this ecosystem, including size proportional biomasses and trophic links is presented in Appendix 10.

Figure 3.11 presents the distribution of the total biomass by trophic level in the CS, where more than 60% of the total biomass in the system was located within the trophic levels lower than 2.5 (primary producers, filter feeders, herbivores, and most invertebrates), suggesting that the CS food web is truncated. The highest contribution to the total biomass in the model was from demersal fishes (i.e., Groupers, Gurnards, Foxfish), comprising about 35% of the total biomass in the system (Figure 3.11). Trophic levels 2 to 2.5 include Blue Sprat, Sandy Sprat, wrasses, butterfishes, mullets, schooling fishes, Western King Prawns, BSC, and other invertebrates, and comprised about 76% of the total biomass in the system (2,654 t/km^2), showing the dominance of these benthic groups in the food web. Note that material classified as detritus in the diets can have a significant influence on the estimated TL. Detrital material consists of both organic and inorganic material, and this has not been distinguished in the current study.

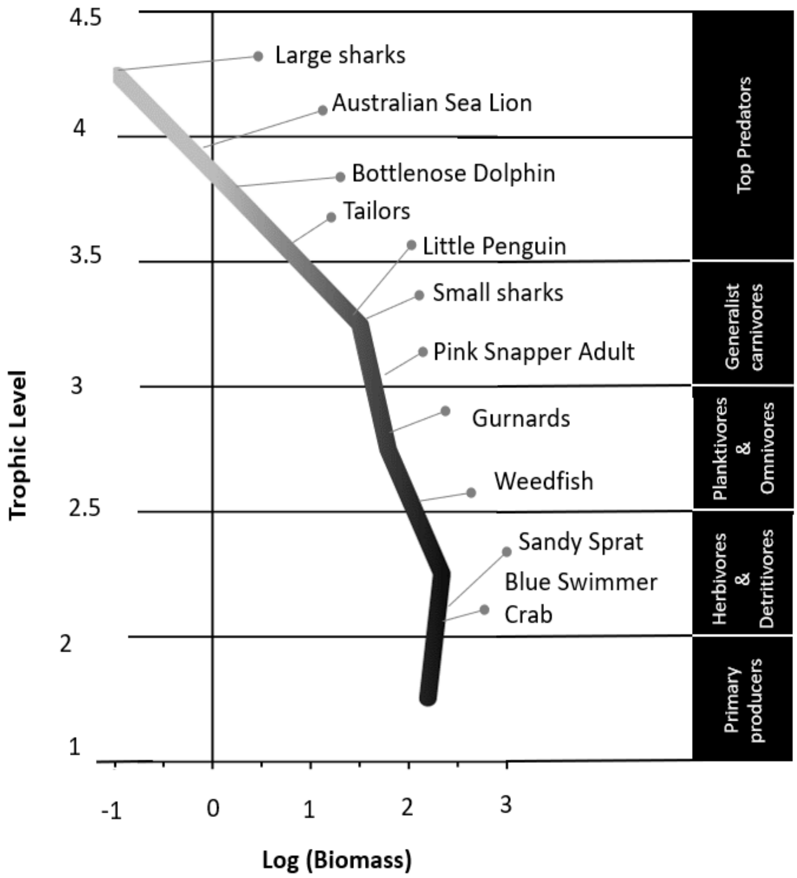


Figure 21 Distribution of the log of the total biomass in each trophic level in the CS ecosystem model derived from the balanced Ecopath model.

3.4.2. Network Analysis

We used the below main outputs from the network analysis to describe the state and maturity of the CS ecosystem following the criteria proposed by Odum (1969) and Ulanowicz (1986):

1. ***Transfer efficiency (TE)***: is calculated as the ratio between the sum of the exports from a given trophic level, plus the flow that is transferred from trophic level to the next, and the throughput for the trophic level. This is presented in the Lindeman Spine (Figure 3.12) with transfer efficiencies (%) of the first four trophic levels. CS had a high value of TE from detritus of 14.3%, which is similar to the TE estimated for the NW Shelf food web and higher than those for Jurien Bay (11.6%) and the Kimberley (5.1%). The high TE in CS shows the contribution of detritus to the trophic network of this system (Table 3.4).
2. ***Total system Throughput (TST)***: TST represents the total flows in the system, including total consumption, total exports, total respiration, and total flows into detritus. It measures the ecological size of a system (Ulanowicz, 1986) and its metabolism (Ortiz *et al*., 2015). The estimated TST for CS is smaller (10, 517 $t \cdot km^{-2} \cdot yr^{-1}$) relative to other food webs in Western Australia such as Jurien Bay (15,343 $t \cdot km^{-2} \cdot yr^{-1}$) or the North West Shelf (68,279 $t \cdot km^{-2} \cdot yr^{-1}$).
3. ***Total Primary Production/Total Respiration (TPP/TR)***: The TPP/TR ratio is generally used to describe maturity of an ecosystem (Odum, 1969). In systems suffering from organic pollution, the TPP/TR ratio is expected to be less than 1 (Christensen *et al.,* 2004). A TPP/TR close to 1 implies that all primary production is used for respiration with no residual production left. In the current study, the TPP/TR ratio (0.6) was much smaller than those estimated for more mature systems such as NW Shelf (0.9), Ningaloo (1.7), Jurien Bay (2.1) and the Kimberley (2.5),(Table 3.4). The TPP/TR ratio for CS suggests that the system was suffering from organic pollution in past states and is consistent with a developing system in terms of its maturity i.e., it is not mature. Odum (1969) describes the evolution of ecosystems from a linear chain to a complex web where flows do not rely only on direct primary production, but also on indirect consumption and respiration (i.e. mainly detritus consumption).
4. ***Net System Production*** (NSP): In Ecopath, the NSP is the difference between the total primary production and total respiration (Christensen *et al.,* 2004), and represents the sum of the productivity of all producers. Systems with large imports may have a negative system production (Odum, 1969; Christensen *et al.,* 2004). The NSP for CS was negative (-1384 $t \cdot km^{-2} \cdot yr^{-1}$) indicating the system is supported partially by energy originating from outside the Sound. coast.
5. ***System Omnivory Index (SOI)***: the SOI can be used as a proxy of food chain complexity. We used this index as a measure of how the feeding interactions are distributed within trophic levels. An omnivory index of zero indicates that the species or functional group is specialised and feeds on a single trophic level. The SOI increases for species or functional groups that feed on many trophic levels (Christensen *et al*., 2004). The SOI for CS is 0.34, higher than those reported for more complex foods, such as the NW Shelf (0.26) and the Kimberley (0.29). It was also higher than the SOIs for Jurien Bay (0.24) and Ningaloo (0.21).
6. **Finn's Cycling Index (FCI)**: represents the fraction of the throughput energy that is recycled. In addition to energy flows, the energy storage also plays an important role in generating network properties (Allesina and Ulanowicz, 2004). The FCI has been identified as an indicator of system maturity, resilience, and stability (Allesina and Ulanowicz, 2004; Christensen *et al*., 2004). In this study, the estimated FCI (4.9) for CS was more than double than that estimated for the Kimberley (1.9), but smaller than the FCI for Jurien Bay (7.1) and NW Shelf (9.5)). This intermediate level of recycling in CS could be important in the case of potential existing pollutants that may be taken up by the same species or functional group due to energy cycling within the Sound.

3.4.3. Lindeman Spine analysis

One way of considering the system is to look at the Lindeman spine, which calculates the energy flows between trophic levels (TL) within the system by reducing a large complex food web into a simple chain (Lindeman, 1942; Ulanowicz, 1995). This means the myriad flows of organic matter within the CS system were summarized using a linear chain for the four trophic levels used to represent the system. The Lindeman spine analysis is included in the ecological-network analysis of Ecopath (Christensen *et al*., 2004). The analysis also allows the path lengths to be visualised and recycling loops to be identified, both of which provide measures of ecosystem maturity (Ulanowicz, 1995).

Results from this analysis showed that transfer efficiencies are highest at trophic level II (16%), declining to 6% from trophic level III to IV (Figure 3.12). It is widely accepted that in many systems the mean energy transfer efficiencies between trophic levels is ~10% (Pauly and Christensen, 1995). The discrepancy between the trophic transfer estimated for the CS ecosystem may be explained by the high biomass of invertebrates and demersal fishes at trophic level II because a large proportion of energy is consumed (i.e. respiration) and stored (i.e. materials that consumers does not digest) by those groups reducing the energy transfer to higher trophic consumers. The Lindeman spine indicated a large decrease in the biomass above trophic level II – from 240 t· km^{-2} to 5.6 t· km^{-2} in trophic level IV (Figure 3.12). Overall, the flows originating from detritus, which comprised an estimated 1107 tons/km^2/year, dominated the organic flows in CS (Figure 3.12). This result highlights both the importance of detritus as an energy source and the ecological role of detritivory in the CS food web.

Table 3.3. Basic parameters of the mass-balanced CS model. Bold numbers were parameters estimated by Ecopath.

	Group name	Trophic level	Habitat area (proportio	Biomass (t/km²)	Production / biomass (/year)	Consumption / biomass (/year)	Ecotrophic Efficiency
1	Large sharks	**4.17**	1	0.0540	0.114	1.9	**0.002**
2	Barracudas	**4.14**	1	0.0544	0.18	3.5	**0.010**
3	Australian Sea Lion	**3.97**	1	0.0086	0.19	24.7	**0.640**
4	Bottlenose Dolphin	**3.74**	1	0.0823	0.08	21.7	**0.131**
5	Tailors	**3.66**	1	0.1790	0.71	19.5	**0.023**
6	Cormorants	**3.59**	1	0.0390	0.09	57.7	**0.067**
7	Squids	**3.59**	1	**1.3218**	0.84	16.6	0.950
8	Australian Pelican	**3.41**	1	0.0190	0.09	70.0	**0.137**
9	Gulls and Terns	**3.35**	1	0.0102	0.14	70.0	**0.310**
10	Little Penguin	**3.33**	0.1	0.0021	0.19	30.1	**0.220**
11	Scaly Mackerel	**3.37**	1	0.1290	1.89	17.2	**0.659**
12	Small sharks	**3.30**	1	0.0028	0.361	2.1	**0.409**
13	Yellowtail Scad	**3.27**	1	0.3199	0.44	4.7	**0.496**
14	Cuttlefish	**3.25**	1	0.0519	0.84	16.6	**0.699**
15	Trevallies	**3.26**	0.1	9.4970	0.32	4.9	**0.305**
16	Flounders	**3.19**	1	3.4380	0.86	7.1	**0.612**
17	Pink Snapper adult	**3.04**	1	0.3447	1.1	2.1	**0.261**
18	Pink Snapper pre-spawner	**3.03**	1	**0.1864**	0.47	4.5	0.950
19	King George Whiting	**3.00**	1	0.9490	0.41	11.4	**0.286**
20	Whiting Species	**3.00**	1	20.70	0.52	16.3	**0.582**
21	Small pelagics	**3.05**	1	7.1538	0.11	8.1	**0.345**
22	Western Australian Octopus	**2.91**	1	0.0866	1.1	7.3	**0.945**
23	Grunters	**2.88**	1	1.1014	1.12	7.8	**0.417**
24	Pipefishes	**2.89**	1	0.0912	0.8	31.6	**0.020**
25	Gurnards	**2.86**	1	0.1900	0.8	11.9	**0.251**
26	Weedfish	**2.66**	1	0.2210	1.85	18.2	**0.140**
27	Soldiers	**2.64**	1	0.8970	0.48	6.3	**0.219**
28	PInk Snapper juvenil	**2.54**	1	**0.0439**	1.58	6.7	0.950
29	Other seabirds	**2.62**	1	0.0005	0.12	37.7	**0.000**
30	Rays	**2.47**	1	6.7726	0.326	4.1	**0.002**
31	Dragonets	**2.59**	1	1.3800	0.84	22.7	**0.374**
32	Southern Garfish	**2.56**	1	0.2852	0.9	13.6	**0.685**
33	Wrasses	**2.40**	1	0.8130	0.47	11.5	**0.549**
34	Butterfishes	**2.31**	0.1	3.0777	1.12	14.4	**0.818**
35	Demersal fish	**2.28**	1	111.6	0.17	4.7	**0.845**
36	Common Silverbelly	**2.21**	1	0.1410	0.98	14.7	**0.536**
37	Goatfishes	**2.18**	1	0.8230	1.09	7.4	**0.726**
38	Blue Sprat	**2.28**	1	23.6240	1.2	31.0	**0.900**
39	Sandy Sprat	**2.28**	1	21.8140	0.96	14.4	**0.625**
40	Pilchard	**2.42**	1	**6.8667**	0.78	26.6	0.950
41	Australian Herring	**2.37**	1	**0.2970**	0.92	16.8	0.995
42	Schooling species	**2.30**	1	0.1930	0.89	12.6	**0.799**
43	Leatherjackets	**2.14**	1	1.3840	0.914	12.3	**0.725**
44	Other crabs	**2.58**	1	0.8853	0.52	21.6	**0.133**
45	Blue Swimmer Crab	**2.50**	1	0.4850	0.52	21.6	**0.148**
46	Mantis shrimp	**2.37**	1	0.0951	7.57	28.9	**0.523**
47	Seastars	**2.31**	1	0.1970	1.49	3.2	**0.663**
48	Migratory waders	**2.17**	1	0.0001	0.18	42.3	**0.000**
49	Seahorses	**2.11**	1	0.0826	0.83	9.2	**0.260**
50	Mullets	**2.04**	1	4.9110	0.76	12.5	**0.844**
51	Rabbitfish	**2.04**	1	**14.3243**	1.52	38.7	0.950
52	Introduced species	**2.13**	0.005	0.4005	2.3	24.0	**0.000**
53	Western King Prawn	**2.11**	1	0.0263	7.57	22.7	**0.192**
54	Other prawns	**2.11**	1	0.1210	7.57	28.9	**0.994**
55	Sea snails	**2.01**	1	0.0492	3.9	16.9	**0.652**
56	Black Mussel	**2.05**	1	0.0001	2.23	9.5	**0.842**
57	Corals	**2.13**	1	0.2699	0.08	3.0	**0.440**
58	Ascidians	**2.23**	1	0.2275	2.3	24.0	**0.533**
59	Sea Cucumbers	**2.12**	1	0.0951	4.45	7.5	**0.836**
60	Sand dollars	**2.00**	1	0.8378	2.9	10.5	**0.556**
61	Sponges	**2.11**	1	0.0972	1.9	3.1	**0.015**
62	Bivalves	**2.12**	1	0.0099	1.35	7.0	**0.533**
63	Polychaetes	**2.00**	1	**34.0581**	4.85	24.2	0.950
64	Bryozoans	**2.11**	1	0.0772	0.2	16.0	**0.194**
65	Urchins	**2.00**	1	16.2448	7.51	9.6	**0.968**
66	Zooplankton	**2.13**	1	**9.8859**	29.6	57.0	0.950
67	Planktotrophic Larva	**2.00**	1	**21.48**	3	27.0	0.950
68	Phytoplankton	**1.00**	1	**27.08**	50.97		0.950
69	Seagrass	**1.00**	1	**66.16**	7.3		0.950
70	Macroalgae	**1.00**	1	**56.65**	2		0.950
71	Macroalgal Epiphyte	**1.00**	1	**39.34**	2		0.950
72	Microphytobenthos	**1.00**	1	**0.1235**	706.5		0.950
73	Detritus	**1.00**	1	**75.2**			0.800

Table 3.4. Summary of the ecosystem attributes estimated by the current CS Ecopath model compared with four other Ecopath models for marine systems in Western Australia.

	Statistics and flows	Cockburn Sound (32° 16' S) [This study]	Jurien Bay (30° 18' S) Loneragan *et al*. (2010)	Ningaloo (22° 48' S) Fulton *et al.* (2011)	NW Shelf (21° 00' S) Lozano-Montes *et al*. (2019)	Kimberley (17° 25' S) Boschetti *et al*. (2017)
TEd	Mean trophic transfer efficiency from detritus (%)	14.3	11.6	- -	14.5	5.1
TEpp	Mean transfer eficiency from primary production (%)	6.4	7.2	- -	14.9	6.1
	Sum of all consumption (t km-2 year^{-1})	5,247	7,682	4,368	38,303	4,780
	Sum of all exports (t km^{-2} year^{-1})	283	24	2039	0.08	0.06
	Sum of all respiratory flows (t km^{-2} year^{-1})	3,527	4,322	2,839	17,184	1,588
	Sum of all flows into detritus (t km^{-2} year^{-1})	1,458	2,410	4,725	12,791	4,726
TST	Total System Throughput (t km^{-2} year^{-1})	10,517	15,343	13,972	68,279	11,096
	Sum of all production (t km^{-2} year^{-1})	2,926	4,478	5,356	28,901	6,213
MTLc	Mean trophic level of the catch	2.72	2.88	2.71	3.89	2.95
NPP	Calculated total net primary production (t km^{-2} year^{-1})	2,142	2,655	4,862	15,443	3,977
TPP/TR	Total primary production/total respiration	0.6	2.1	1.7	0.9	2.5
NSP	Net system production (t km^{-2} year^{-1})	-1384	-1667	2023	-1741	2388
TPP/B	Total primary production/total biomass	4.1	2.1	26.9	5.8	17.4
B/TR	Total biomass/total throughput	0.05	0.08	0.013	0.04	0.02
B	Total biomass (excluding detritus)(t km^{-2})	520	1,224	180	2,654	227
TC	Total catches (t km^{-2} year^{-1})	0.32	0.53	0.44	0.078	0.06
SOI	System Omnivory Index	0.34	0.24	0.21	0.26	0.29
	Ecopath pedigree	0.68	0.72	- -	0.73	0.74
	Shannon diversity index	2.7	2.9	2.1	3.2	2.86
FCI	Finn's cycle index (% of total throughput)	4.9	7.1	- -	9.5	1.94
	Finn's mean path length	2.7	3.1	- -	3.97	6.98
	Study area (km^{2})	260	823	10,400	46,670	316,966
	Number of groups	73	80	53	73	59

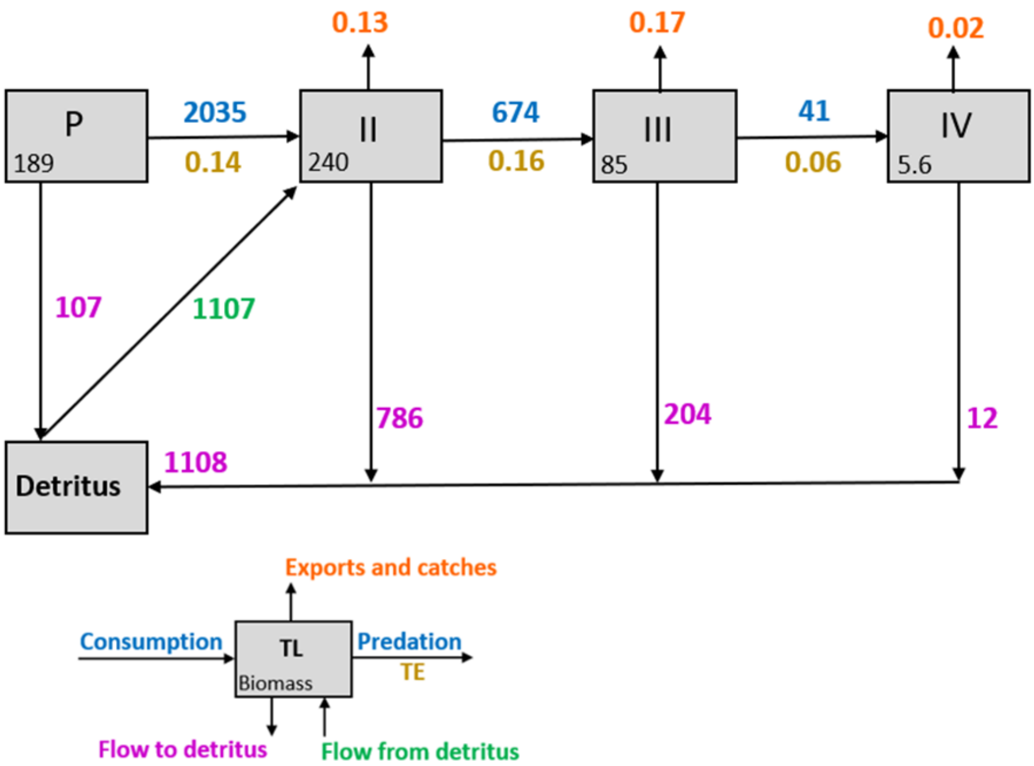


Figure 3.12. The Lindeman Spine analysis representing the flow network and mean energy transfer efficiency (%) of the CS system. Flows out of the compartment box represent exports and catches (orange; t ·km^{-2} year^{-1}). Flows to detritus are in pink and flows from detritus are in green. The numbers adjacent to the arrows indicate the value of the flow in t· km^{-2} year^{-1}. Biomass is expressed in t· km^{-2}

3.4.4. Mixed Trophic Impacts (MTI) Analysis

We used routines from the network analysis proposed by Ulanowicz (1986) and Ulanowicz and Puccia (1990) such as the mixed trophic impact (MTI) to assess the direct and indirect trophic interactions among compartments of the food web, including impacts of commercial and recreational fishery practices throughout the CS. The MTI analysis evaluates the effect of small increases in the biomass of one group on the biomass of the other groups, and thus provides a form of sensitivity analysis (Christensen *et al*., 2005). The MTI analysis included the 76 groups in the model (73 functional groups, two commercial fishing fleets and one recreational fishing) and it allowed us to capture the dynamic behaviour of the ecosystem and the way in which trophic interactions may influence the structure and function of the CS ecosystem. The results of the MTI are presented graphically for 16 groups of top predators (e.g. large sharks, barracudas, Australian sea lion, bottlenose dolphin, seabirds, and small sharks), seabirds (cormorants, Australian pelican [*Pelecanus conspicillatus*], little penguin, terns and gulls, migratory waders), demersal fishes (flounders, rays, mullets, wrasses, and other demersal fish), and three fisheries (CSLPMF, Jigging, recreational fishing) (Figure 3.13). In addition, the MTI and consumption or catch (t km^{-2} year^{-1}) for four target species in the Sound: PS (adult), BSC, Squids, and "Small pelagics" (Sandy Sprat, Blue Sprat, Australian Herring, and Pilchard) are presented in Figures 3.13. Appendix 11 presents the positive and negative impacts from the MTI analysis for all 76 groups considered in the Ecopath food web model.

Results of the MTI analysis highlighted the negative effects (shown by shades of red) of high trophic levels groups such as large sharks, Australian sea lion and bottlenose dolphins, on prey groups, including species of conservation interest, such as little penguin, and fished species, such as PS and BSC (Figure 3.13). The results from this analysis suggest that top predators can have important direct and indirect effects on the trophic structure in CS. Marine top predators are often conspicuous and wide ranging and integrate information from bottom to top of the food web (Hazen *et al.,* 2019) and they may buffer the negative impacts of climate change by mitigating against the loss of biodiversity (Bossart 2006; Estes *et al*., 2016). This is particularly important because CS is also facing the cumulative effects of climate change and economic development.

Among the fish groups, the "Demersal fish" group (including Goatfishes, wrasses, flounders) had a large negative impact (shown by shades of red) on the lower trophic groups in the food web, such as Wrasses, prawns, mantis shrimp, and urchins (Figure 3.13). In this trophic analysis, commercial and recreational fisheries showed a modest negative direct impact on specific target groups in the food web, but the MTI analysis did not identify any marked indirect effects of fishing.

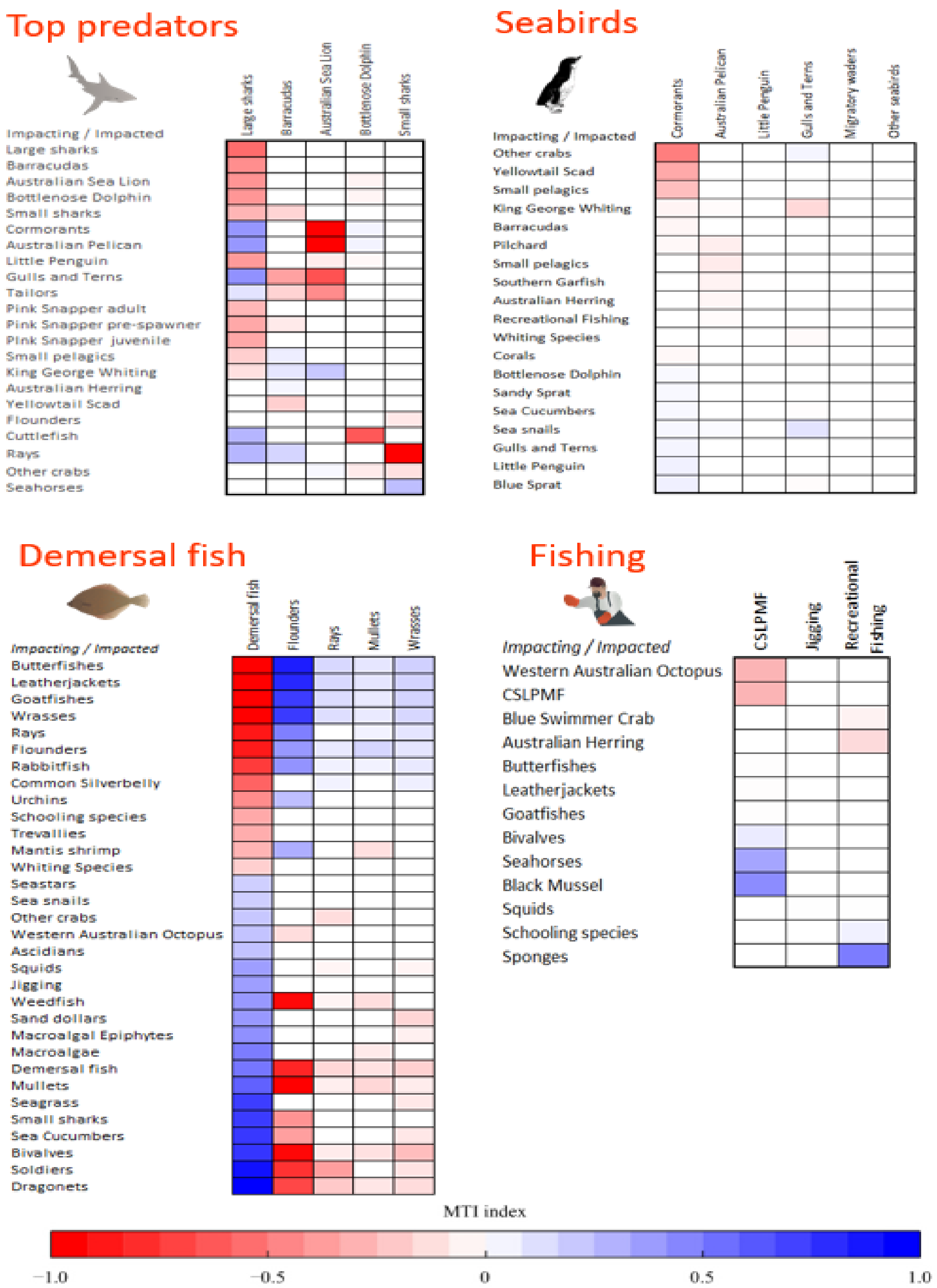


Figure 3.13. The results of Mixed Trophic Impacts (MTI) analyses of selected groups of the CS food web model. Positive (blue) and negative (red) values of mixed trophic impact index represent positive and negative effects, respectively, resulting from a simulated 10% increase in the biomass of the major component in the system a) top predators, b) little penguins, c) demersal fish, d) commercial and recreational fishing.

3.4.5. Keystone species

The plot of keystone index # 3 (KS) in CS against the relative total impact (RTI) (Figure 3.14) allows the most influential species in the food web to be identified. This analysis shows that Small Sharks (KS =5.3), Australian sea lion (KS=5.1), Large Sharks (KS=4.2), and bottlenose dolphins (KS=4.1) were the most important keystone groups in CS (shown on Y axis of Figure 3.14). This could be because their diets comprise many functional groups at different level trophic levels. The results from this analysis identified the ecological role of the above keystone groups in the CS food web which can be defined as structuring groups by processes associated with predation (top-down forces). The Small sharks group is an aggregated functional group containing Port Jackson Sharks (*Heterodontus portusjacksoni*), Gummy Shark (*Mustelus antarticus*), and Wobbegong Shark (*Orectolobus maculatus*). "Large sharks" is also an aggregated group containing White Sharks (*Carcharodon carcharias*), Smooth Hammerhead Shark (*Sphyrna zygaena*), Tiger Shark (*Galeocerdo cuvier*), and Spinner Shark (*Carcharhinus brevipinna*). These groups are of conservation importance, as some of the species within them are currently listed under the EPBC Act.

Demersal fish (i.e. bass groper, western foxfish, wester blue groper, little gurnard perch) and flounders and flatheads (southern bluespotted flathead, rock flathead, yellowtail flathead, smalltooth flounder, and lefteye flounder) were also important groups in influencing the community structure by having the largest contribution to the total relative impacts (RTI = 1.0 and RTI=0.75, respectively) on the community structure (shown on the X axis of Figure 3.14). The high RTI of demersal fish may indicate that the CS ecosystem is driven by bottom-up processes associated with these low trophic level groups (<3) that play a large role in supporting a range of predators higher in the food web. Appendix 12 shows the keystone position for the 73 living groups in the CS model. Species of conservation significance were ranked by the keystones index as follows: cormorants (6), gulls and terns (7), Australian pelican (10) and little penguin (14); The keystones rankings for the main fished species were: Western Rock Octopus (9), PS pre-spawner (25), BSC(32), PS Adult (35), and King George Whiting (39).

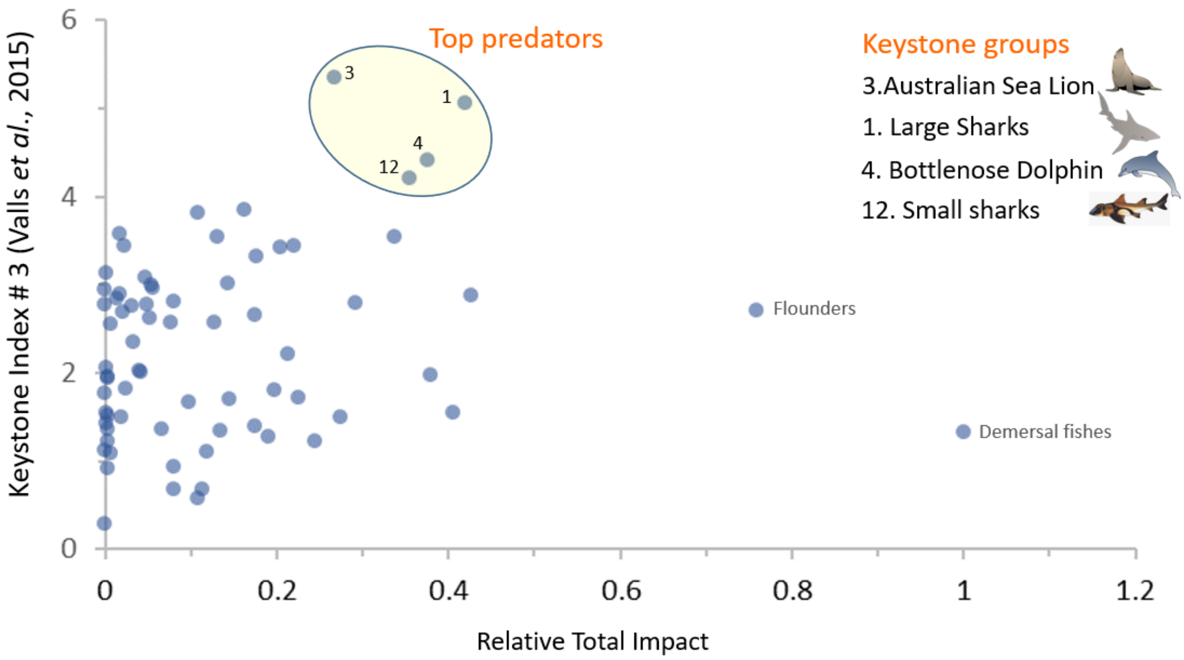


Figure 3.14. Identification of keystone species in the CS ecosystem from the plot of the relationship between Relative Total Impacts (RTI) and the Keystone Index (Valls *et al.,* 2015). The most important functional groups for structuring the ecosystem are shown in the yellow circle.

3.4.6. Ecological Indicators

The values of the ecological indicators from the CS model report on the state and condition of the CS food web in a snapshot representing 2020-2022 (Table 3.5). Linking these ecological indicators to ecosystem changes and pressures on the system requires the development of a temporal dynamic food web of the Sound using the Ecosim component of Ecopath, which was beyond the scope of the current project. Evaluating different scenarios of change would be an important component of any future quantitative modelling of CS.

Table 3.5. The values of the 36 ecological indicators estimated by the Ecopath model for CS to characterise the baseline conditions for 2020-2022. Indicators are grouped into five *categories*.

Category	Indicator	Value	Description	Units
Ecosystem-Level	TST	10,517	Total system throughput	$t \cdot km^{-2} \cdot year^{-1}$
	TC	5,247	Total consumtion	$t \cdot km^{-2} \cdot year^{-1}$
	TEX	283	Total export	$t \cdot km^{-2} \cdot year^{-1}$
	TR	3,527	Total respiration	$t \cdot km^{-2} \cdot year^{-1}$
	TDET	1,458	Total flows into detritus	$t \cdot km^{-2} \cdot year^{-1}$
	NST	-1,358	Net System Production	$t \cdot km^{-2} \cdot year^{-1}$
	TPP/TR	0.61	Total Primary production / Total Respiration	
Use of Energy	MTE	8.4	Mean Trasnfer Energy	%
	SOI	0.34	System Omnivory Index. It is a descriptor from the network analysis of the complexity of the food web, and it is related to stability and maturity of ecosystems (Odum, 2009)	$t \cdot km^{-2} \cdot year^{-1}$
	FCI	4.2	Finn's cycling Index	$t \cdot km^{-2} \cdot year^{-1}$
Biomass-based	B	520.4	Total biomass in the system (it excludes detritus).	$t \cdot km^{-2}$
	mTL	2.34	Mean Trophic Level of the system	
	Commercial B	1.4	Biomass of commecial species	$t \cdot km^{-2}$
	Recreational B	30.9	Biomass of Recreational species	$t \cdot km^{-2}$
	Fish B	224.4	Fish Biomass.	$t \cdot km^{-2}$
	Invert B	55.2	Invertebrate Biomass	$t \cdot km^{-2}$
	Invert/Fish B	0.24	Invertebrate / Fish Biomass	$t \cdot km^{-2}$
	Demersal B	129.1	Demersal B	$t \cdot km^{-2}$
	Pelagic B	95.3	Pelagic B	$t \cdot km^{-2}$
	Demersal/Pelagic B	1.35	Demersal / Pealgic Biomass	
	Pred B	0.42	Predatory Biomass of functional groiups with a trophic level higher than 3.5	$t \cdot km^{-2}$
	Kempton's Q	3.2	Kempton's Q - calculated automatically by Ecopath.	
	Shannon's H	2.73	Shannon Biodiversity Index (H') is related to the weighted geometric mean of the proportion biomass of all functional groups in the model.	
Fisheries	Tot_C	0.32	Total Catch	$t \cdot km^{-2}$
	mTL_c	2.7	Trophic Level of the Catch	
	Fish_C	0.12	Fish catch	$t \cdot km^{-2}$
	Invert_C	0.11	Invertebrate Catch	$t \cdot km^{-2}$
Conservation and Introduced species	Endemic_B	0.086	Biomass of WA endemic species in Australia. For the model included the Western Australian octopus	$t \cdot km^{-2}$
	IUCN / Wild Conservation Act species B	0.15	Biomass of species under IUCN and Wildlife Conservation Act. For the model, these groups are included: Little Penguin (protected by Wildlife Conservation Act); Sharks (VU, vulnerable IUCN). Seahorses and Pipefishes (Vulnerable); Migratory seabirds are protected under IA- (International Agreement, IUCN).	$t \cdot km^{-2}$
	Mammals_B	0.09	Biomass of Mammals	$t \cdot km^{-2}$
	Seabirds_B	0.05	Biomass of seabirds	$t \cdot km^{-2}$
	Seagrass_B	66.1*	Biomass of seagrass. * Estimated by Ecopath	$t \cdot km^{-2}$
	Coral_B	0.12	Biomass of corals	$t \cdot km^{-2}$
	Seagrass_Cover	~ 20%	Seagrass % cover in the system	%
	Coral_cover	~ 2%	Coral % cover in the system	%
	Introduced_Species_B	0.004	Biomass of Introduced Species. Two introduced species were included in the model: Dead's man fingers (*Codium fragile* subsp. *Fragile*), The carpet sea squirt (*Didemnum vexillum*).	$t \cdot km^{-2}$

3.5. Discussion

Understanding the factors that govern the relationship between structure, stability and functioning of food webs has been a central problem in ecology for many decades. The first steps in answering key questions about the structure and functioning of the CS ecosystem was the construction of the quantitative Ecopath model for the present-day conditions (2020-2022). The model describes the energy and mass fluxes, the trophic interactions of predators, prey, and fisheries. The Ecopath model synthesized the biological data from 30 sites, collected using large and small otter trawl nets, benthic sled nets, 21.5m beach seine nets, 61.5m beach seine nets and BRUV in 2021-22 by Westport-WAMSI Projects 2.4 "*Benthic Communities in soft-sediment and hard substrates*" and 4.2.1 "*Spatial distribution and temporal variability of key fish species* " and 4.2.1 "*Spatial distribution and temporal variability in life stages of key fish species in Cockburn Sound*".

These data, and ultimately the balanced model, were used to assemble estimates of the abundance and biomass of fish and invertebrate communities in the region. The network of species connections within this food web is useful for developing a better understanding the ecological roles of fished species (i.e. BSC, PS, SM, Western Rock Octopus, and squids) and species of conservation significance (i.e. little penguin, bottlenose dolphin, Australian sea lion) in the Sound. The results from the network analysis identified trophic patterns and ecological roles of top predators (i.e. sharks, barracuda, mammals, seabirds) in the system.

The quality of the data used in the model was estimated thorough the Pedigree Index, which estimates how much data comes from the model domain (Heymans *et al.,* 2016). The overall Pedigree Index for the CS model was 0.68, a similar value compared with those estimated to other Ecopath models in Western Australia (i.e. Loneragan *et al*., 2010; Boschetti *et al*., 2017; Lozano *et al*., 2019) and higher than many of the 150 Ecopath models worldwide where a wide range of pedigree values have been reported (0.16 – 0.71; Morrissette *et al*., 2006). During the process of mass-balancing the model, important gaps in the biology of some groups were identified, providing directions for further research and guidelines for future monitoring programs. For example, the abundances and biomasses in CS of groups such as PS (adults, pre-spawners, juveniles), small pelagic fishes, seabirds, corals, squids, seagrass, and other benthic primary producers (macroalgae, epiphytes, microphytobenthos) are unknown. Also, the values of ecotrophic efficiency (EE > 1.0), which provides an indication of the overall consumption compared with respiration, during the first balancing of the model were unrealistic for groups such as crabs, Western King Prawns, cuttlefish, urchins, corals, goatfishes, Australian Herring, and King George Whiting. This indicates the need for more, higher quality data for these groups to improve the model. The trophic imbalances of these groups should be resolved in the future by improving the understanding of their biology, particularly their abundance, biomass, and diet, rather than by solving for these properties in the linear equations of the Ecopath model. The sensitivity analysis (using 500 Monte Carlo runs) showed that the major uncertainties in the input data were for the biological information of some benthic invertebrate groups (i.e. corals, crabs, prawns, urchins, holothurians, polychaetes). Addressing these knowledge gaps with more biological data would enhance the reliability of the results of the model.

We used descriptors from the network analysis of the model to estimate trophic interactions, trophic transfer, and energy flows among the 73 living groups in the CS food web. The results suggested that compared with four other marine systems along the coast of Western Australia (the Kimberley, Northwest Shelf, Ningaloo, and Jurien Bay), CS is complex and highly connected ecosystem (System omnivory index, SOI = 0.34), in a late state of development (Total primary production/Total respiration ratio, TPP/TR = 0.6), but not mature (a possible measure of ecosystem stability; Christensen, 1995) compared with some of the other Western Australia systems such as NW Shelf or Kimberley.

The Ecopath results suggest that the CS food web is dependent on both external energies entering the Sound (Net System Production, NSP = -1384 $t \cdot km^{-2} \cdot yr^{-1}$) and the recycling of nutrients (e.g. FCI = 4.9). The flows originated from detritus represented ~10% of the total organic flows, suggesting that CS is still dependant on regenerated nutrients. A modelled phytoplankton productivity in CS (based on nitrogen budgets) has shown that it is primarily a recycling system (Greenwood *et al.,* 2016). During the third workshop of the project (March 15th, 2023; Appendix 13), the change in nutrient status of CS was discussed: the reduction of anthropogenic nitrogen inputs in CS over the last 30 years could have moved the system from eutrophic to oligotrophic, and anecdotal comments from DPIRD (and others) suggested that this could be related to declines in detritus and detritivorous species. Further development of historical Ecopath models to represent past states of CS (e.g. 1960s, 1980s, 2000s, 2010s) would be valuable to assess the historical impacts of development and changes in nutrient inputs to CS (see section 4.2 for details).

The transfer efficiency was highest at trophic level (TL) 2 (invertebrates and demersal fishes) and the contribution of energy transformations by top predators (groups at TL >3.5) was low, suggesting that the transfer and recycling of energy is retained and accumulated in the lower section of the food web (groups with TL <2.5). Recycling of organic matter and detritivory are important elements in enrichment and nutrient cycling of this food web (Finn's Cycling Index, FCI = 4.9). Nutrient cycling has a major impact on ecosystem dynamics and stability (Ulanowicz, 1969; Theis *et al*., 2021). Our results provide broader insight into the main mechanisms governing energy flows and processes shaping the trophic structure of the CS ecosystem.

Analysis of the relative trophic impacts on the system highlighted that top predators (TL>3.5) such as large and small sharks (i.e. white shark, *Carcharodon carcharias*; tiger shark, *Galeocerdo cuvier*; spinner shark, *Carcharhinus brevipinna*; Port Jackson shark, *Heterodontus portusjacksoni*), bottlenose dolphin (*Tursiops aduncus*), Australian sea lion (*Neophoca cinerea*), and cormorants (i.e. pied cormorant, *Phalacrocorax varius*; little pied cormorant, *Microcarbo melanoleucos*; little black cormorant, *Phalacrocorax sulcirostris*), had a large negative impact on prey groups, including PS, King George whiting and small pelagics. In this trophic analysis, habitat-forming species such seagrasses and other habitat-forming species (mainly corals and sponges) showed a modest positive impact on the food web as they are not an important source of food but provide refuge from predators. This is important as there is evidence that the abundance of seagrass in coastal ecosystems is positively correlated with fish and invertebrate species richness, biomass, abundance, and trophic structure (e.g. Loneragan *et al*., 2013; Fraser *et al.,* 2017; Kendrick *et al*., 2018; McMahon *et a*l., 2022; Jones *et al*., 2021), something which could be explored in greater depth in the future using the Ecosim component of EwE. At present, the results from the mixed trophic impact analyses (MTIs) are likely to underestimate the sensitivity of CS to changes in the biomass of seagrasses because the spatial dynamics associated with habitat utilisation and habitat quality were not explored in this study. Further evaluation of the importance of seagrasses, sponges, and corals (enhancing the survival of fish and crustacean species), is important for understanding ecosystem impacts and evaluating change in CS. This requires the development of a spatial, dynamic, ecosystem model (Ecospace), based on the distribution of these habitats and important processes in CS.

The Ecopath model identified the ecological role of keystone groups defined as structuring species by processes associated with predation (top-down forces) with sharks, bottlenose dolphin, Australian sea lion, and cormorants as functionally important species in the system. Keystone species help to maintain local diversity within a community by controlling populations of species that would otherwise dominate the community (Scott *et al*., 1993). They also have a disproportionate role in maintaining the structure of an ecological community given their biomasses in the system relative to other species or functional groups (Scott *et al*., 1993; Power *et al*., 1996).

The ecological indicators generated in this study provide baseline information on the trophic structure, energetics, and function of the CS ecosystem. The values of the 36 indicators estimated for the baseline state in 2020-2022 can be used to inform scientist and managers of the current state of the system. Tracking these indicators through time provides information on changing conditions of the CS food web and how the food web responds to stressors and disturbances (e.g. infrastructure development and climate change). This can be done by developing different scenarios of change for CS and developing a temporal dynamic model using Ecosim, to evaluate the effect of these scenarios on the food web. If past states of the Sound are reconstructed, the change in these indicators to the current condition also provide an understanding of historical changes in ecosystem structure and function. The development of scenarios of change for evaluation and Ecosim were not in the scope of scope of the current study.

Overall, the Ecopath model has been invaluable tool for synthesising and communicating ecosystem understanding and knowledge of biological components and processes among diverse disciplines in marine science, the private sector, and management agencies responsible for CS. It has brought together a diverse group of experts from government institutions (WAMSI, Westport, DPIRD, DBCA, WAFIC, CSIRO, DWER, CCWA), academia (UWA, ECU, MU) and industry to gather data and information and forge it into a broad consensus about coastal ecosystems function, trophic interactions, and infrastructure development in the region. The workshop process used in developing the conceptual and qualitative ecosystem models and the Ecopath model has increased awareness of the Ecopath suite of programs (Ecosim and Ecospace) that could be applied to investigating the effects of dredging and shading on primary and low order secondary production in CS.

3.6. Conclusions

The complexity of the CS ecosystem makes it difficult to evaluate interactions among different species without using a quantitative modelling approach. The Ecopath food web model developed in the project provides an effective tool for analysing the trophic structure and key ecosystem attributes and overall functioning of this system. It also provides a comprehensive means for identifying the important pathways and ecosystem elements by which impacts from stressors, including cumulative impacts, can alter ecosystem structure and function.

This model provided a summary of our current knowledge of the biomass, consumptions, production, food web and trophic flows in CS for the 2020-2022 period. It has also demonstrated its capacity for integrating data and information from other Westport-WAMSI projects to support a synthesis of current knowledge of ecological and ecosystem processes in CS.

The Ecopath model identified the ecological role of keystone groups defined as structuring species by processes associated with predation (top-down forces) with sharks, bottlenose dolphin, Australian sea lion, and cormorants as functionally important species in the system. Outputs from the model also identified the significant biomass of benthic fishes in the system (i.e. western foxfish, little gurnard perch, sea mullet) and their potential to produce negative effects if their production is affected. This is particularly important for understanding the processes and interactions within the system, including the ecological role of both low and high trophic level groups, in supporting plans for conservation and management.

Many factors may affect the performance of the model in describing the structure and trophic interactions of CS. For example, the lack of complete, current biomass for some functional groups (e.g. PS adults, pre-spawners, juveniles, small pelagic fishes, plankton groups and benthic primary producers), meant that biomasses in CS were estimated by the model. A second factor is the that we were not able to include recent estimates of recreational fishing catch and effort for key species in the system (e.g. Australian herring, King George whiting, mulloway, Australian salmon, blue sprat, butterfishes, and other whiting species). These data are now available and a strategy for incorporating them in a revised Ecopath model for CS has been discussed with DPIRD. A third key factor lies in the diet composition of species and functional groups, where the contribution of detritus as a food source for detritivorous fish and invertebrates is an undetermined component of this food web. These uncertainties could introduce inaccuracies in the predicted outputs of the model. Hence, further information on the biology, abundance and diets of these species should be targeted for further research.

Chapter 4: General discussion

Biological communities in CS are organized in food webs and the nature of key trophic linkages and ecosystem processes (how and when material flows between populations) is incomplete. Resolving this knowledge gap is a fundamental step required for environmental and biodiversity management. In this study, we quantified the nature of the CS food web through the development of conceptual, qualitative, and quantitative ecosystem models that provided a baseline understanding of key ecosystem processes, drivers, and pressures in the region for 2020-2022. These models enhance our capacity to identify and manage environmental cumulative impacts from current and planned future developments in this system.

The project relied on two-way communication with other researchers, management agencies and interest groups in CS. Three workshops were developed to facilitate the communication to identify key elements of qualitative models including pressures and important influences of change in CS and to provide understanding for developing the Ecopath model. The integral and cooperative participation of direct stakeholders from Westport, WAMSI, DPIRD, DBCA, and DWER in the building of our ecosystem models played a vital role in linking social, economic, and ecological factors in relation to understanding potential ecosystem change. Important knowledge gaps of unknown responses in the models were highlighted during the final project workshop (March 15, 2023) (See Appendix 13 for details). The closing discussion of the third workshop emphasized the importance in future of (i) integrating new WAMSI data into a revised Ecopath model, (ii) reconstructing past states of the CS ecosystem and (iii) developing temporal and spatial scenarios of the whole system to assess the impacts of dredging, habitat alteration (e.g. artificial habitats), and cumulative stressors. The value of linking the top-down quantitative food-web model (Ecopath) with the bottom-up water quality model being developed in WWMSP Project 1.2 (led by Associate Professor Matt Hipsey) was also identified in Workshop 3. This connection of the models would provide a better understanding of the estimates for primary production, detritus and zooplankton in the system and the uncertainties associated with management trade-offs for different management options. This information is relevant to CS managers, but not easily obtained by food-web models or water quality models in isolation. This linked approach could reduce uncertainties in model predictions and support better-informed decisions for an ecosystem-based management of the region.

The models developed in this study integrate the information and data available in CS and they provide a summary of our current knowledge of the biomass, consumption, production, and trophic flows in the region. The quantitative, Ecopath, ecosystem model highlighted the complexity of CS's ecology, showing the role of higher and lower trophic groups in this food web, including keystone species. This is particularly important because understanding the processes and interactions within the system can support plans for conservation and management.

Some of the more novel conclusions of our qualitative modelling work relate to fished species. Overall, the qualitative models for pink snapper, blue swimmer crabs and scaly mackerel behaved similarly to one another. Results from these models showed strong negative reactions of adults and many life stages to an increase in port activities such as dredging and shipping traffic. Increased "management" of these activities in general, was predicted to have a positive effect on the fished species and conservation significance groups in CS by all qualitative models. In the PS infrastructure model, management was split into water management and fisheries management, and both management nodes were predicted to positively impact PS spawners and pre-spawners. These results highlight the vital role of management agencies and the need for coordination and cooperation among agencies and the industry to implement management strategies focused on both the marine environment and the food webs they support.

4.1. Implications for key stakeholders

In this study, the cooperative participation of direct stakeholders from Westport, WAMSI, DPIRD, and DBCA in the building of our conceptual, qualitative, and quantitative ecosystem models played a vital role in linking social, economic, and ecological factors in relation to understanding potential ecosystem change. Overall, the conceptual and qualitative models developed in this study display current knowledge of the five species selected (PS, BSC, SM, little penguin, and seagrass), which can be considered important tools for communication with stakeholders helping in the understanding of how CS would respond to current and future pressures. They also provided a very effective communication pathway and mechanism for encouraging two-way knowledge transfer among diverse groups of people.

The quantitative Ecopath ecosystem modelling of this study provided a framework for identifying key research questions, pressures, and keystone species in CS and assigning priorities for ecosystem approaches to management. Results from this study also provided a useful suite of ecosystem-level performance indicators for CS for the period of 2020-2022. These indicators could be used to investigate how the system may respond to future ecological perturbations and infrastructure development.

4.2. Recommendations

1. Revise the Ecopath model to incorporate data currently being gathered by other projects of the WWMSP, and the latest recreational fishing data from DPIRD.
2. Develop conceptual and qualitative models for components of the CS system that were seen as important during the current project or that are identified as priorities from current WWMSP projects e.g. blue sprat, zooplankton, detritus and detritivory. These serve as important communication and knowledge transfer mechanisms on the functioning of CS to diverse groups of people.
3. Develop a temporal-dynamic ecosystem model (Ecosim) using the structure and outputs of Ecopath model presented in this study. The Ecosim model will have the capacity to run scenarios, developed with CS stakeholders, to explore changes in CS associated with climate change and dredging. This research was not an objective of the current study.
4. Develop scenarios to be evaluated for the system in consultation with stakeholders.
5. Develop a spatial dynamic ecosystem model (Ecospace) for CS to better assess the importance of seagrasses and other habitat-forming groups (i.e. sponges, corals, and macroalgae) for the CS food web. This model would also allow the spatial footprint of the proposed new port to be assessed with greater certainty. .
6. During the final project workshop, it was suggested that a reconstruction of past states of CS (i.e. periods 1970s, 1990s, and 2010s) would be very valuable, along with developing temporal and spatial scenarios of the whole system, to assess the historical impacts of dredging and cumulative impacts of development on the Sound. Furthermore, the development of past states

of CS, using Ecopath with Ecosim, would provide the basis for hindcasting the present-day conditions of the model. The development of dynamic scenarios for evaluation in Ecosim was not part of the current study.

7. Link the top-down quantitative food-web model (Ecopath) with the bottom-up water quality model under construction in WWMSP Project 1.2 (Matt Hipsey) for a better understanding of the performance of both models and management trade-offs associated with management strategies.
8. Develop a compiled version of the software that allows a diverse range of users to run different scenarios of change in the CS ecosystem. This would serve to enhance understanding of potential future states of CS in response to different pressures.

4.3. Further development

Uncertainty around model parameters is one of the major limitations in the predictions made by the Ecopath model. The sensitivity analysis and mass-balancing of the model indicated that the CS model was sensitive to changes in the biomass of benthic invertebrates (i.e. Western King Prawn, Bivalves, Black Mussels, Urchins, Holothurians, octopus, and other crabs). Hence, information of the biology and abundance of these species should be targeted for further research and incorporated in a revised CS Ecopath model.

4.4. Communication

The results from the Conceptual, Qualitative and Quantitative (Ecopath) models of CS were presented in the Australian Society of Fish Biology Conference 2022 (Surfers Paradise, QLD) on 9-10 November, 2022. Feedback from these presentations were used to revise the models. This modelling work was also presented at a public seminar at DPIRD (Hillarys, Western Australia) on 22 June of 2022 and all stages of the model development have been presented during the three project workshops which were run face-to-face and on-line, with about 40 participants in each workshop.

4.5. Project materials developed

Two scientific papers from this study (one from qualitative seagrass modelling, and another from the Ecopath quantitative modelling) are planned to be submitted to Aquatic Conservation: Marine and Freshwater, and Marine Ecology Journal. These papers will potentially include as co-authors other scientists from the WWMSP e.g. DPIRD (Danielle Johnston, Daniel Yeoh, Gary Jackson), UWA (Gary Kendrick), ECU (Kathryn McMahon), and CSIRO (Jeff Dambacher and Beth Fulton).

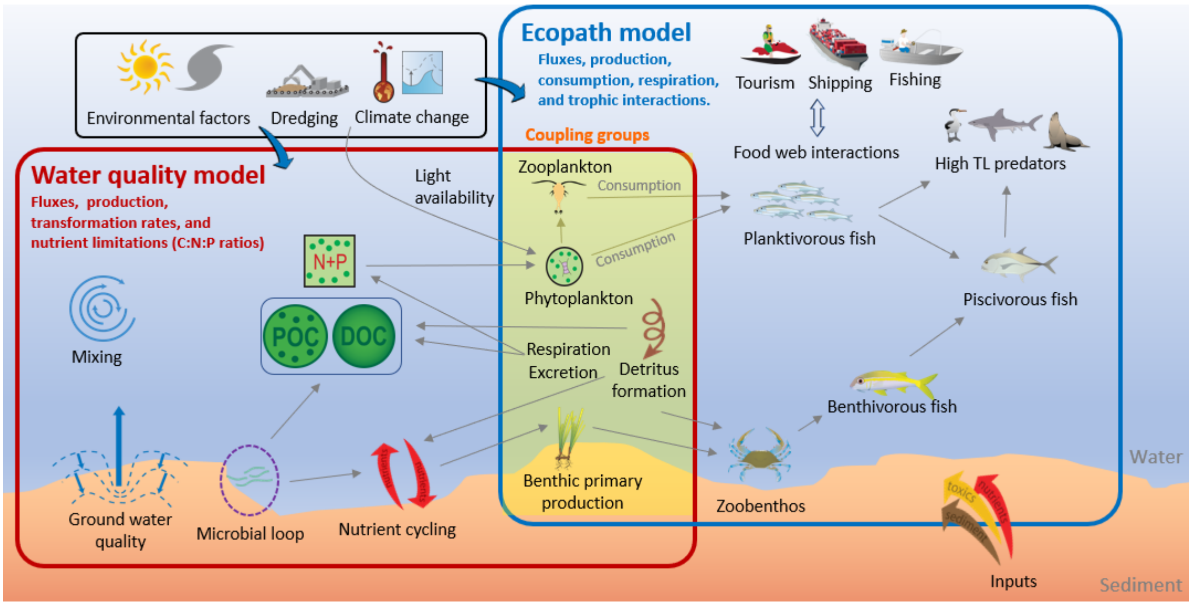


Figure 4.1. Conceptual framework of the coupling between biogeochemistry (water quality model) and food web (Ecopath model) interactions through fluxes, transformation rates, detritus formation and ecosystem metabolism (yellow shade).

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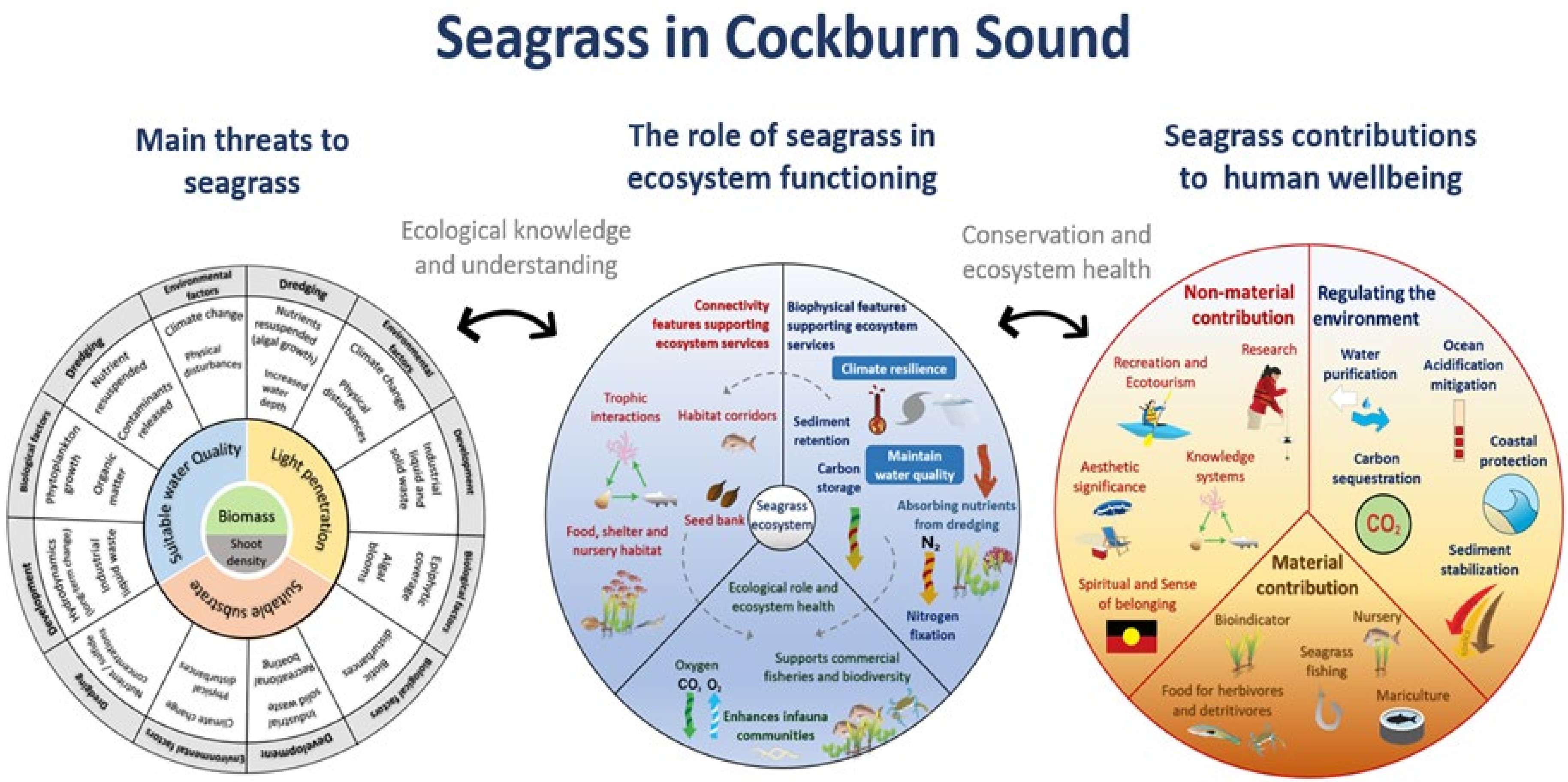
Appendices

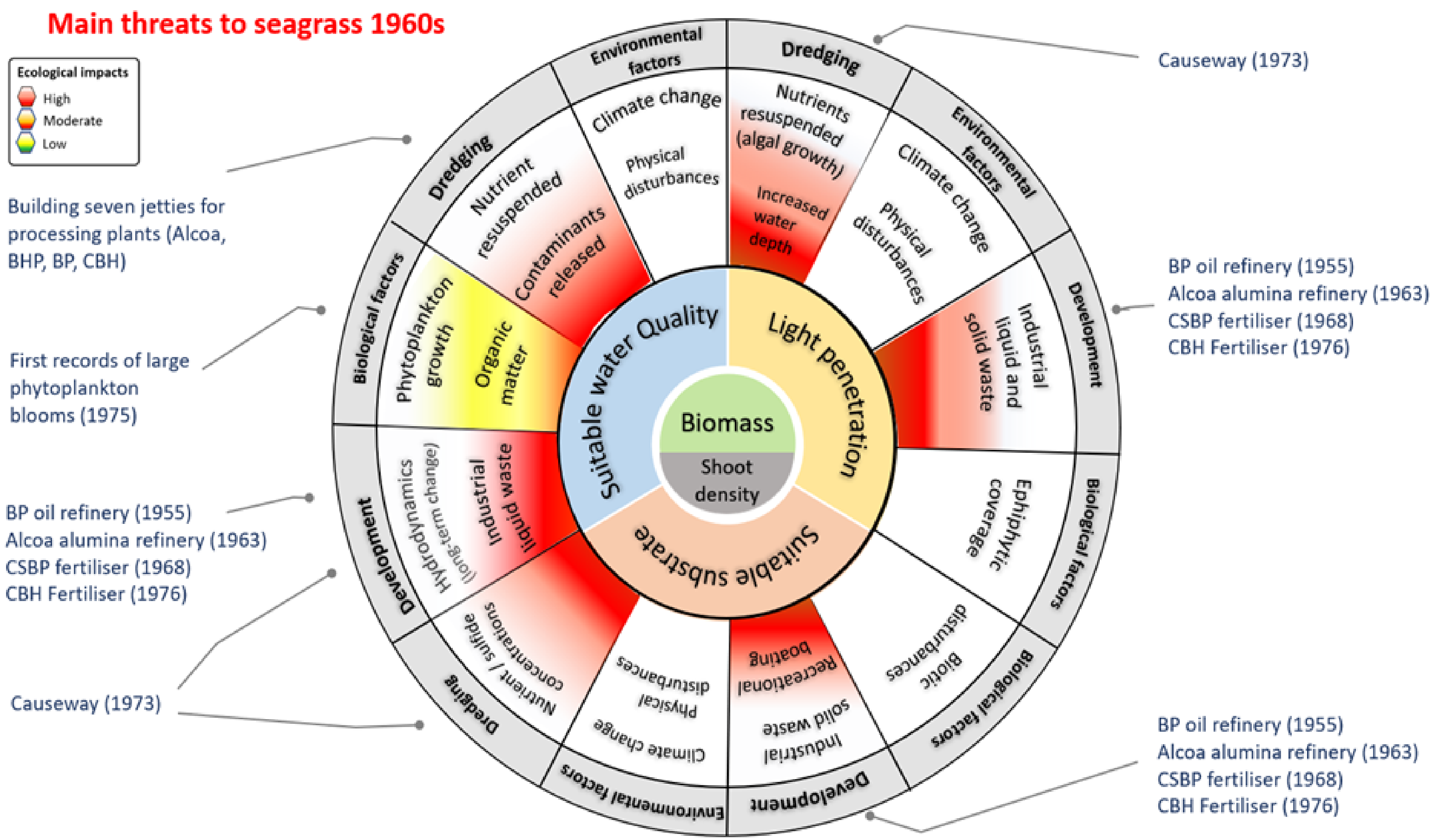
Appendix 1. Conceptual models

1. **Historical development of conceptual models for seagrass** (e.g. *Posidonia sinuosa*)

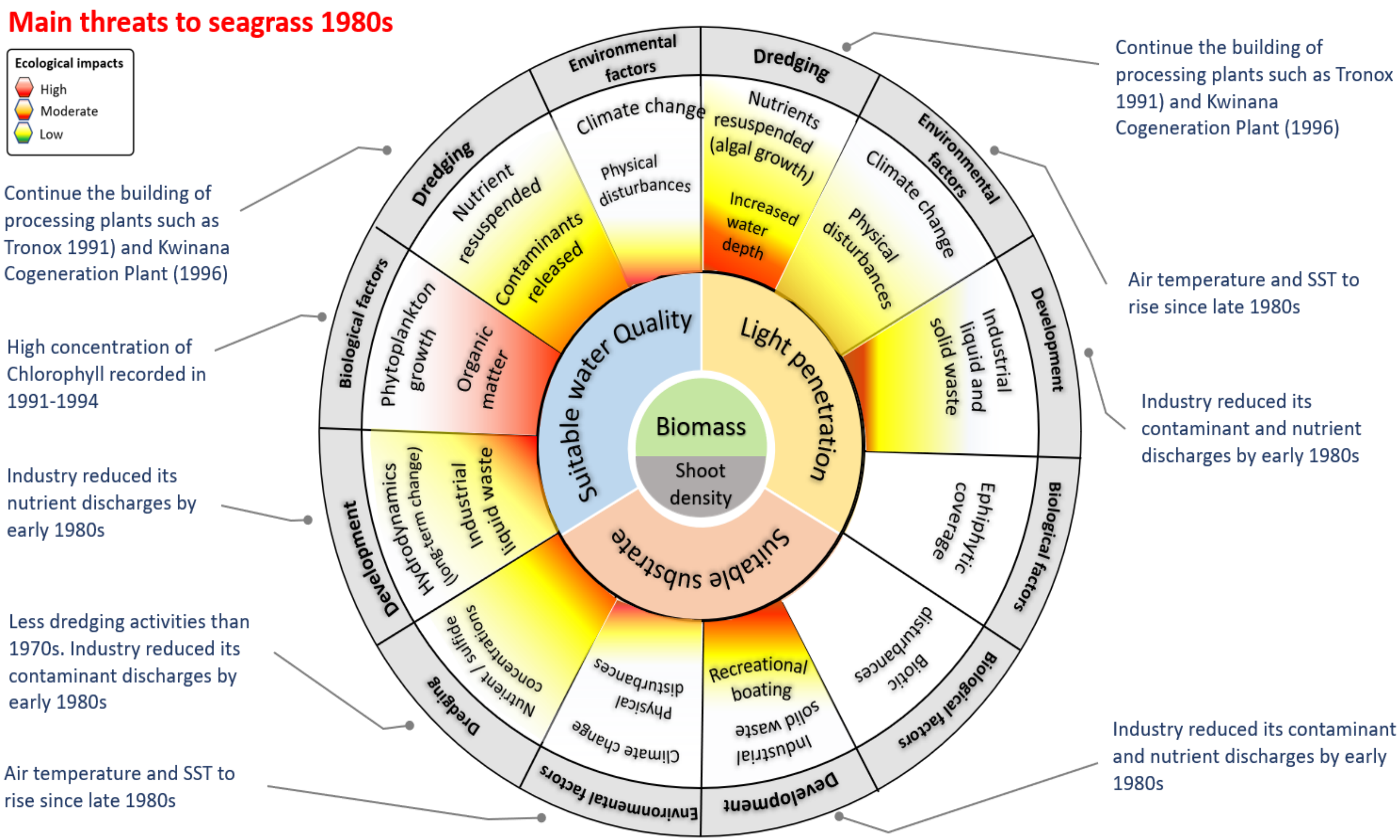
Seagrasses form important benthic habitats in CS, supporting rich fauna communities and biodiversity while providing important ecosystem services. Up to 80% of seagrasses were lost in CS as a result of poor water quality between the 1960s and 1980s. Since then, water quality conditions have improved considerably, yet seagrass decline has continued in some areas within CS and in neighbouring Warnbro Sound (Fraser *et al.*, 2015). The preliminary conceptual model developed for seagrass for current conditions (Conceptual model 1) includes the main drivers, and stressors and core ecosystem components and interrelationships discussed during the first workshop of the project (May 2022). A series of historical conceptual models for seagrass representative of 1960s (Conceptual model 2), 1980s (Conceptual model 3) and 2020s (Conceptual model 8) were developed to gain understanding in the environmental (e.g. water quality, light penetration, climate change) and anthropogenic stressors (e.g. dredging, port development) that could contribute to continued decline of seagrass in CS. These preliminary conceptual models are used as initial development of impacts for those stressors that were determined (workshop # 1) to be the most important in seagrass dynamics, and to guide the use of further numerical models (Ecopath) to develop quantitative ecosystem models (Ecopath).Seagrass conceptual models were presented during workshop #2 and feedback received allowed us to develop a qualitative seagrass model that was presented during workshop #3 (15 March 2023).



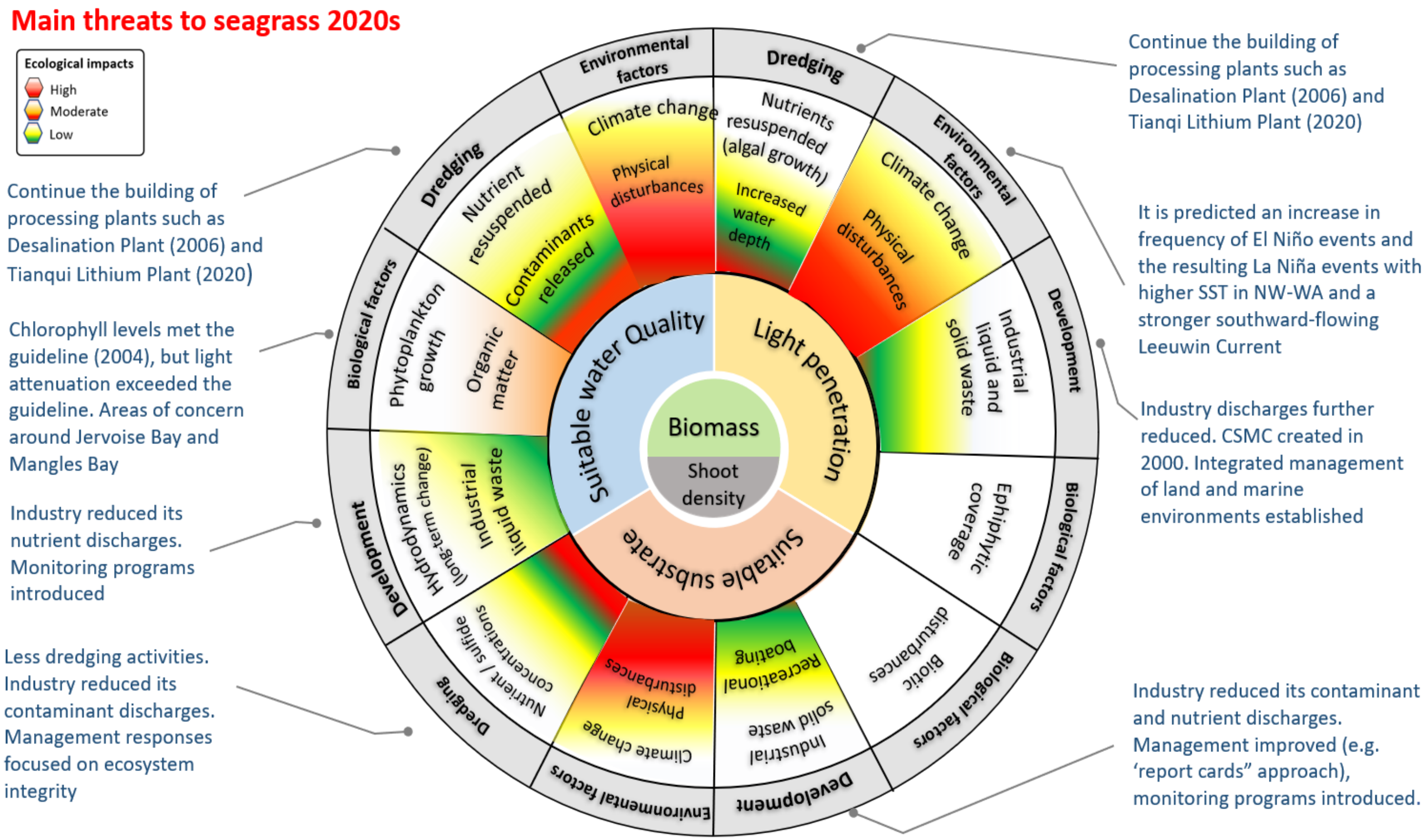
Conceptual model 1. Model for seagrass representing the relationships among stressors, ecosystem functioning and ecosystem services in CS.



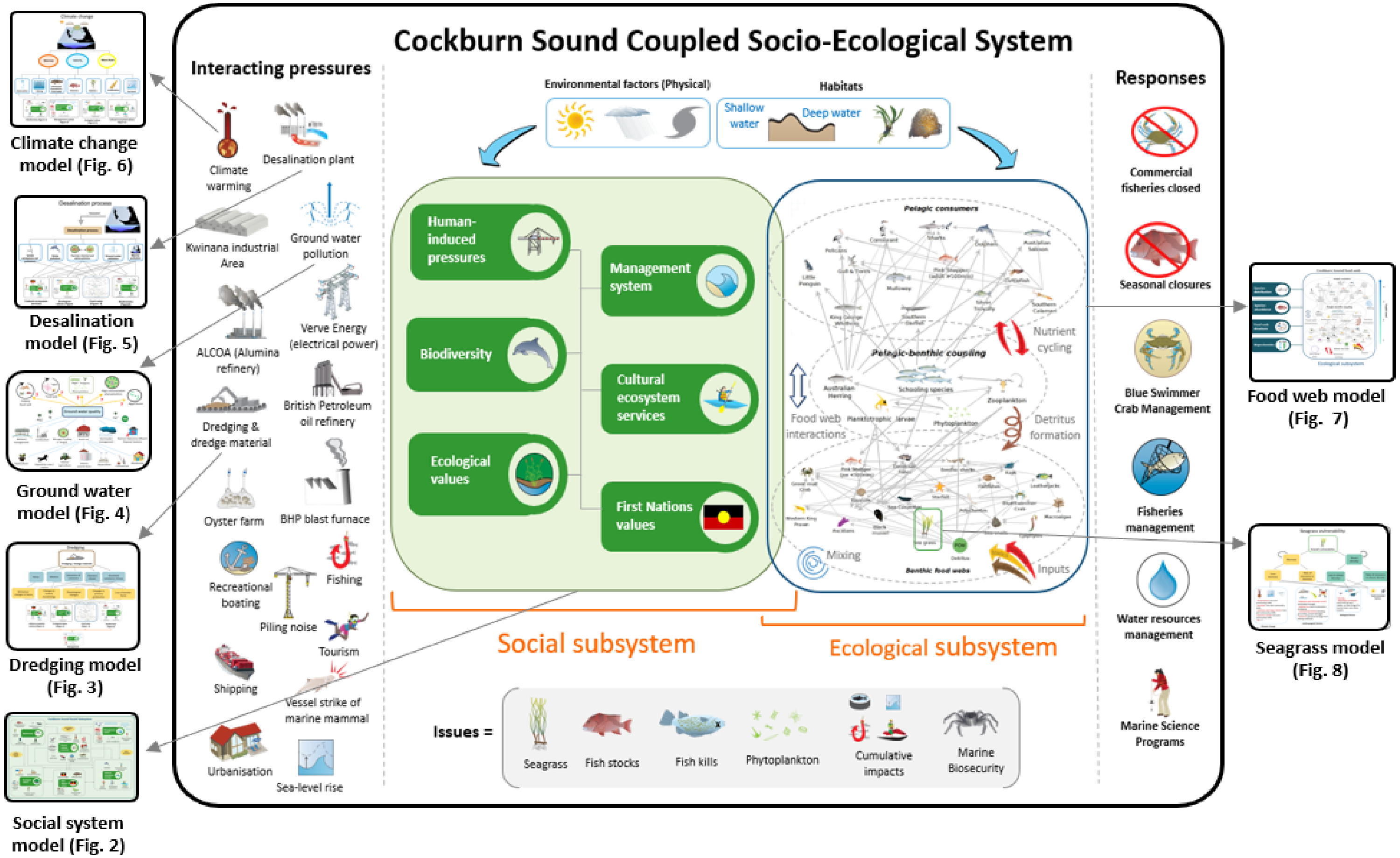
Conceptual model 2. Model for seagrass representing the environmental conditions and human activities from 1960 to 1980 in CS



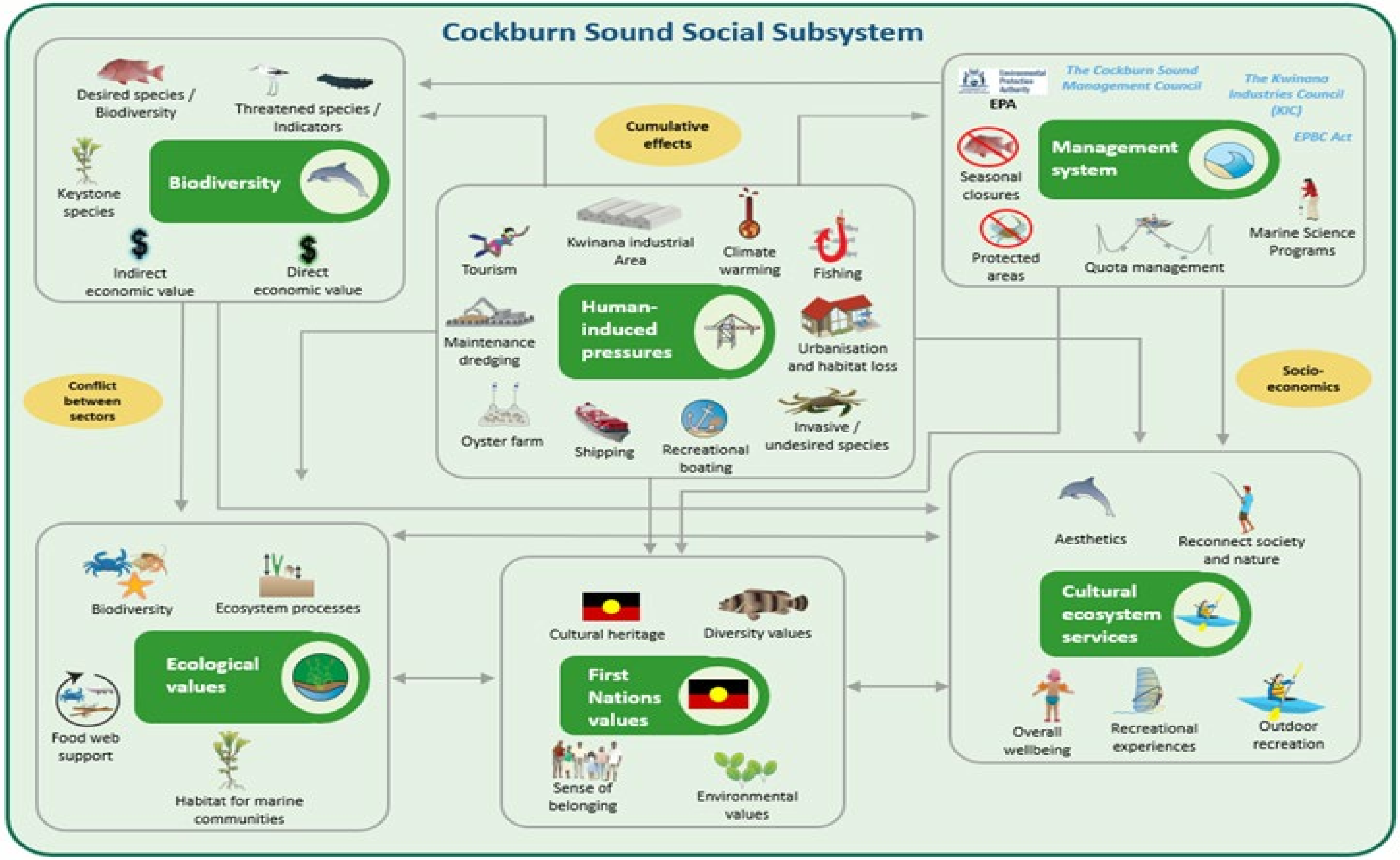
Conceptual model 3. Model for seagrass representing the environmental conditions and human activities from 1980 to 2000 in CS



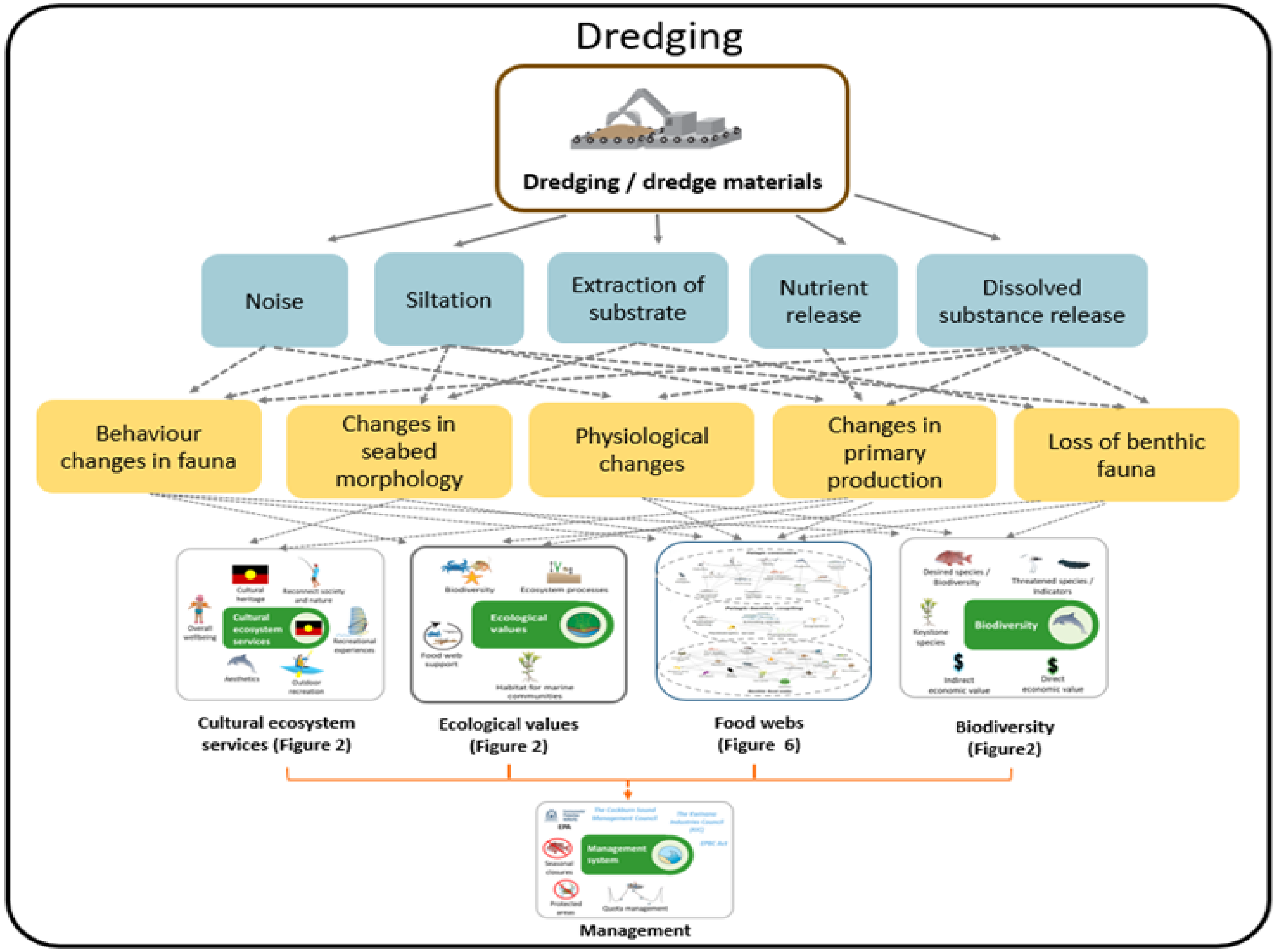
Conceptual model 4. Model for seagrass representing the environmental conditions and human activities from 2000 to 2020 in CS.



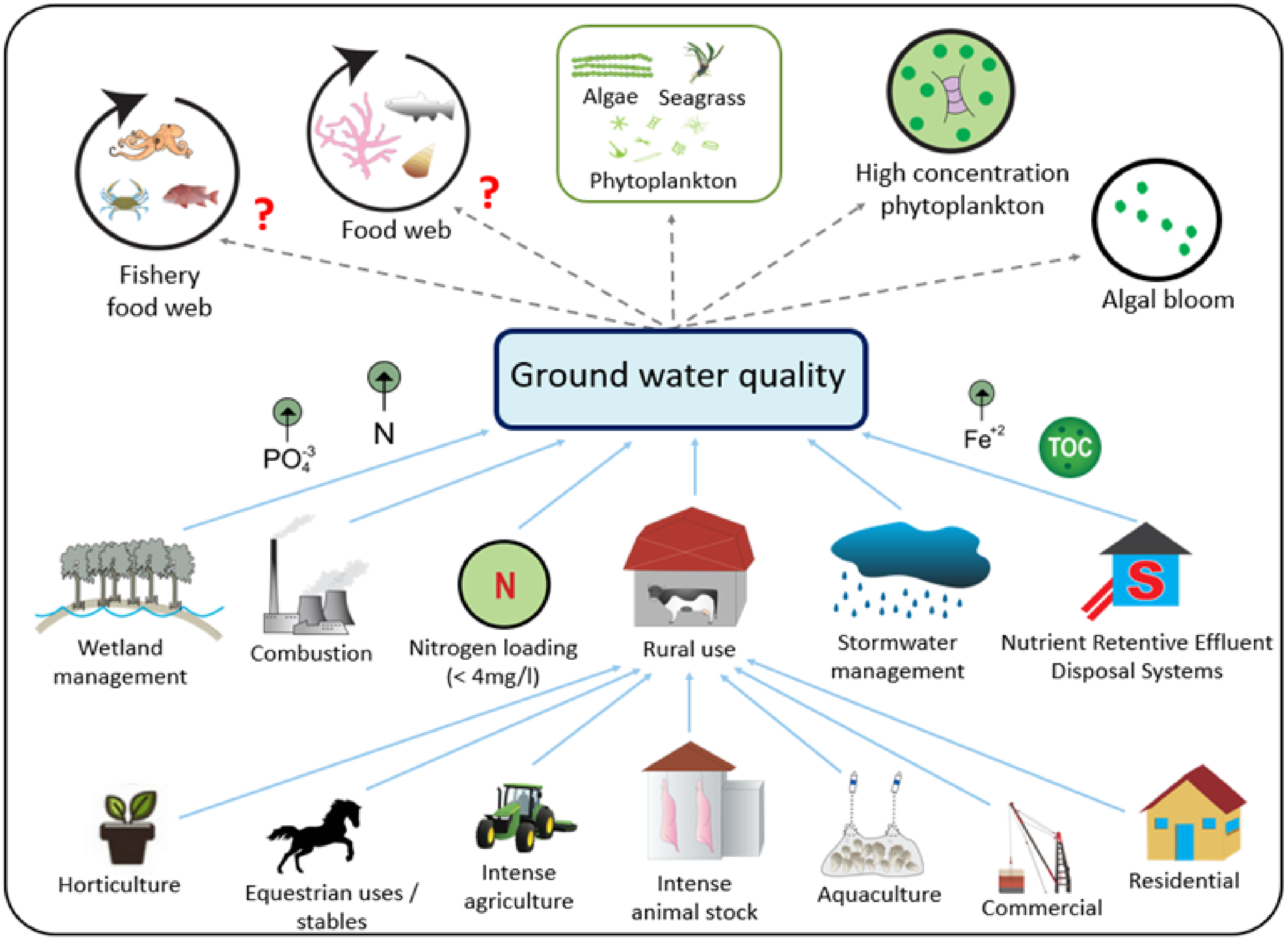
Conceptual model 5. Model of the functioning of the CS system, including main interacting pressures, environment, habitats, main species, ecological issues, and management responses.



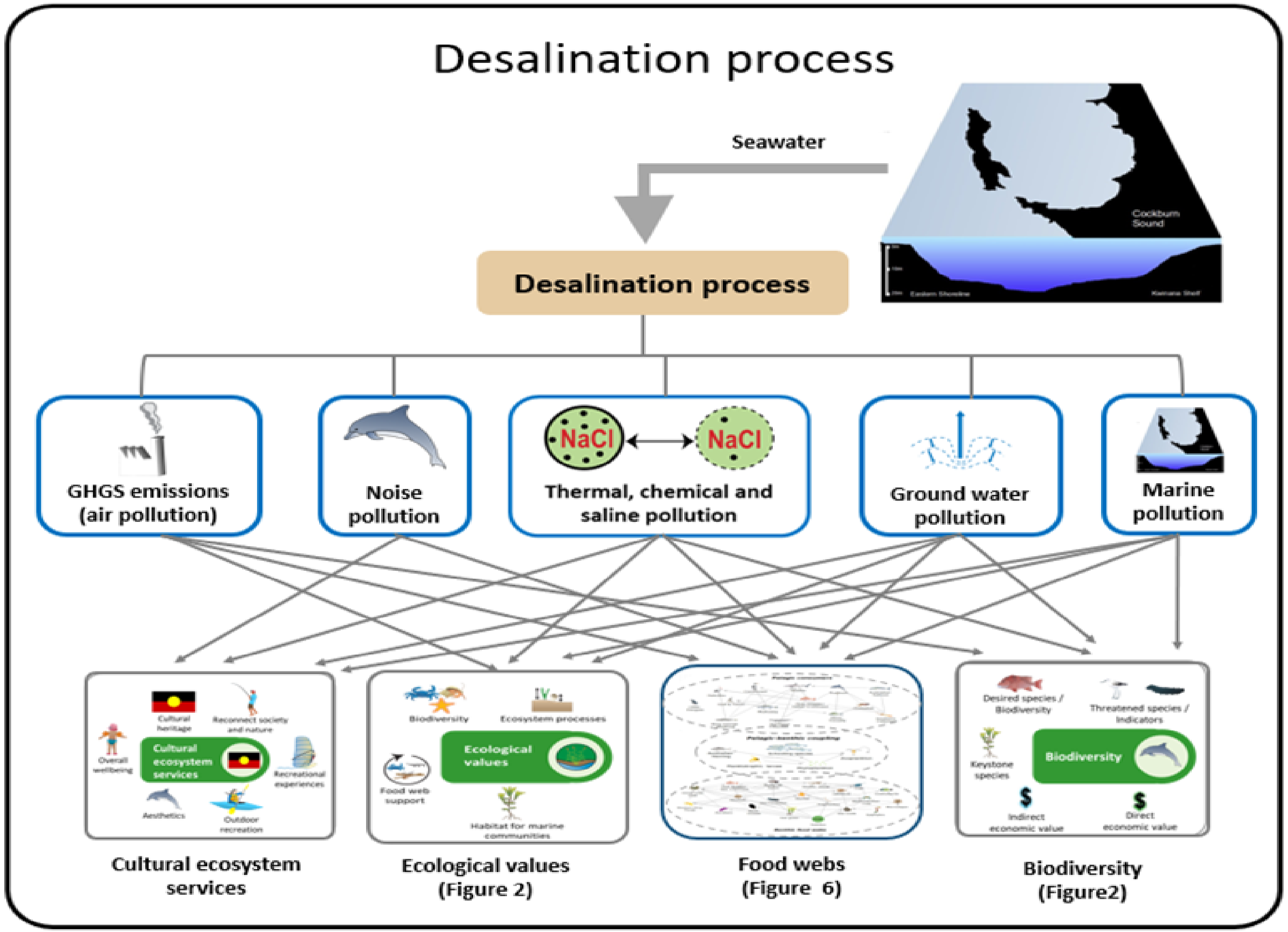
Conceptual model 6. Model of the social subsystem of CS including anthropogenic pressures, ecological, social, and cultural values, and management systems.



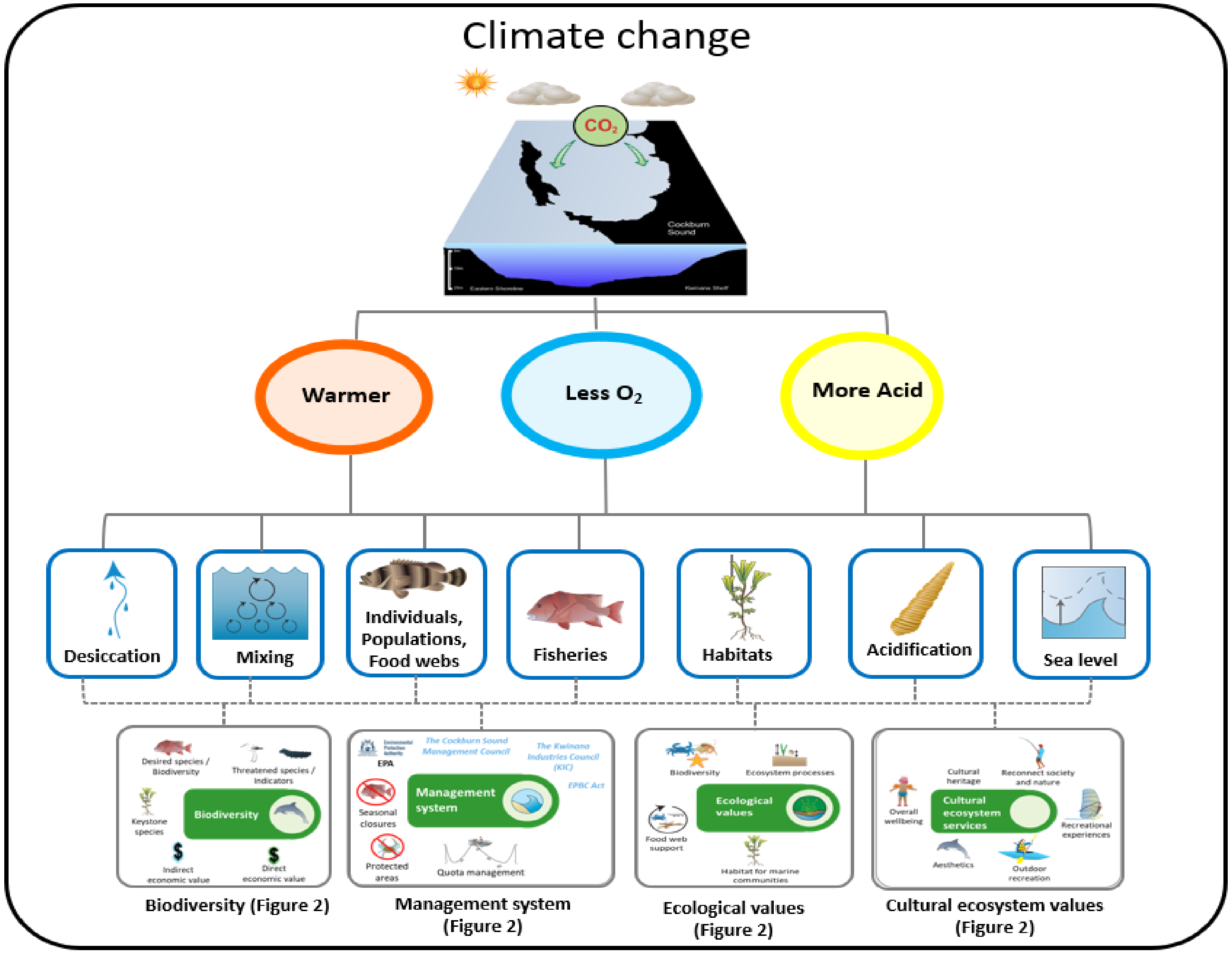
Conceptual model 7. Model for dredging activities and dredge material in CS



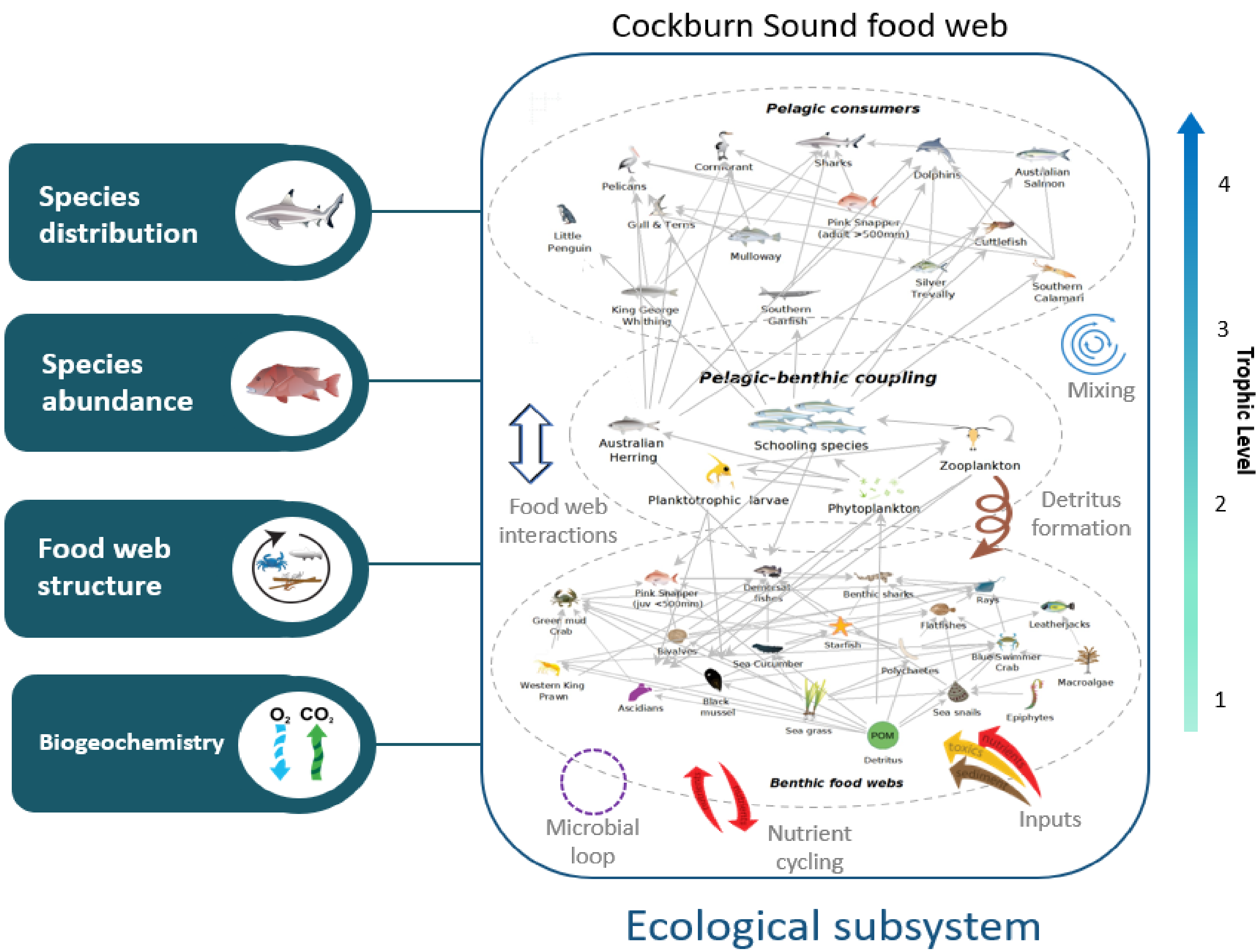
Conceptual model 8. Model for the effects of ground water quality on CS



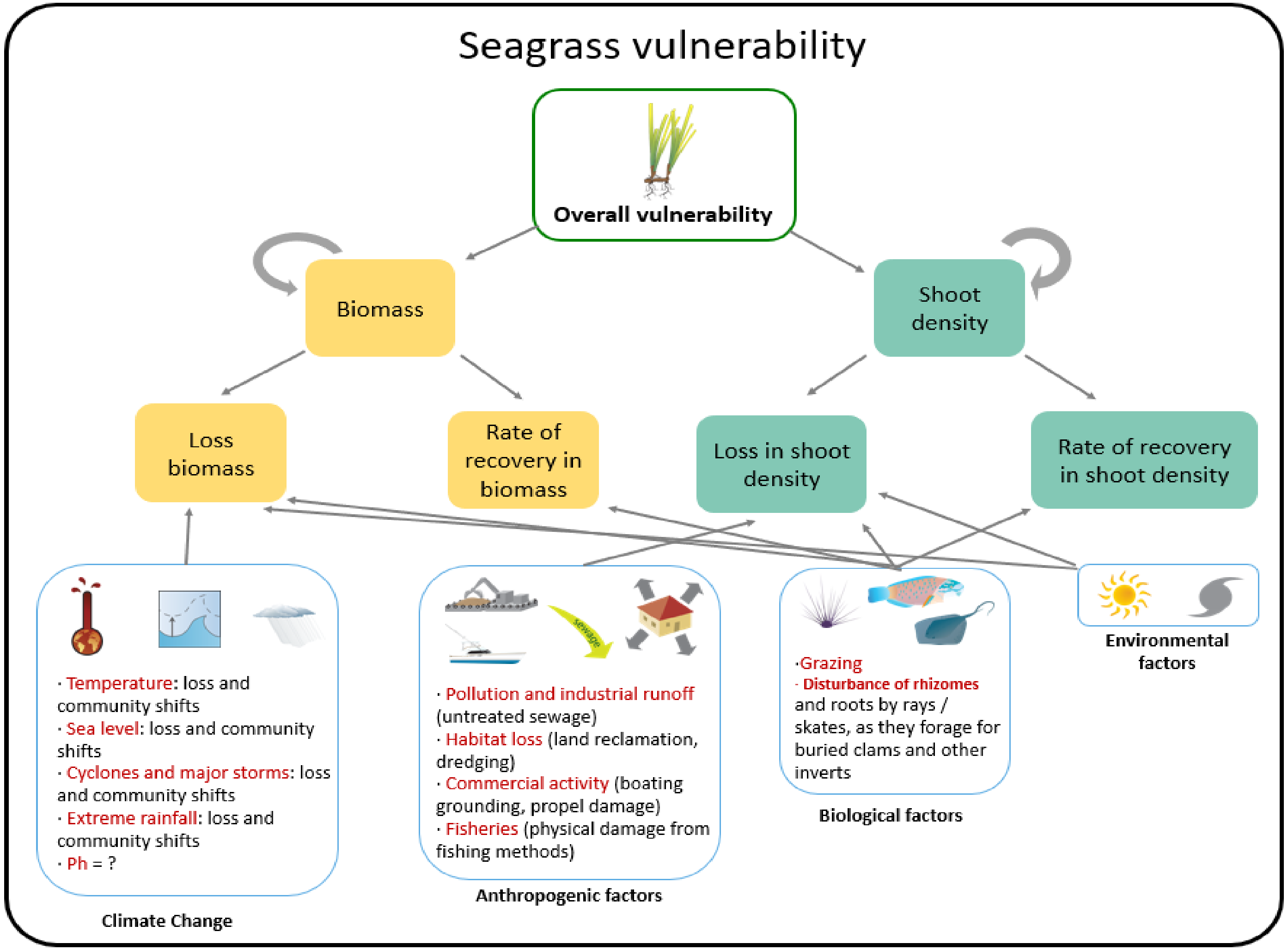
Conceptual model 9. Model of the effects of desalination on the social and ecological systems on CS.



Conceptual model 10. Model of Climate change effects on the social and ecological systems of CS.



Conceptual model 11. Model of CS food web



Conceptual model 12. Model of the seagrass vulnerability in CS

Appendix 2. Qualitative Modelling

1. **Blue Swimmer Crab (BSC)**.

The stability of the community matrix (**Table 2.3**) for BSC life cycle was examined using the Hurwitz criterion I and ii (C≥1). The negative sign of all coefficients (Fn) of the adjoint matrix suggest a very stable model. Also, the value of C was 7.2 x 10^5, which indicates that the model is stable (see Dambacher *et al*. 2002).

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -10, -47, -135, -260, -348, -325, -207, -85, -20, -2]$$

$$positive\_feedback = [\ 0\ \ 0\ \ 0\ \ 1\ \ 7\ \ 22\ \ 40\ \ 45\ \ 31\ \ 12\ \ 2\ ]$$

$$negative\_feedback = [\ -1\ \ -10\ \ -47\ \ -136\ \ -267\ \ -370\ \ -365\ \ -252\ \ -116\ \ -32\ \ -4\ ]$$

$$absolute\_feedback = [\ 1\ \ 10\ \ 47\ \ 137\ \ 274\ \ 392\ \ 405\ \ 297\ \ 147\ \ 44\ \ 6\ ]$$

$$wFn = [\ -1.\ \ -1.\ \ -1.\ \ -0.99\ \ -0.95\ \ -0.89\ \ -0.80\ \ -0.70\ \ -0.58\ \ -0.45\ \ -0.33\ ]$$

"Criterion ii"

$$wD_9 = 7.8 \times 10^{-6}$$

$$ratio\_to\_model\_C = 720000.$$

"Class I Model"

Matrix of Probability of correct sign used to evaluate the certainty of the predictions derived from the adjoint matrix [-A]

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.68	1.0
1.0	0.79	1.0	1.0	0.91	1.0	0.91	0.91	0.72	0.94
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.60	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.63	1.0
1.0	1.0	1.0	1.0	0.79	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	0.50	0.92
1.0	1.0	1.0	1.0	1.0	1.0	0.79	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.79	0.77	0.77
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	0.77
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	0.77

2. **Scaly Mackerel (SM)**

Stability criteria (Dambacher *et al.*, 2002) of the SM biology community matrix

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -8, -28, -56, -70, -55, -25, -5, 0]$$

$$positive\_feedback = [\ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1\ \ 3\ \ 3\ \ 1\ ]$$

$$negative\_feedback = [\ -1\ \ -8\ \ -28\ \ -56\ \ -70\ \ -56\ \ -28\ \ -8\ \ -1\ ]$$

$$absolute\_feedback = [\ 1\ \ 8\ \ 28\ \ 56\ \ 70\ \ 57\ \ 31\ \ 11\ \ 2\ ]$$

$$wFn = [\ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -0.96\ \ -0.81\ \ -0.45\ \ 0.\ ]$$

"Criterion ii"

$$wD_7 = 0.0033$$

$$ratio\_to\_model\_C = 10000.$$

"Class I Model"

Probabilities of correct sign for the adjoint matrix of the SM biology model.

"Based on average proportion of correct sign"

$$\begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 0.50 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 \end{bmatrix}$$

Stability criteria (Dambacher *et al.*, 2002) of the Climate change SM model:

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -11, -55, -165, -330, -461, -456, -315, -145, -40, -5, 0]$$

$$positive\_feedback = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 6 & 15 & 20 & 15 & 6 & 1 \end{bmatrix}$$

$$negative\_feedback = \begin{bmatrix} -1 & -11 & -55 & -165 & -330 & -462 & -462 & -330 & -165 & -55 & -11 & -1 \end{bmatrix}$$

$$absolute\_feedback = \begin{bmatrix} 1 & 11 & 55 & 165 & 330 & 463 & 468 & 345 & 185 & 70 & 17 & 2 \end{bmatrix}$$

$$wFn = \begin{bmatrix} -1. & -1. & -1. & -1. & -1. & -1.0 & -0.97 & -0.91 & -0.78 & -0.57 & -0.29 & 0. \end{bmatrix}$$

"Criterion ii"

$$wD_{10} = 3.0 \times 10^{-6}$$

$$ratio\_to\_model\_C = 1.4 \times 10^{8}$$

"Class I Model"

Probabilities of correct sign for the adjoint matrix of the Climate Change SM model

"Based on average proportion of correct sign"

$$\begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 1.0 & 1.0 & 1.0 & 0.50 & 0.50 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 0.50 & 1.0 & 1.0 & 0.50 & 0.50 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 1.0 & 0.50 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 & 0.50 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 0.50 \end{bmatrix}$$

3. Pink Snapper

Stability criteria (Dambacher *et al.*, 2002) of PS biology community matrix

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -9, -36, -84, -126, -125, -80, -30, -5, 0]$$

$$positive\_feedback = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 4 & 6 & 4 & 1 \end{bmatrix}$$

$$negative\_feedback = \begin{bmatrix} -1 & -9 & -36 & -84 & -126 & -126 & -84 & -36 & -9 & -1 \end{bmatrix}$$

$$absolute\_feedback = \begin{bmatrix} 1 & 9 & 36 & 84 & 126 & 127 & 88 & 42 & 13 & 2 \end{bmatrix}$$

$$wFn = \begin{bmatrix} -1. & -1. & -1. & -1. & -1. & -0.98 & -0.91 & -0.71 & -0.38 & 0. \end{bmatrix}$$

"Criterion ii"

$$wD_{8} = 0.00043$$

$$ratio\_to\_model\_C = 180000.$$

"Class I Model"

Probabilities of correct sign for the adjoint matrix of PS biology model.

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	0.50
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50

Stability criteria (Dambacher *et al.*, 2002) of PS infrastructure development model derived from community matrix.

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -13, -78, -286, -715, -1286, -1708, -1688, -1231, -645, -230, -50, -5, 0]$$

$$positive\_feedback = [\ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1\ \ 8\ \ 28\ \ 56\ \ 70\ \ 56\ \ 28\ \ 8\ \ 1\ ]$$

$$negative\_feedback = [\ -1\ \ -13\ \ -78\ \ -286\ \ -715\ \ -1287\ \ -1716\ \ -1716\ \ -1287\ \ -715\ \ -286\ \ -78\ \ -13\ \ -1\ ]$$

$$absolute\_feedback = [\ 1\ \ 13\ \ 78\ \ 286\ \ 715\ \ 1288\ \ 1724\ \ 1744\ \ 1343\ \ 785\ \ 342\ \ 106\ \ 21\ \ 2\ ]$$

$$wFn = [\ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.0\ \ -0.99\ \ -0.97\ \ -0.92\ \ -0.82\ \ -0.67\ \ -0.47\ \ -0.24\ \ 0.\ ]$$

"Criterion ii"

$$wD_{12} = 6.3 \times 10^{-9}$$

$$ratio\_to\_model\_C = 5.5 \times 10^{11}$$

"Class I Model"

Probabilities of correct sign for the adjoint matrix of PS infrastructure development model.

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	1.0	0.50	0.50	1.0	0.50
1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	0.50	1.0	0.50
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	0.50
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	0.50
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50

4. Seagrass

Stability criteria (Dambacher *et al.*, 2002) of seagrass biology community matrix

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -10, -45, -119, -202, -225, -160, -65, -9, 3, 1]$$

$$positive\_feedback = [\ 0 \ \ 0 \ \ 0 \ \ 1 \ \ 8 \ \ 27 \ \ 50 \ \ 55 \ \ 36 \ \ 13 \ \ 2\ ]$$

$$negative\_feedback = [\ -1 \ \ -10 \ \ -45 \ \ -120 \ \ -210 \ \ -252 \ \ -210 \ \ -120 \ \ -45 \ \ -10 \ \ -1\ ]$$

$$absolute\_feedback = [\ 1 \ \ 10 \ \ 45 \ \ 121 \ \ 218 \ \ 279 \ \ 260 \ \ 175 \ \ 81 \ \ 23 \ \ 3\ ]$$

$$wFn = [\ -1. \ \ -1. \ \ -1. \ \ -0.98 \ \ -0.93 \ \ -0.81 \ \ -0.62 \ \ -0.37 \ \ -0.11 \ \ 0.13 \ \ 0.33\ ]$$

"Criterion ii"

$$wD_9 = 2.9 \times 10^{-6}$$

$$ratio\_to\_model\_C = 270000.$$

"Class I Model"

Probabilities of correct sign for the adjoint matrix of biology seagrass model.

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	0.50	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	0.50	0.50	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	0.50	0.50	0.50	1.0	1.0	0.77	0.77	1.0	1.0
1.0	1.0	1.0	1.0	0.50	1.0	0.77	0.77	1.0	1.0
1.0	1.0	1.0	1.0	0.50	0.50	0.77	0.77	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77

Stability criteria (Dambacher *et al.*, 2002) of seagrass Infrastructure Development seagrass model

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -15, -105, -454, -1352, -2926, -4730, -5775, -5313, -3619, -1749, -540, -70, 16, 8, 1]$$

$$positive\_feedback = [\ 0 \ \ 0 \ \ 0 \ \ 1 \ \ 13 \ \ 77 \ \ 275 \ \ 660 \ \ 1122 \ \ 1386 \ \ 1254 \ \ 825 \ \ 385 \ \ 121 \ \ 23 \ \ 2\ ]$$

$$negative\_feedback = [\ -1 \ \ -15 \ \ -105 \ \ -455 \ \ -1365 \ \ -3003 \ \ -5005 \ \ -6435 \ \ -6435 \ \ -5005 \ \ -3003 \ \ -1365 \ \ -455 \ \ -105 \ \ -15 \ \ -1\ ]$$

$$absolute\_feedback = [\ 1 \ \ 15 \ \ 105 \ \ 456 \ \ 1378 \ \ 3080 \ \ 5280 \ \ 7095 \ \ 7557 \ \ 6391 \ \ 4257 \ \ 2190 \ \ 840 \ \ 226 \ \ 38 \ \ 3\ ]$$

$$wFn = [\ -1. \ \ -1. \ \ -1. \ \ -1.0 \ \ -0.98 \ \ -0.95 \ \ -0.90 \ \ -0.81 \ \ -0.70 \ \ -0.57 \ \ -0.41 \ \ -0.25 \ \ -0.083 \ \ 0.071 \ \ 0.21 \ \ 0.33\ ]$$

"Criterion ii"

$$wD_{14} = 5.0 \times 10^{-14}$$

$$ratio\_to\_model\_C = 1.2 \times 10^{14}$$

"Class I Model"

Probabilities of correct sign for the adjoint matrix of infrastructure development seagrass model.

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	0.50	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	0.50	0.50	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	0.50	0.50	0.50	1.0	1.0	0.77	0.77	1.0	1.0	1.0	1.0	1.0	1.0	0.94
1.0	1.0	1.0	1.0	0.50	1.0	0.77	0.77	1.0	1.0	0.79	0.77	0.77	0.79	0.79
1.0	1.0	1.0	1.0	0.50	0.50	0.77	0.77	1.0	1.0	0.79	0.77	0.77	0.79	0.79
1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	1.0	0.77	0.77
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	0.77	1.0	0.77	0.77
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0	0.77	0.77	0.77
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	0.77
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77

Little penguin

Model A: Prey availability

Community matrix [A]

"Qualitatively Specified Community Matrix (°A)"

$A :=$

−1	1	1	−1	0	0	0	0	0	1
1	−1	0	0	0	0	0	0	−1	0
0	0	−1	−1	0	0	−1	−1	−1	0
0	0	0	−1	0	0	0	0	0	0
0	0	0	0	−1	0	0	0	0	−1
0	0	0	0	0	−1	1	0	0	−1
0	0	0	0	0	0	−1	0	0	−1
0	0	0	1	0	0	0	−1	0	0
0	0	0	0	0	0	0	0	−1	0
0	0	0	0	0	0	0	0	0	−1

Adjoint matrix [-A]

"adjoint (-A)"

1	1	1	−3	0	0	−1	−1	−2	2
1	1	1	−3	0	0	−1	−1	−2	2
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Stability analysis

"Criterion i"

$poly\_coef\_F0\_to\_Fn = [-1, -10, -44, -112, -182, -196, -140, -64, -17, -2, 0]$

$positive\_feedback = [\ 0\ \ 0\ \ 1\ \ 8\ \ 28\ \ 56\ \ 70\ \ 56\ \ 28\ \ 8\ \ 1\ ]$

$negative\_feedback = [\ -1\ \ -10\ \ -45\ \ -120\ \ -210\ \ -252\ \ -210\ \ -120\ \ -45\ \ -10\ \ -1\ ]$

$absolute\_feedback = [\ 1\ \ 10\ \ 46\ \ 128\ \ 238\ \ 308\ \ 280\ \ 176\ \ 73\ \ 18\ \ 2\ ]$

$wFn = [\ -1.\ \ -1.\ \ -0.96\ \ -0.88\ \ -0.76\ \ -0.64\ \ -0.50\ \ -0.36\ \ -0.23\ \ -0.11\ \ 0.\ ]$

"Criterion ii"

$wD_9 = 9.4 \times 10^{-7}$

$ratio\_to\_model\_C = 88000.$

"Class I Model"

Probabilities of correct sign

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	0.50	0.50	1.0	1.0	0.50	0.50	0.50	0.50
1.0	1.0	1.0	0.50	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	0.50	1.0	1.0	1.0	1.0	0.50
1.0	1.0	1.0	1.0	1.0	0.50	0.50	1.0	1.0	0.50
1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	0.50
1.0	1.0	1.0	0.50	1.0	1.0	1.0	0.50	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50

Model B: Chick survival

Community matrix [A]

Adjoint matrix [-A]

"Qualitatively Specified Community Matrix (°A)"

$A :=$

−1	1	0	−1	0	0	0	0	0	1
0	−1	0	0	0	0	0	0	−1	0
0	0	−1	−1	0	0	0	−1	−1	0
0	0	0	−1	0	0	0	0	0	0
0	0	0	0	−1	0	0	0	0	−1
0	0	0	0	0	−1	1	0	0	−1
0	0	0	0	0	0	−1	0	0	−1
0	0	0	1	0	0	0	−1	−1	0
0	0	0	0	0	0	0	0	−1	0
0	0	0	0	0	0	0	0	0	−1

"adjoint (-A)"

1	1	0	−1	0	0	0	0	−1	1
0	1	0	0	0	0	0	0	−1	0
0	0	1	−2	0	0	0	−1	0	0
0	0	0	1	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	−1
0	0	0	0	0	1	1	0	0	−2
0	0	0	0	0	0	1	0	0	−1
0	0	0	1	0	0	0	1	−1	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Stability analysis

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -10, -45, -120, -210, -252, -210, -120, -45, -10, -1]$$

$$positive\_feedback = [\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ ]$$

$$negative\_feedback = [\ -1\ \ -10\ \ -45\ \ -120\ \ -210\ \ -252\ \ -210\ \ -120\ \ -45\ \ -10\ \ -1\ ]$$

$$absolute\_feedback = [\ 1\ \ 10\ \ 45\ \ 120\ \ 210\ \ 252\ \ 210\ \ 120\ \ 45\ \ 10\ \ 1\ ]$$

$$wFn = [\ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ ]$$

"Criterion ii"

$$wD_9 = 0.000086$$

$$ratio\_to\_model\_C = 8.0 \times 10^{6}$$

"Class I Model"

Probabilities of correct sign

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Model C: Boat strikes

Community matrix [A]

"Qualitatively Specified Community Matrix (°A)"

$A :=$

−1	1	1	−1	−1	0	0	0	0	1
1	−1	0	0	0	0	0	0	−1	0
0	0	−1	−1	0	0	0	−1	0	0
0	0	0	−1	0	0	0	0	0	0
0	0	0	0	−1	0	0	0	0	−1
0	0	0	0	0	−1	1	0	0	−1
0	0	0	0	0	0	−1	0	0	−1
0	0	0	1	0	0	0	−1	−1	0
0	0	0	0	0	0	0	0	−1	0
0	0	0	0	0	0	0	0	0	−1

Adjoint matrix [-A]

"adjoint (-A)"

1	1	1	−3	−1	0	0	−1	0	2
1	1	1	−3	−1	0	0	−1	0	2
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Stability analysis

"Criterion i"

$$poly\_coef\_F0\_to\_Fn = [-1, -10, -44, -112, -182, -196, -140, -64, -17, -2, 0]$$

$$positive\_feedback = [\ 0\ \ 0\ \ 1\ \ 8\ \ 28\ \ 56\ \ 70\ \ 56\ \ 28\ \ 8\ \ 1\ ]$$

$$negative\_feedback = [\ -1\ \ -10\ \ -45\ \ -120\ \ -210\ \ -252\ \ -210\ \ -120\ \ -45\ \ -10\ \ -1\ ]$$

$$absolute\_feedback = [\ 1\ \ 10\ \ 46\ \ 128\ \ 238\ \ 308\ \ 280\ \ 176\ \ 73\ \ 18\ \ 2\ ]$$

$$wFn = [\ -1.\ \ -1.\ \ -0.96\ \ -0.88\ \ -0.76\ \ -0.64\ \ -0.50\ \ -0.36\ \ -0.23\ \ -0.11\ \ 0.\ ]$$

"Criterion ii"

$$wD_9 = 9.4 \times 10^{-7}$$

$$ratio\_to\_model\_C = 88000.$$

"Class I Model"

Probabilities of correct sign

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	0.50	0.50	1.0	1.0	1.0	0.50	0.50	1.0
1.0	1.0	1.0	0.50	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	0.50	1.0	1.0	1.0	1.0	0.50
1.0	1.0	1.0	1.0	1.0	0.50	0.50	1.0	1.0	0.50
1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0	1.0	0.50
1.0	1.0	1.0	0.50	1.0	1.0	1.0	0.50	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50

Model D: Port activities increased

Community matrix [A]

"Qualitatively Specified Community Matrix (°A)"

$A :=$

−1	1	1	−1	0	0	−1	0	0	1
1	−1	0	0	0	0	0	0	−1	0
0	0	−1	−1	0	0	−1	−1	−1	0
0	0	0	−1	0	0	0	0	0	0
0	0	0	0	−1	0	0	0	0	−1
0	0	0	0	0	−1	1	0	0	−1
0	0	0	0	0	0	−1	0	0	−1
0	0	0	1	0	0	0	−1	−1	0
0	0	0	0	0	0	0	0	−1	0
0	0	0	0	0	0	0	0	0	−1

Adjoint matrix [-A]

"adjoint (-A)"

1	1	1	−3	0	0	−1	−1	−1	2
1	1	1	−3	0	0	−1	−1	−1	2
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Stability analysis

"Criterion i"

$poly\_coef\_F0\_to\_Fn = [-1, -10, -45, -120, -210, -252, -210, -120, -45, -10, -1]$

$positive\_feedback = [\,0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\,]$

$negative\_feedback = [\,-1\ \ -10\ \ -45\ \ -120\ \ -210\ \ -252\ \ -210\ \ -120\ \ -45\ \ -10\ \ -1\,]$

$absolute\_feedback = [\,1\ \ 10\ \ 45\ \ 120\ \ 210\ \ 252\ \ 210\ \ 120\ \ 45\ \ 10\ \ 1\,]$

$wFn = [\,-1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\ \ -1.\,]$

"Criterion ii"

$wD_9 = 0.000086$

$ratio\_to\_model\_C = 8.0 \times 10^6$

"Class I Model"

Probabilities of correct sign

"Based on average proportion of correct sign"

1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.77	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.50	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Appendix 3. Functional groups of the Ecopath model

Category	#	Ecological group	Representative taxa	Rationale
High commercial fishing species	1	Pink Snapper >560mm	*Chrysophrys auratus*	Commercial and Recreational fishing
	2	Blue Swimmer Crab	*Portunus armatus*	Commercial / conservation interest
	3	Scaly Mackerel	*Sardinella lemuru*	Commercial fishing
	4	Australian Herring	*Arripis georgianus*	Commercial / Recreational fishing
	5	Pilchard	*Sardinops neopilchardus*	Commecial fishing / baitfish
	6	Southern Garfish	*Hyporhamphus melanochir*	Commercial and Recreational fishing
	7	Squids (Southern Calamari, southern bobtail calamari)	Southern calamari squid (*Sepioteuthis australis*), Southern Bobtail squid (*Euprymna tasmanica*)	Commercial and Recreational fishing
	8	Butterfishes	*Western Butterfish (Pentapodus vitta),* other butterfishes *(Pampus* spp, *Peprilus* spp, *Stromateus* spp)	Commercial and recreational fishing
	9	Trevallies	*Pseudocaranx georgianus*	Commercial /Recreational fishing interest
	10	King George Whiting	*Sillaginodes punctata*	Commercial /Recreational fishing interest
	11	Yellowtail Scad	*Trachurus novaezelandiae*	Commercial fishing
	12	Western Australian Common Octopus	*Octopus djilba*	Commercial fishing
	13	Black mussel	*Mytilus* spp	Aquaculture
High recreational fishing species	14	Wrasses	western king wrasse *Coris auricularis* and brownspotted wrasse *Notolabrus parilus*	Recreational fishing interest
	15	Whiting species (non King George species)	Whiting *(Sillago spp)*	Recreational fishing interest
	16	Flounders and flatheads	Southern bluespotted flathead (*Pseudorhobus speculator*), rock flathead (*P. laevigatus*) and yellowtail flathead (*P. westraliae*) Smalltooth Flounder (*P. jenynsii*), Lefteye Flounder (*Arnoglosus* spp),	Recreational fishing interest
	17	Mulloway	*Argyrosomus japonicus*	Conservation / Recreational fishing interest
	18	Western Australia Butterfish	*Pentapodus vitta*	Recreational fishing interest
	19	Western King Prawn	*Penaeus latisulcatus*	Recreational fishing interest
	20	Other crabs	Swimmer (*Portunus rugosus*), Four-lobed swimmer (*Thalamitas sima*)-	Recreational fishing interest
High conservation species	21	Large sharks	*White (Carcharodon carcharias), Smooth Hammerhead shark (Shyrna zygaena), Tiger shark (Galeocerdo cuvier), Spinner shark (Carcharhinus brevipinna)*	Conservation interest
	22	Small sharks	*Port Jackson shark (Heterodontus portusjacksoni), Gummy shark (Mustelus antarticus), Wobbegong shark (Orectolobus maculatus)*	Conservation interest
	23	Shark juveniles	Port Jackson *(Heterodontus portusjacksoni),* Spinner *(Carcharhinus brevipinna)*	Conservation interest
	24	Bottlenose dolphin	*Tursiops aduncus*	Conservation interest
	25	Australian Pelican	*Pelecanus conspicillatus*	Conservation interest
	26	Gulls and Terns	Bridled Tern (*Onychoprion anaethetus*), Fairy Tern (*Sternula nereis*), Caspian Tern (*Hydroprogne caspia*), Crested Tern (*Thalasseus bergii*), Pacific Gull (*Larus pacificus*)	Conservation interest
	27	Migratory waders	Sanderling (*Calidris alba*), Grey plover (*Pluvialis squatarola*), Ruddy turnstone (*Arenaria interpres*), bar-tailed godwit (*Limosa lapponica*), Grey-tailed Tattler (*Tringa brevipes*)	Conservation interest

Appendix 3. Continuation.

	28	Pink Snapper pre-spawner (250-560mm)	*Chrysophrys auratus*	Conservation interest
	29	PInk Snapper coastal juvenile (60-250mm)	*Chrysophrys auratus*	Conservation interest
	30	Pipefishes	*Smooth Pipefish (Lissocampus caudalis), Western Crested Pipefish (Mitotichthys meraculus)*	Aggregate group
	31	Seahorses	Shorthead Seahorse *(Hippocampus breviceps)*	Conservation / Indicator species
	32	Sponges	*Tedania sp, Ciocalypta sp, Holopsamma sp, Leucosolenida sp, Tethya cf. Ingalli*	Conservation / Indicator species
	33	Australian Sea Lion	*Neophoca cinerea*	Conservation interest
Category	34	**Ecological group**	**Representative taxa**	**Rationale**
Sentinel Species (biological indicators)	35	Sea cucumbers	*Cercodema anceps, Colochirus quadrangularis*	Conservation / Indicator species
	36	Corals	Faviidae family	Conservation / primary production
	37	Little penguin	*Eudyptula minor*	Conservation interest
	38	Cormorants	Pied Cormorant (*Phalacrocorax varius*), Little Pied Cormorant (*Microcarbo melanoleucos*), Little Black Cormorant (*Phalacrocorax sulcirostris*)	Conservation interest
	39	Rays	Souther Eagle Ray (*Myliobatis australis*), Southern Fiddler Ray (*Trygonorrhia fasciata*), Sparseley-spotted syingaree (Urulophus paucimaculatus) and Rhinobatidae spp	Aggregate group
	40	Ascidians (sea squirts) and sea pens	Ascidian spp colonial *(Herdmania sp)*, Ascidian spp solitary (*Herdmania spp*), Sea Pen (*Cavernularia* spp)	Aggregate group
	41	Infaunal polychaetes	*Sabella spallanzanii*	Aggregate group
	42	Introduced species	Dead's man fingers *(Codium fragile subsp. Fragile), The* carpet sea squirt *(Didemnum vexillum)*	introduced species with potential to become invasive
	43	Rabbitfish	*Siganus sp*	Tropicalization of herbivore communities
	44	Phytoplankton	Chain-forming diatoms (e.g. Chaetoceros, Leptocylindrus), other diatoms (e.g. Nitzschia, Cylindrotheca, Rhizosolenia); dinoflagellates (e.g. Gymnodinioids)	Primary production
	45	Stripped barracuda	*Sphyraena obtusata*	Aggregate group
	46	Western Stripped Grunter	*Helotes octolineatus*	Aggregate group
	47	Small pelagics	, Blue Mackerel *(Scomber australasicus)*, Common Jack Mackerel *(Trachurus symmetricus)*	Aggregate group / baitfish
	48	Schooling species	Common Hardyhead (Atherinomorus vaigiensis), Australian anchovy (*Engraulis australis*),	Aggregate group
	49	Weedfish	Aedelaide weedfish *(Heteroclinus adelaidae)*, weed-whiting *(Siphonognathus attenuatus)*, *Southern Crested Weedfish (Cristiceps australis)*	Aggregate group
	50	Common Silverbelly	*Paraquula melbournensis*	Aggregate group
	51	Soldier	*Gymnapisters marmoratus*	Aggregate group

Appendix 3. Continuation.

Other fishes	52	Western Dragonet	*Pseudocalliurichthys goodladi*	Aggregate group
	53	Mullets	Yelloweye Mullet *(Aldrichetta forsteri),* Sea Mullet *(Mugil cephalus)*	Aggregate group
	54	Demersal fish	Bass Groper *(* Polyprion americanus), Western Foxfish *(Bodianus frenchii*); Western Blue Groper (*Achoerodus gouldii*), Little Gurnard Perch (*Maxillicosta scabriceps*)	Aggregate group / Minor recreational fishing interest
	55	Leatherjackets and boxfishes	Bridled leatherjack (Acanthaluters spilomelanurus), Rough leatherjack (Scobinichthys granulatus), Fanbelly Leatherjack (Monocanthus chinensis), Yellowstriped Leatherjacket (*Meuschenia flaviolineata*), Western Smooth Boxfish (*Anoplocapros amygdaloides*)	Aggregate group
	56	Sandy Sprat (White bait)	Hyperlophus vittatus	Aggregate group / baitfish
	57	Spiny Gurnard	*Lepidotrigla papilio*	Conservation / Aggregate group
	58	Goatfishes	*Australian Goatfih (Upeneus australiae), Blue sport Goatfish*	Aggregate group
Other invertebrates	59	Bivalves	*Musculista glaberrima, Dosinia incisas, Anomia trigonopsis, Circe sulcate,*	Aggregate group
	60	Cuttlefish	Bragg's (*Sepia braggi*), *Sepia novaehollandie*	Aggregate group
	61	Seastars	Seastar (*Astropecten preissi*), Seastar (*Stellaster inspinosus*), Seastar (*Ludia australiae*), Brittlestar (*Macrophiothrix spongicola*)	Aggregate group
	62	Mantis shrimp	*Belosquilla laevis*	Aggregate group
	63	Other prawns (velvet prawns)	Metapenaeopsis fusca, M. lindae, M. spp	Aggregate group
	64	Urchins	*Temnopleurus michaelseni*	Aggregate group
	65	Bryozoans	phylum bryozoa	
	66	Sea snails	*Astralium tentorium, Bedeva paive, Bulla botanica, Pervicacia sp, Vermetid sp.*	Aggregate group
Nekton	67	Zooplankton	Mainly calanoid copepods	Secondary production
	68	Planktotrophic larvae	Larval stages if fish and invertebrates	Secondary production
Primary producers	69	Seagrass	*Posidonia australis, P. sinuosa*	Conservation / Primary production
	70	Microphytobenthos	microscopic algae on the sediments	Primary production
	71	Macroalgal Epiphytes	Mainly crustose coralline algae and filamentous species of Rhodophyta on seagrass	Conservation / Primary production
	72	Macroalage	*Ecklonia radiatea*	Primary production
Non-living	73	Detritus	Particulate (POM) and Dissolved (DOM) organic matter produced by the decomposition of organisms	Energy cycling

Appendix 4. Growth and mortality estimates

Functional Group	Species	L∞ (cm)	W∞ (g)	K ($year^{-1}$)	t_0 (years)	M $year^{-1}$ (Jensen, 1996)	M $year^{-1}$ (Palomares, 1998) at 20°C	F $year^{-1}$	Food type	Aspect Ratio	Q/B ($year^{-1}$) at 20°C
Large sharks	*Carcharodon carcharias* Great white shark	676	$2.07x10^6$	0.07	-1.07	0.081	0.09		4	1.6	1.2
	Sphyrna zygaena Smooth Hammerhead	525	$3.9x10^5$	0.07	-1.02	0.083	0.1		4	1.6	1.5
	Galeocerdo cuvier Tiger shark	575	$1.05x10^6$	0.09	-0.87	0.18	0.13		4	1.6	1.7
	Carcharhinus brevipinna Spinner shark	265	$1.29x10^5$	0.21	-0.45	0.289	0.31		4	1.6	2.9
Small sharks	*Heterodontus portusjacksoni* Port Jackson shark	173	$4.3x10^4$	0.06	-1.83	0.102	0.11		4	1.6	2.3
	Mustelus antarticus Gummy shark	202	$4.49x10^4$	0.12	-0.85	0.147	0.16		4	1.6	2.8
	Orectolobus maculatus Wobbegong shark	335	$9.66x10^4$	0.08	-1.13	0.089	0.1		4	1.6	3.1
Shark juveniles	*Heterodontus portusjacksoni* Port Jackson shark	60	760	1.39	-0.09	1.16	1.32		4	1.6	4.2
Rays and Shovelheads	*Myliobatis australis* Souther Eagle Ray	123.1	4.5x104	0.2	-0.48	0.29	0.31		4	1.6	2.8
	Trygonorrhia fasciata Southern Fiddler Ray	123.1	1.8x104	0.14	-0.83	0.203	0.23		4	1.6	5.9
	Urulophus paucimaculatus Sparseley-spotted syingaree	60	784	0.23	-0.6	0.291	0.33		4	1.6	6.4
Pink Snapper *Chrysophrys auratus*	Pink Snapper spawners (>560mm)	136.8	4.1x104	0.04	-2.96	0.082	0.09		3	1.32	2.7
	Pink Snapper pre-spawner (250-560mm)	56		0.26	-0.56	0.39	0.47		3	1.32	4.5
	Pink Snapper coastal juvenile (60-250mm)	25		1.06	-0.16	1.39	1.58		3	1.32	6.7
Wrasses	*Coris sandeyeri* King Wrasse	26.3	181	0.32	-0.54	0.48	0.52		3	1.32	17.9
	Notolabrus parilus Brown Spotted Wrasses	41.5	$1.02x10^3$	0.15	-1.05	0.31	0.34		3	1.32	13
Skipjack Trevally	*Pseudocaranx wrighti*	72.4	$3.07x10^3$	0.44	-0.25	0.47	0.58		2	6.55	4.4
Flounders and flatheads	*Pseudorhobus jenynsii* Smalltooth Flounder	35.6	444	0.48	-0.32	0.76	0.82		3	1.32	6.8
	Arnoglosus spp Lefteye Flounder	18	41	0.56	-0.29	0.81	0.86		3	1.32	11
	Inegocia japonica Rusty Flathead	36.6	361	0.32	-0.49	0.52	0.6		3	1.32	7.1
	Onigocia spinosa Midget Flathead	26.3	107	0.44	-0.39	0.84	0.92		3	1.32	1.5
Demersal fishes	*Polyprion americanus* Bass Groper	215	$1.5x10^5$	0.03	-3.52	0.04	0.06		3	1.32	2.1
	Bodianus frenchii Western Foxfish	47.6	$1.6x10^3$	0.06	-2.6	0.11	0.15		3	1.32	11.6
	Achoerodus gouldii Western Blue Groper	182.6	$1.29x10^5$	0.02	-5.61	0.034	0.05		3	1.32	2.1
	Maxillicosta scabriceps Little Gurnard Perch	12.8	21	0.85	-0.2	1.11	1.28		3	1.32	12.6
Australian Salmon	*Arripis trutta*	91.5	$1.03x10^3$	0.15	-0.84	0.22	0.27		3	1.9	15.5
Mulloway	*Argyrosomus japonicus*	136	$7.5x10^4$	0.16	-0.7	0.21	0.26		3	1.32	2.8

Appendix 4. Continuation

Leatherjackets and Boxfishes	*Meuschenia flaviolineata* Yellowstriped Leatherjacket	31.5	312.6	0.34	-0.48	0.58	0.65	3	1.32	16
	Anoplocapros amygdaloides Western Smooth Boxfish	33.5	352	0.36	-0.37	0.56	0.65	3	1.32	16
Spiny Gurnard	*Lepidotrigla papilio*	21.1	93.9	0.53	-0.28	0.76	0.8	3	1.32	9.3
Longspine Dragonet	*Pseudocalliurichthys goodladi*	10.7	12.3	0.88	-0.2	1.13	1.38	3	1.32	31
Yellowtail Scad	*Trachurus novaezelandiae*	42	551	0.31	-0.49	0.44	0.47	3	1.9	4.7
Australian Goatfish	*Upeneus australiae*	16.9	86.1	0.57	-0.33	0.97	1.09	3	1.32	9.5
Scaly Mackerel	*Sardinella lemuru*	19.4	60	1.01	-0.18	1.82	1.99	3	1.9	22.4
Southern Garfish	*Hyporhamphus melanochir*	54	600	0.43	-0.24	0.83	0.9	3	1.9	17.9
Other Garfishes	three-by-two garfish *(Hemiramphus robustus), other garfish (* Hemiramphus *spp)*	31.5	359	0.66	-0.24	1.02	1.19	3	1.32	14.2
Pilchards	*Sardinops neopilchardus*	33.8	486	0.33	-0.49	0.73	0.78	3	1.9	26.6
Blue Sprat	*Spratelloides robustus*	12.8	21	0.57	-0.3	1.09	1.2	3	1.9	31
Maray	*Etrumeus jacksoniensis*	33	117	1.65	-0.1	1.97	2.13	3	1.9	20.2
Australian herring	*Arripis georgiana*	41	169	0.9	-0.19	0.69	0.72	3	1.9	20.3
Pikes	Longfin Pike (*Dinolestes lewini*), Snook (*Sphyraena novahollandiae*)	86.6	6495	0.17	-0.71	0.26	0.27	3	1.32	5
Sandy Sprat (White bait)	*Hyperlophus vittatus*	100	11.7	0.59	-0.3	0.92	0.97	3	1.9	16
Western Stripped Grunter	*Helotes octolineatus*	28	188	0.44	-0.39	0.79	0.83	3	1.32	17.4
Sea King Fish (juvenile)	*Seriola hippos*	80		0.94	-0.11	1.07	1.13	2	6.55	13.3
Whiting species (non King George species)	*Sillago* spp	21.5	250	0.26	-0.63	0.49	0.52	3	1.32	16.3
Weed-Whiting	*Siphonognathus attenuatus*	12.8	21	1.05	-0.19	1.64	1.85	3	1.32	26.3
Schooling species	*Engraulis australis* Australian anchovy	15	40	0.35	-0.38	0.87	0.91	3	1.32	24.4
	Atherinomorus vaigiensis Common Hardyhead	18	52	0.41	-0.39	0.77	0.81	3	1.32	10.2
Western Australia Butterfish	*Pentapodus vitta*	27.3	265	0.51	-0.33	0.71	0.86	2	1.9	16.6
Common Silverbelly	*Paraquula melbournensis*	23.2	124.9	0.66	-0.26	0.91	0.98	2	1.9	19.3
Soldier	*Gymnapisters marmoratus*	21.4	98	0.12	-1.58	0.28	0.33	2	1.32	9.2
Rabbitfish	*Siganus sp*	25	261	0.86	-0.2	1.52	1.66	2	1.32	38.7
Mullets	*Aldrichetta forsteri* Yelloweye Mullet	43	640	0.44	-0.34	0.69	0.73	3	1.9	23.9
Pipefishes	*Lissocampus caudalis* Smooth Pipefish	10.7	12.3	0.44	-0.41	0.77	0.82	3	1.32	31
	Mitotichthys meraculus Western Crested Pipefish	23.4	128	0.39	-0.38	0.71	0.78	3	1.32	19.2

Appendix 5. Diet matrix

	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Large sharks	0.0001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Barracudas	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Australian Sea Lion	0.01046	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Bottlenose Dolphin	0.00865	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Tailors	0.00111	0.005	0.009	0	0	0	0	0	0	0	0	0	0	0	0
6	Cormorants	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0
7	Squids	0	0	0.196	0.125	0.024	0.01	0	0	0	0	0.01	0	0	0.02	0
8	Australian Pelican	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0
9	Gulls and Terns	0.00011	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0
10	Little Penguin	0.00087	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Scaly Mackerel	0	0	0	0	0.005	9E-04	0.003	0	0	0.007	0	0	0	0	0
12	Small sharks	0.00322	5E-04	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Yellowtail Scad	0.09886	0.092	0.088	0	0	0.011	0	0	0	0	0	0	0	0	0
14	Cuttlefish	0	0	0.015	0.011	0.002	0	0	0	0	0	0	0	0	0	0
15	Trevallies	0.10912	0.143	0	0.025	0.001	0.021	0.033	0	0	0	0	0	0	0.041	0
16	Flounders	0	0	0	0	0	0	0	0	0	0	0	0.001	0	0	0
17	Pink Snapper adult	0.12863	0.01	0.088	0.037	0	0	0	0	0	0	0	0.001	0	0	0
18	Pink Snapper pre-spawner	0.12863	0	0.022	0.037	0	0	0	0	0	0	0	0	0	0	0
19	King George Whiting	0	0	5E-04	0.002	0	0.011	0.002	0.003	0.011	0.002	0	0	0	0	0
20	Whiting Species	0	0	0.106	0.091	0.009	0.107	0.164	0.052	0.023	0.044	0	0	0.033	0	0.038
21	Small pelagics	0	0.051	0	0	0.055	0.024	0	0.013	0	0	0	0	0	0	0
22	Western Australian Octopus	0	0	1E-04	0	0	0	0	0	0	0	0	0	0	0	0
23	Grunters	0	0	0	0	0	0	0	0	0	0	0	0	0	8E-04	0
24	Pipefishes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Gurnards	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Weedfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Soldiers	0	0	0	0	0	0	0	0	0	0	0	2E-04	0	0	0
28	PInk Snapper juvenile	0	0	1E-03	0.037	0	0	0	0	0	0	0	0	0	0	0
29	Other seabirds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Rays	0	0	0	0	0	0	0	0	0	0	0	0.084	0	0	0
31	Dragonets	0	0	0	0	0	0.003	0	0	0	0	0	0	0	0	0
32	Southern Garfish	0	0	0	0.001	0.001	0.003	0.007	0.007	0	0.01	0	0	0	0.007	0
33	Wrasses	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0
34	Butterfishes	0	0	0	0	0	0.003	0	0.003	0	0	0	0.007	0	0.046	0
35	Demersal fish	0	0.031	0.049	0.01	0	0	0.083	0	0	0	0	0.556	0	0.083	0
36	Common Silverbelly	0	0	0	0	0	7E-04	0.003	8E-04	0	0	0	0	0	0.003	0
37	Goatfishes	0	0	0	0	0	0	0.002	0	0	0	0	0	0	0.002	0
38	Blue Sprat	0	0	0.106	0.171	0.045	0.106	0.082	0.11	0.255	0.546	0.102	0	0.175	0	0.108
39	Sandy Sprat	0	0	0.06	0.136	0.027	0.106	0.082	0.11	0.227	0.364	0.102	0	0.175	0	0.087
40	Pilchard	0	0	0.033	0.063	0.012	0.052	0.049	0.113	0.114	0.027	0.102	0	0.146	0.041	0
41	Australian Herring	0	0	0.001	0.001	0.011	0.001	0	0.007	1E-04	0	0.032	0	0.013	0.007	0
42	Schooling species	0	0	0	0.001	9E-04	0.001	0.004	0.001	7E-04	0	0.001	0	4E-04	8E-04	0
43	Leatherjackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	Other crabs	0	0	0	7E-04	0	0.006	0	0	0	0	0	0	0.02	0	0
45	Blue Swimmer Crab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Mantis shrimp	0	0	0	0	0	0	0	0	0	0	0	0	0	0.002	0
47	Seastars	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.004
48	Migratory waders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	Seahorses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Mullets	0	0	0	6E-04	0.027	0.01	0.011	0.031	0	0	0	0	0	0.011	0
51	Rabbitfish	0	0	0	0	0	0.023	0	0.013	0	0	0	0.017	0	0	0
52	Introduced species	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	Western King Prawn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	Other prawns	0	0	0	0	0	0	0	0	0	0	0	0	0	0.004	0
55	Sea snails	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	Black Mussel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Corals	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	Ascidians	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.005
59	Sea Cucumbers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	Sand dollars	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.021
61	Sponges	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	Bivalves	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	Polychaetes	0	0	0	0	0	0	0	0	0	0	0	0	0	0.304	0.024
64	Bryozoans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Urchins	0	0	0	0	0	0	0	0	0	0	0	0	0	0.023	0.082
66	Zooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0.438	0	0
67	Planktotrophic Larvae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Phytoplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Seagrass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	Macroalgae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	Macroalgal Epiphytes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	Microphytobenthos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73	Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 5. Continuation

Prey \ predator	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0.074602	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0.006639	0	0	0	0	0	0	0	0	0.003
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.005
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0.046	0	0	0.07
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	4.15E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0.009	0	0	0	0	0	0
26	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0.002	0.013418	0	0	0	0	0	0	0	0	0	0	0	0	0.002	0	0.01
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0.406	0	0	0	0	0	0.476	0.031334	0	0	0	0	0	0	0.061	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0.001	0	0.001243	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0.276	0	0.074602	0	0	0	0	0	0.053	0	0	0.123
39	0	0	0	0	0	0.071	0	0.149204	0	0	0	0	0	0.032	0	0	0.123
40	0	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0.035
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	1E-04	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	6.04E-05	0.001041	6E-04	0	0	0.001	0	0	0	9E-04	0	8E-04	0	1E-04	0	0
45	0	0.00121	0.005417	0	0	0	0.001	0	0	0	0	0	0.001	0	0	0	0
46	1E-04	0	0	0	6E-04	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0.007026	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0.021	0	0	0	0	0	2E-04	0	2E-04	0	0
50	0.112	0.010164	0	0	0	0	0.011	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.032	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	1E-04	0.00132	1E-04	0	9E-04	0	0	0.001	0	0	0
54	0	0	0	0.002	0.003	0	0.003	0	1E-04	0	9E-04	0.001	0	0	0	0	0
55	0	0	0	0.001	0	0	0.001	0	0.009	0	0.019	0	0	0	0	0	0.001
56	0	0	0	0	0	0	2E-04	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0.004406	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0.011	6E-04	0	0	0	0
60	0	0.053027	0.073461	0.008	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	1E-04	0	0	0	0	0	0.001	0	0	0	0	0	0	0	0	0	0
63	0.047	0.053027	0	0.211	0.342	0	0	0.051476	0.047	0.734	0.6	0	0.075	0.024	0.035	0.352	0.017
64	0	0	0	0	0	0	0	0	0	0.001	0	0	0	0	0	0	0
65	0.104	0.073684	0.114058	0.114	0.084	0	0.169	0.010943	0	0.02	0.019	0.424	0.465	0	0.227	0	0
66	0	0	0	0	0	0.072	0	0.149204	0.566	0	0	0	0	0	0	0.117	0
67	0	0	0	0	0	0	0	0.001439	0.189	0	0	0	0	0	0	0	0
68	0	0	0	0	0	0.099	0	0	0.189	0	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0	0.029841	0	0	0	0	0	0	0	0	0.175
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.35
71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.088
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0.225	0.296308	0	0.122	0.35	0.249	0.457	0.211	0.453	0.352	0

Appendix 5. Continuation.

Prey \ predator	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0.0006	6E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	#####	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0.0008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0.00648	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	4E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0.2016616	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02044	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0.004	0	0	0	0	0	0	0	0
43	0	0	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0.0012602	0	1E-04	6E-04	0	0	0	0	0	0	0	0.001	0	0	0	0	0
47	0	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0.038	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0.004	0	0	0	0	0	0	0	0	0.001064	0.000912	0	0	0
54	0	0	0	0	0.001	0	0	0	0	0	0	0	0.001138	0.000912	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000912	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.24E-05	0	0
57	0	0	0	0	0	0	0	0	0	0	0	1E-04	0	0	0.011835	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0.00515	0	0.011	1E-04	0	0	0	0	0	0	0.001	0.001274	0	0	0	0
60	0.0163739	0	0	0	0	0	0	0	0	0	0	0	0	0	0.043877	0	0
61	0	0	0	0	0	0	0	0	0	0	0	1E-04	6.15E-05	4.88E-05	0	0	0
62	8.49E-05	1.00E-05	0	0	0	0	0	0	0	0	0	1E-04	0	9.12E-05	7.16E-05	0	0
63	0.0378483	0.18402	0	0	0	0	0	0	0	0	0.086	0.204	0.247959	0.364876	0.219383	0.032	1E-03
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0.0878152	0.07174	0.129	0.19	0.12	0	0	0	0	0	0	0.02	0	0	0.010836	0	0
66	0	0	0	0	0	0.185	0.185	0.278	0.139	0.205	0	0	0	0	0	0	0.095
67	0	0	0	0	0	1E-03	1E-03	1E-03	9E-04	0.02	0	0	0	0	0	0	0
68	0	0	0	0	0	0.556	0.556	0.463	0.295	0.614	0	0	0	0	0	0	0.476
69	0	0	0	0	0	0	0	0	0	0	0	0.061	0.024269	0.009163	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0.197	0.051	0.012285	0.045815	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	0.051	0.012285	0.018326	0	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0.009163	0	0	0
73	0.654956	0.61709	0.483	0.794	0.549	0	0	0	0	0	0.348	0	0.208286	0.54978	0.693545	0.16	0.428

Appendix 5. Continuation.

Prey \ predator	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	1.00E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	0.02744	9.68E-05	0	0.105	0.105	0.01	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0.031912	0.098	0	0	0	0.048	0.109	0.2	0.105	0	0.1	0.099	0	0.1	0	0	1E-03
67	0	0.000967	0.02	0	0	0	0	0.012	1E-03	0	0	1E-03	0.01	0	0	0	0.104	0
68	0	9.67E-05	0.882	0	0	0	0.865	0.761	0.4	0	0	0.5	0.594	0	0.6	0	0.694	0.4
69	0	0.821889	0	0	0	0	0	0	0	0.021	0	0	0	1E-03	0	0	0	0
70	0	0.048346	0	0.105	0.105	0.198	0	0	0	0.053	0	0	0	0.01	0	0.424	0	0
71	0.06861	0.048346	0	0.105	0.105	0.297	0	0	0	0	0.05	0	0	0.01	0	0.212	0	0
72	0	0	0	0.053	0.053	1E-03	0	0	0	0.105	0.05	0	0	0.098	0	0.009	0	0
73	0.68612	0.048346	0	0.632	0.632	0.495	0.087	0.119	0.399	0.715	0.1	0.4	0.297	0.881	0.3	0.265	0	0

Appendix 6. Pedigree of the model

Default options for pedigree routine for each input parameter used in the Ecopath CS model. Default (percentage confidence intervals [CI]) are defined based on values proposed by Christensen *et al.,* (2000) as below:

Parameter	Pedigree index	Default CI (± %)	Colour assigned
Biomass			
Sampling based, high precision	1	10	
Sampling based, low precision	0.7	40	
Approximate or indirect method	0.4	50-80	
Gueststimate	0	80	
From other model	0	80	
Estimated by Ecopath	0	n.a.	
P/B and Q/B ratios			
Same group/species, same system	1	10	
Same group/species, similar system	0.8	20	
Similar group/species in same system	0.7	30	
Similar species in similar system	0.6	40	
Empiral relationship	0.5	50	
From other Ecopath model	0.2	80	
Guesstimate	0.1	90	
Estimated by Ecopath	0	n.a.	
Diet compostions			
Quantitative, detailed, diet composition study	1	30	
Quantitative but limited diet composition study	0.7	40	
Qualitative diet composition study	0.5	50	
General knowledge for same group/species	0.2	80	
From other Ecopath model	0	80	
General knowledge of related group/species	0	80	
Catches			
Local study, high precision/complete	1	10	
Local study, low precision/incomplete	0.7	30	
National statistics	0.5	50	
FAO statistics	0.2	80	
From other Ecopath model	0	90	
Guesstimate	0	90	

Appendix 6. Continuation

	Group name	Biomass in habitat area	Production / biomass	Consumption / biomass	Diet	Catch
1	Large sharks					
2	Barracudas					
3	Australian Sea Lion					
4	Bottlenose Dolphin					
5	Tailors					
6	Cormorants					
7	Squids					
8	Australian Pelican					
9	Gulls and Terns					
10	Little Penguin					
11	Scaly Mackerel					
12	Small sharks					
13	Yellowtail Scad					
14	Cuttlefish					
15	Trevallies					
16	Flounders					
17	Pink Snapper adult					
18	Pink Snapper pre-spawner					
19	King George Whiting					
20	Whiting Species					
21	Small pelagics					
22	Western Australian Octopus					
23	Grunters					
24	Pipefishes					
25	Gurnards					
26	Weedfish					
27	Soldiers					
28	PInk Snapper juvenile					
29	Other seabirds					
30	Rays					
31	Dragonets					
32	Southern Garfish					
33	Wrasses					
34	Butterfishes					
35	Demersal fish					
36	Common Silverbelly					
37	Goatfishes					
38	Blue Sprat					
39	Sandy Sprat					
40	Pilchard					
41	Australian Herring					
42	Schooling species					
43	Leatherjackets					
44	Other crabs					
45	Blue Swimmer Crab					
46	Mantis shrimp					
47	Seastars					
48	Migratory waders					
49	Seahorses					
50	Mullets					
51	Rabbitfish					
52	Introduced species					
53	Western King Prawn					
54	Other prawns					
55	Sea snails					
56	Black Mussel					
57	Corals					
58	Ascidians					
59	Sea Cucumbers					
60	Sand dollars					
61	Sponges					
62	Bivalves					
63	Polychaetes					
64	Bryozoans					
65	Urchins					
66	Zooplankton					
67	Planktotrophic Larvae					
68	Phytoplankton					
69	Seagrass					
70	Macroalgae					
71	Macroalgal Epiphytes					
72	Microphytobenthos					
73	Detritus					

Appendix 7. Pre-balance (PREBAL) diagnostics of the model

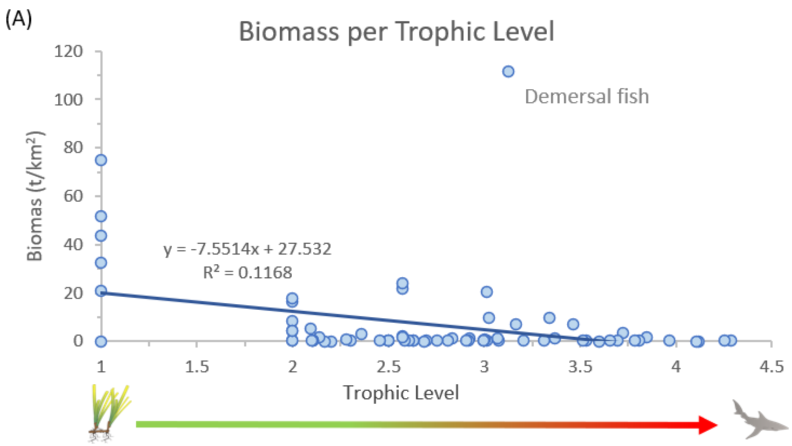
In accordance with Heymans et al. (2016), we analysed the performance of the CS model by running a set of pre-balanced (PREBAL) diagnostics routine. These below diagnostics are based on biological, and fisheries principles and it is recommended to conduct them before balance the model (Link, 2010; Heymans et al., 2016).

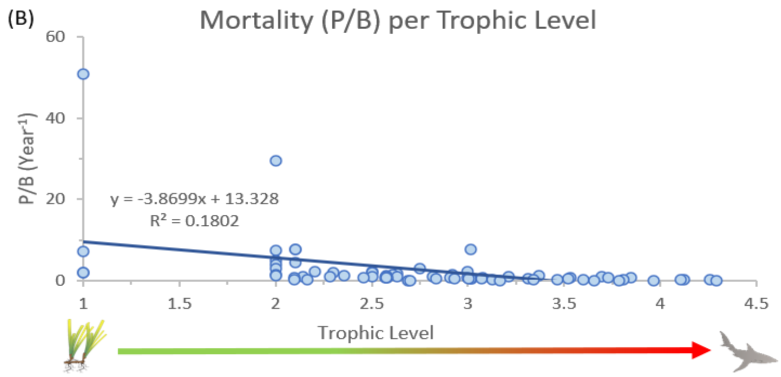
a. *Biomass per trophic level*: The PREBAL criteria include the distribution of biomass per trophic level. It is expected that the slope of the biomass (on a long scale) decline by 5-10% across all the taxa arrayed by trophic level (Link, 2010). The PREBAL-CS displayed a declining slope of the biomass (Panel A). Values above and below the slope-line were checked for data integrity before initiating the mass-balance of the model. The biomass estimates of these groups were checked before the mass-balancing.

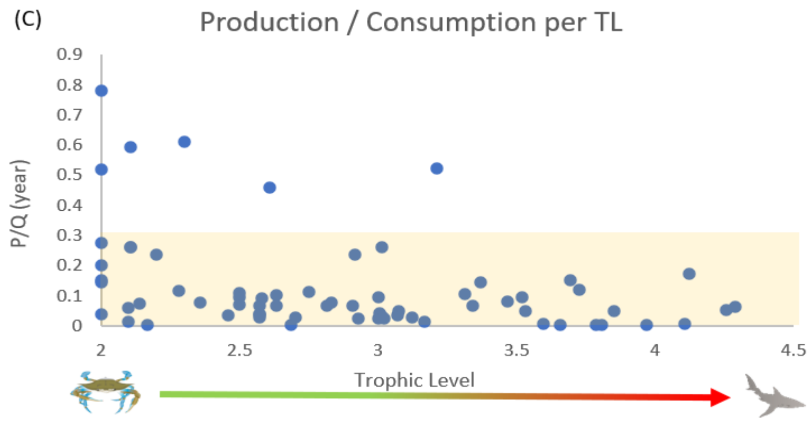
b. *Annual Production/Biomass (P/B)*: In the model, the instantaneous mortality equals total production over mean biomass (Christensen and Walters, 2004), this means that total morality (Z) = (production/biomass) = P/B. As expected, the distribution of the ratios of P/B in the model has a negative slope (Panel B). This outcome was expected because many lower trophic level groups (r-selected species) have short life spans characterized by higher mortality rates.

c. *Production to Consumption ratio (P/Q) or the gross food conversion*: P/Q in the model indicates that a group cannot produce more than a fraction of what it has eaten, based on the 2nd law of thermodynamics (Link, 2010). Because consumption is expected to be between two to ten times higher than production, in most cases, P/Q ratios will range between 0.05 to 0.5 (except for fast growing organisms and corals) as shown in Panel C. Most of the P/Q values of the 66 consumer groups in the model were within the range of 0.05 to 0.5 (except for Bryozoa, Squids, and corals) (Panel C). Groups with P/Q values higher than 0.5 were checked again their input values such as biomasses, mortalities, consumption, predation rates (based on diet matrix) before initiate the balance of the model.

The above PREBALs diagnostics are only meant to be the first check of the model before beginning the mass-balance process where further parameterization of some groups was conducted. Overall, the performance of the PREBAL diagnostics indicated that our pre-balanced model was in general thermodynamically consistent.


(A)
Biomass per Trophic Level
Demersal fish
y = -7.5514x + 27.532
R² = 0.1168
Biomas (t/km²)
Trophic Level
120
100
80
60
40
20
0
1
1.5
2
2.5
3
3.5
4
4.5

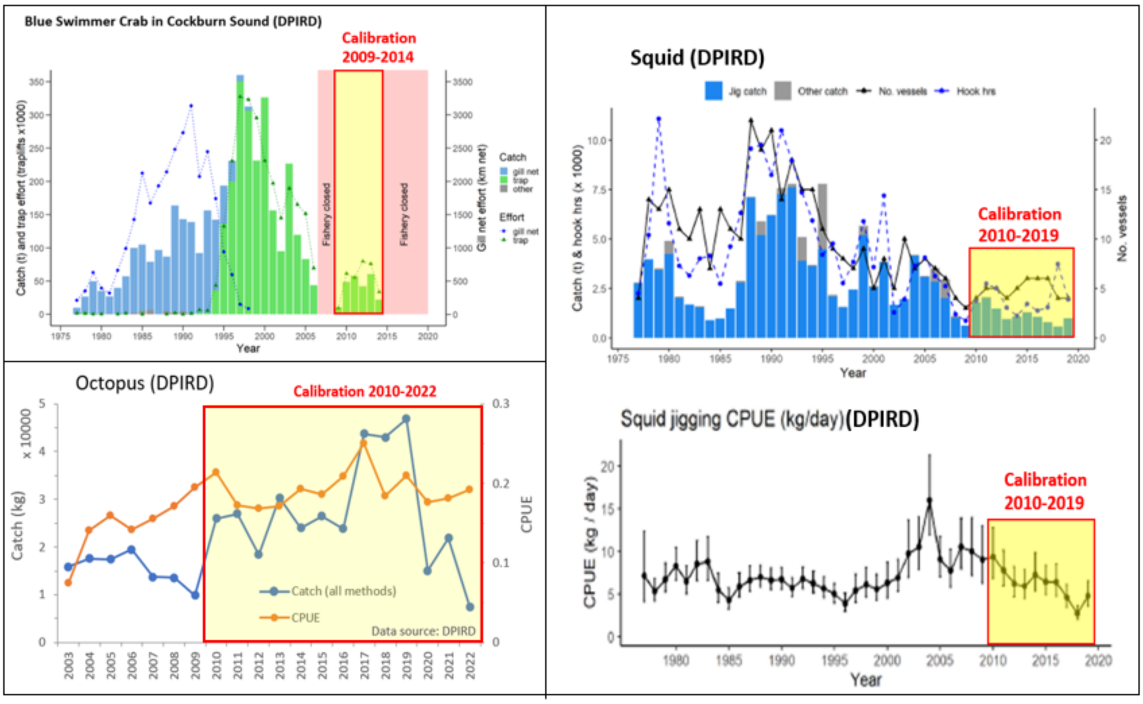

(B)
Mortality (P/B) per Trophic Level
y = -3.8699x + 13.328
R² = 0.1802
P/B (Year⁻¹)
Trophic Level
60
40
20
0
1
1.5
2
2.5
3
3.5
4
4.5


(C)
Production / Consumption per TL
P/Q (year)
Trophic Level
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
2.5
3
3.5
4
4.5

Appendix 8. DPIRD time series data of CPUE and catch

For BSC, Western Australia Octopus, and squids in CS. The yellow rectangles represent the data from 2010-2022 used for fitting of the CS Ecopath model.

Fisheries data (DPIRD) used to calibrate the Cockburn Sound Ecopath model



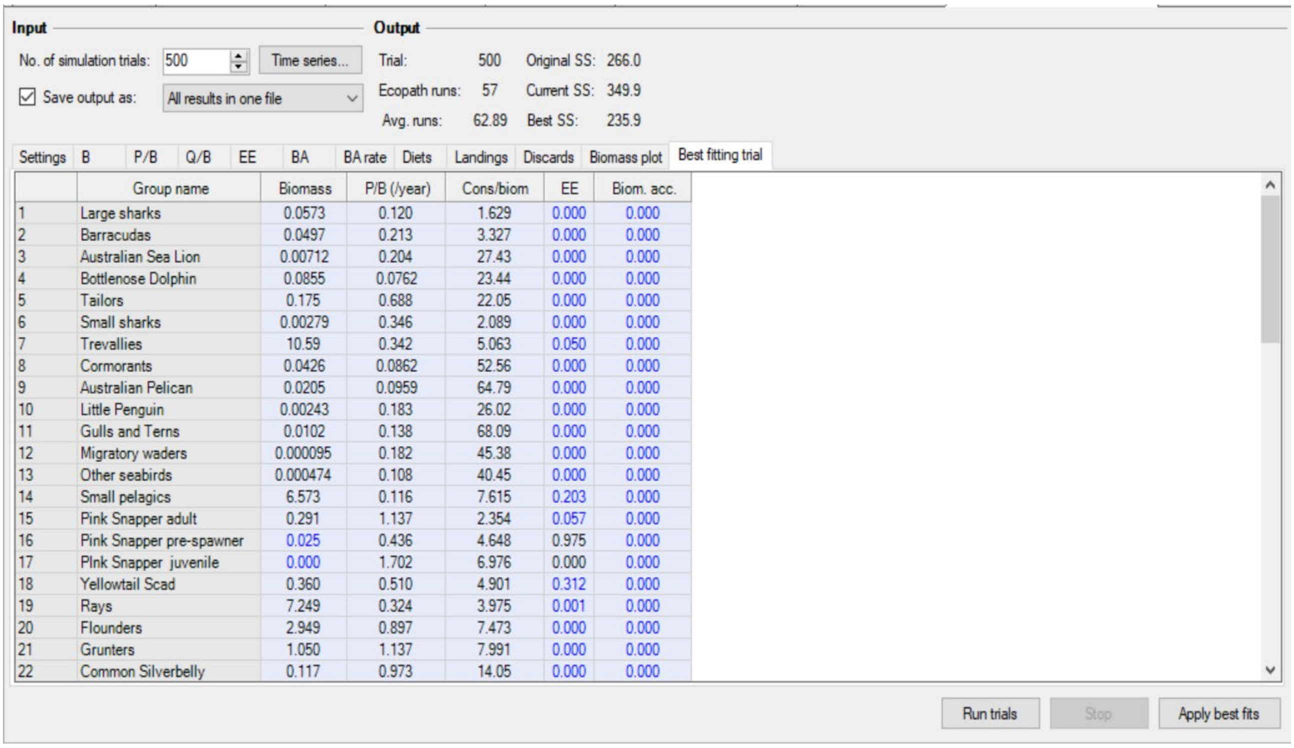
Appendix 9. Addressing uncertainty: Monte Carlo approach

Ecosim is the dynamic component of Ecopath with Ecosim software (EwE) and it contains a module that allows users to use a Monte Carlo simulation approach to search for Ecopath parameter-combinations that improve the fit of the model to time series data (i.e., reduce the weighted sum of squared deviations, SS). The sum of square residuals (SS) represents the difference between the observed value and the predicted value in the model (Christensen *et al*., 2004). In Ecosim, the Monte Carlo routine is used to test the sensitivity of Ecosim's outputs to Ecopath input parameters. In this study, we used Monte Carlo simulations to reduce the SS of the Ecopath input parameters.

We set 500 trials, where each trial represents an Ecosim run with a randomly selected set of Ecopath parameters of B, P/B, Q/B and EE for each group (Christensen *et al*.,2004). We used the coefficient of variation (CV) set in the Pedigree section of the Ecopath model to define the upper and lower limit of the distribution used to draw the random values of B, P/B, Q/B and EE for each group. The best-balanced model (i.e. the one with the lowest weighted SS) from the 500 trials was retained. Note, only a dozen of trials of the 500 trails resulted in a balanced model. Then, we checked the range of the input parameters resulting from the Monte Carlo trials and conducted the pre-balanced diagnostics again to evaluate the performance of the model.

Figure A shows the outputs of the 500 Monte Carlo trials of the CS model, where at the top right-hand side of the figure is the original (before the simulation) weighted Sum of Squares deviations (SS). After the 500 trials were completed, the best SS shows the lowest SS achieved and it is automatically displayed by Ecosim in the lower tab as shown in Figure 1 of this Appendix.

After the 500 Monte Carlo trials, we estimated the percentage change of the main input parameters (B, P/B, Q/B) as shown in Figure B. Biomass was the input parameter with the smallest change after the trials. Functional groups with trophic level <2.5 (invertebrates and primary producers) were associated with the highest uncertainty in Biomass and they displayed the biggest changes in Biomass (Fig.2 of this Appendix). For example, the biomass of Polychaetes changed by 38% after the trials. The percentage change of P/B in the functional groups ranged from -10% to +40% and invertebrate groups (e.g. sponges and sea snails) were again associated with high uncertainty. The greatest change in the input parameters was displayed by consumption over biomass (Q/B) of small demersal "fishes" with trophic levels <2.5 (e.g. sea horses, black mussels, gurnards), with changes ranging from -20% to +90% (Fig. B of this Appendix).



	Group name	Biomass	P/B (/year)	Cons/biom	EE	Biom. acc.
1	Large sharks	0.0573	0.120	1.629	0.000	0.000
2	Barracudas	0.0497	0.213	3.327	0.000	0.000
3	Australian Sea Lion	0.00712	0.204	27.43	0.000	0.000
4	Bottlenose Dolphin	0.0855	0.0762	23.44	0.000	0.000
5	Tailors	0.175	0.688	22.05	0.000	0.000
6	Small sharks	0.00279	0.346	2.089	0.000	0.000
7	Trevallies	10.59	0.342	5.063	0.050	0.000
8	Cormorants	0.0426	0.0862	52.56	0.000	0.000
9	Australian Pelican	0.0205	0.0959	64.79	0.000	0.000
10	Little Penguin	0.00243	0.183	26.02	0.000	0.000
11	Gulls and Terns	0.0102	0.138	68.09	0.000	0.000
12	Migratory waders	0.000095	0.182	45.38	0.000	0.000
13	Other seabirds	0.000474	0.108	40.45	0.000	0.000
14	Small pelagics	6.573	0.116	7.615	0.203	0.000
15	Pink Snapper adult	0.291	1.137	2.354	0.057	0.000
16	Pink Snapper pre-spawner	0.025	0.436	4.648	0.975	0.000
17	PInk Snapper juvenile	0.000	1.702	6.976	0.000	0.000
18	Yellowtail Scad	0.360	0.510	4.901	0.312	0.000
19	Rays	7.249	0.324	3.975	0.001	0.000
20	Flounders	2.949	0.897	7.473	0.000	0.000
21	Grunters	1.050	1.137	7.991	0.000	0.000
22	Common Silverbelly	0.117	0.973	14.05	0.000	0.000

Figure A. Screenshot of the Monte Carlo routine in Ecosim. We conducted 500 trials and the best (lower SS) resulting CS model (balanced) was retained using the "Apply best fit" tab.

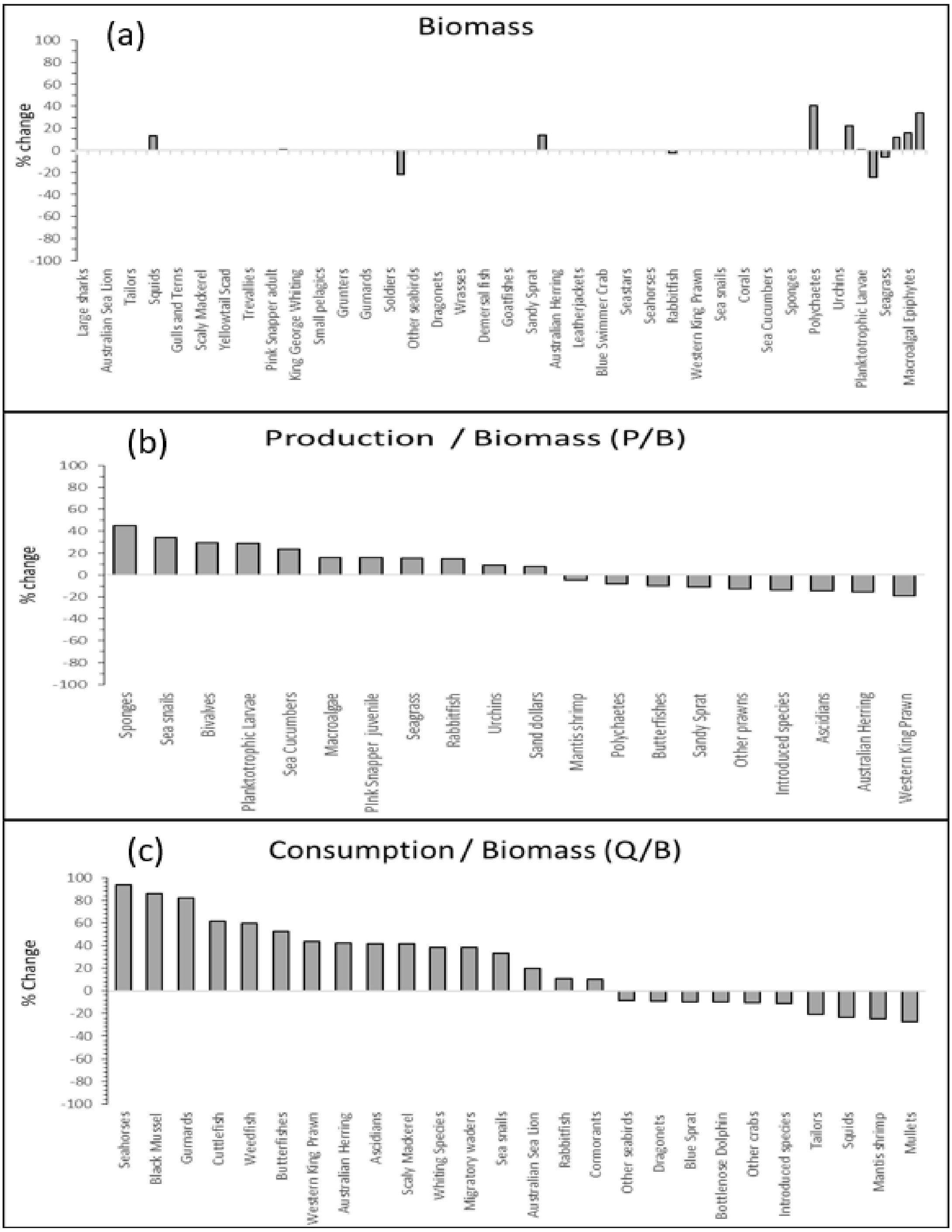
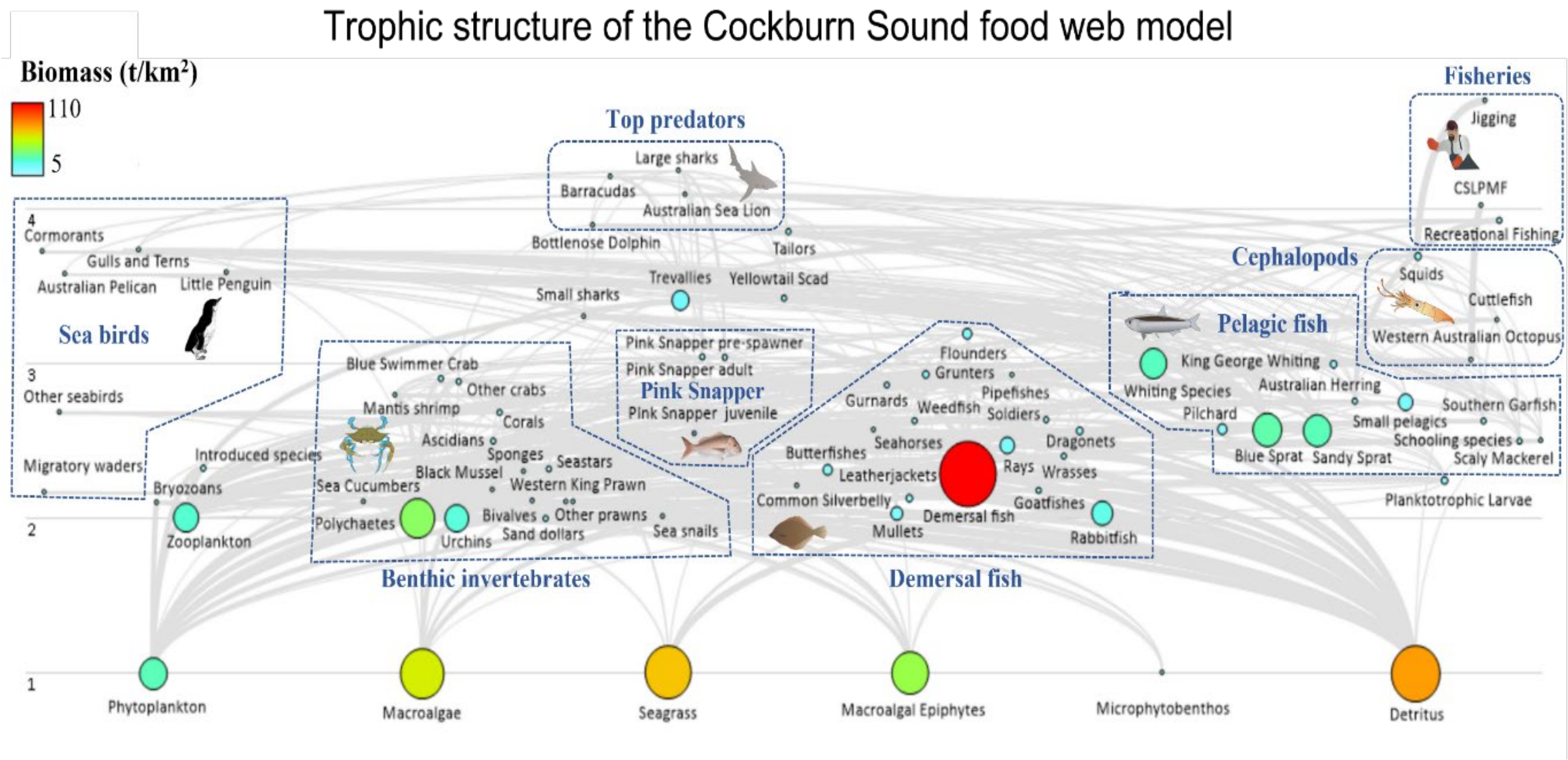


Figure B. Percentage change of the main input parameters (a) Biomass, (b) Production over biomass (P/B), and (c) Consumption over biomass (Q/B) after 500 Monte Carlo trials in Ecosim (see text for details).

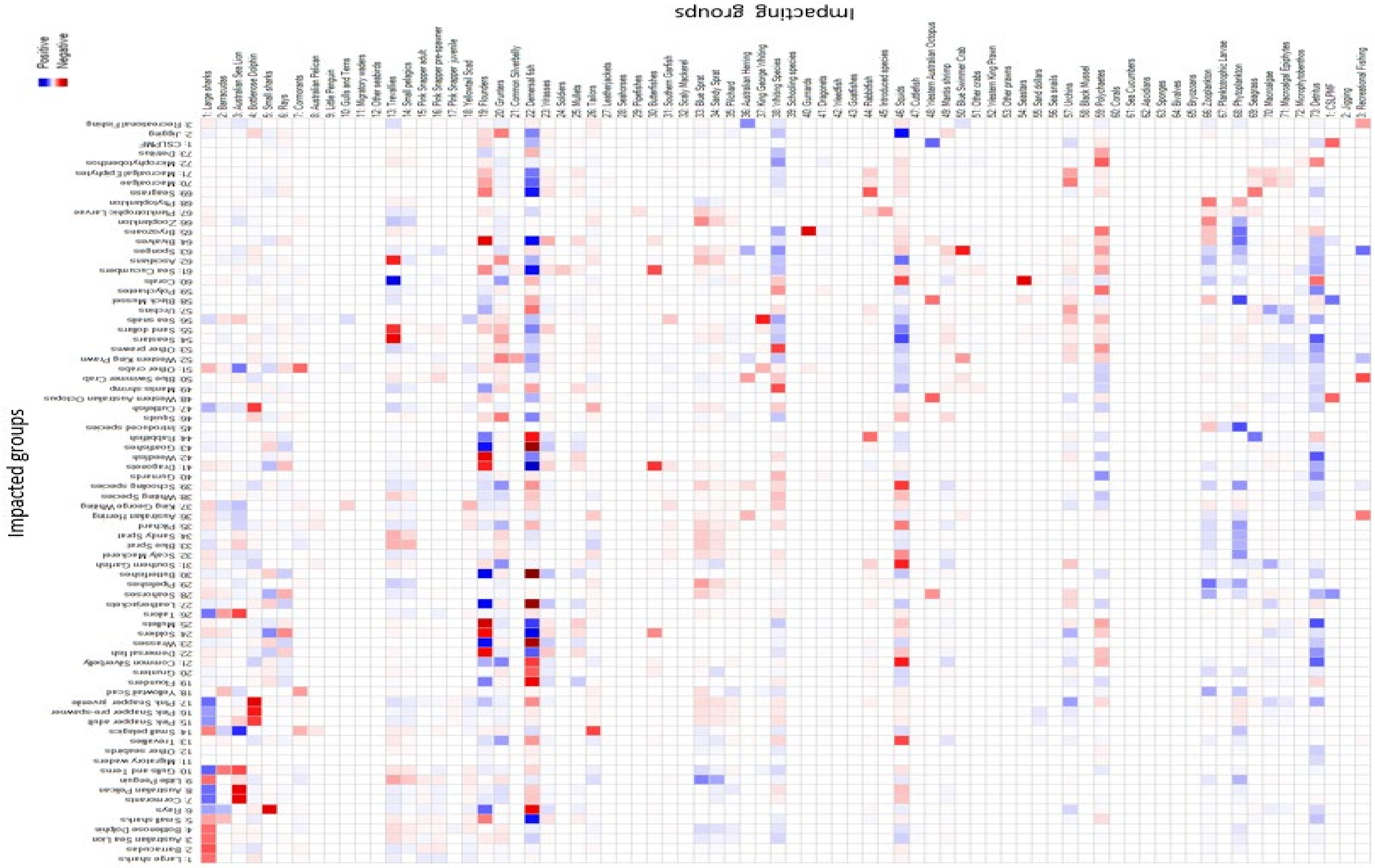
Appendix 10. ***CS food web diagram.***

Functional groups are represented by circles, with size and colour proportional to their biomass (t wet weight km^{-2}). Dashed areas encircle major trophic groups including top predators (trophic level > 4.0), sea birds, PS life stages (adult, pre-spawner, juvenile), pelagic fish, demersal fish, benthic invertebrates, cephalopods, and operating fisheries.



Appendix 11. Mixed Trophic Impacts (MTI) of the food web model.

Positive (blue) and negative (red) values of mixed trophic impact index represent positive and negative effects, respectively.



Appendix 12. Keystone species index***, relative total impact, and keystone position of the 73 groups of the CS model.***

Group name	Keystone index	Relative total impact	Keystone position
1 Large sharks	4.2	0.376	3°
2 Barracudas	3.8	0.163	5°
3 Australian Sea Lion	5.1	0.420	2°
4 Bottlenose Dolphin	4.0	0.354	4°
5 Tailors	3.4	0.204	12°
6 Cormorants	3.8	0.108	6°
7 Squids	2.9	0.427	21°
8 Australian Pelican	3.4	0.022	10°
9 Gulls and Terns	3.6	0.017	7°
10 Little Penguin	3.1	0.001	14°
11 Scaly Mackerel	3.0	0.054	17°
12 Small sharks	5.3	0.267	1°
13 Yellowtail Scad	3.0	0.143	16°
14 Cuttlefish	2.9	0.017	20°
15 Trevallies	2.0	0.380	40°
16 Flounders	2.7	0.759	28°
17 Pink Snapper adult	2.3	0.033	35°
18 Pink Snapper pre-spawner	2.8	0.049	25°
19 King George Whiting	2.0	0.042	39°
20 Whiting Species	1.5	0.275	53°
21 Small pelagics	1.8	0.197	44°
22 Western Australian Octopus	3.5	0.131	9°
23 Grunters	2.8	0.292	24°
24 Pipefishes	3.1	0.048	11°
25 Gurnards	3.4	0.220	8°
26 Weedfish	3.6	0.337	15°
27 Soldiers	2.0	0.041	38°
28 PInk Snapper juvenile	2.8	0.013	22°
29 Other seabirds	2.8	0.000	26°
30 Rays	1.7	0.145	47°
31 Dragonets	1.5	0.019	52°
32 Southern Garfish	2.6	0.052	31°
33 Wrasses	2.6	0.127	33°
34 Butterfishes	2.2	0.213	36°
35 Demersal fish	1.3	1.000	59°
36 Common Silverbelly	3.0	0.055	18°
37 Goatfishes	0.9	0.003	67°
38 Blue Sprat	1.3	0.191	60°
39 Sandy Sprat	1.1	0.119	64°
40 Pilchard	1.4	0.067	57°
41 Australian Herring	2.8	0.081	23°
42 Schooling species	1.4	0.002	54°
43 Leatherjackets	1.1	0.007	65°
44 Other crabs	2.7	0.174	30°
45 Blue Swimmer Crab	2.6	0.077	32°
46 Mantis shrimp	2.7	0.020	29°
47 Seastars	3.3	0.176	13°
48 Migratory waders	0.8	0.000	68°
49 Seahorses	1.9	0.003	41°
50 Mullets	1.7	0.098	48°
51 Rabbitfish	1.3	0.134	58°
52 Introduced species	1.2	0.003	62°
53 Western King Prawn	2.1	0.001	37°
54 Other prawns	1.5	0.002	50°
55 Sea snails	2.6	0.008	34°
56 Black Mussel	3.0	0.000	19°
57 Corals	1.4	0.003	56°
58 Ascidians	1.5	0.003	51°
59 Sea Cucumbers	1.9	0.003	42°
60 Sand dollars	1.8	0.024	43°
61 Sponges	0.3	0.000	72°
62 Bivalves	1.8	0.000	45°
63 Polychaetes	1.2	0.245	61°
64 Bryozoans	1.1	0.000	63°
65 Urchins	1.4	0.175	55°
66 Zooplankton	1.7	0.226	46°
67 Planktotrophic Larvae	0.9	0.080	66°
68 Phytoplankton	1.5	0.406	49°
69 Seagrass	0.6	0.108	71°
70 Macroalgae	0.7	0.114	70°
71 Macroalgal Epiphytes	0.7	0.081	69°
72 Microphytobenthos	2.8	0.031	27°

Appendix 13. Summary reports of the three project workshops

1. Workshop #1 (May 12th, 2022; IOMRC)

The workshop was well attended and brought together more than thirty participants from government and non-government organisations, including Westport, CSMC, WAFIC, DPIRD, DWER, DBCA, Recfishwest, WAMSI, UWA, ECU, and MU. Participation in the workshop was lively and we valued all their input and contributions.

- The first session of the workshop focused on conceptual modelling, including social and ecological (food web) aspects of CS. The workshop identified some key ecological processes and pressures that are relevant for a better understanding of how CS functions. For example, the impact of dredging and light reduction on seagrass and how this will feed into the rest of the food web. Also, the design of the port will involve the removal of soft sediment habitat and addition of hard substrate habitat is a key factor to incorporate into the conceptual model framework. The type of substrate used in construction can be biologically productive and provide new habitat for species.

- The second session introduced qualitative modelling using digraph and social network diagrams. Participants highlighted the need to develop a spatial understanding of how specific species use the area as species are not uniformly spread across the Sound. A second point discussed was to use the models to explore the early impact of the port development on the fishing sector, including the potential impacts that cooling water use for potential hydrogen production may have on the recruitment of PS and other target species. Participants mentioned the need to consider the future operations of the port in the model (e.g. the impact of increased shipping traffic on animal behaviour, such as spawning and school formation of small pelagics, and the spread of non-indigenous species).

- The third session presented the quantitative ecosystem modelling using Ecopath with Ecosim Software (EwE). Discussion focused on the biological structure of the model, and it was suggested to keep a list of rare species with low abundance within CS. It was also suggested to include a category titled "sentinel species" to be used as early biological indicators when conditions of system change (e.g. phytoplankton and jellyfish). The workshop also heard that invasive species require additional attention. Feedback and suggestions are being incorporated into the model development.

- We have received feedback on the qualitative model for little penguins and the functional groups in the EwE model that has been helpful and much appreciated. The feedback during the workshop and following it has increased the number of functional groups we are considering from 64 to 72 groups. We will be following up on the data available for different groups with experts on these groups.

2. Workshop # 2 (October 19th, IOMRC)

The aim of the workshop was to provide an overview of progress on conceptual, qualitative, and quantitative models developed, including the revised biological structure and data collection of the Ecopath model. These are some of the main discussion outcomes from the workshop:

- Feedback on major factors influencing seagrass models (historical and current conditions) were received. The models should consider factors that prevent the reestablishment of seagrass. The structure of these seagrass models will be revised with support of experts in seagrass.

- Discussions were held on refinement of qualitative models for BSC, SM, PS, and little penguin.

- Sources of information were identified for catch of recreational fishers. Additional shore-based reports were provided by workshop participants.

- Timelines and activities of the project were reviewed. No additional development of new qualitative models was suggested. However, indirect impacts, and species resilience are important elements to consider in further development of these models.

- It was noted that the Ecopath with Ecosim software has the capacity to incorporate environmental drivers and niche concepts (e.g. salinity, temperature, and habitat) to look at cumulative effects. This may be used to inform management and planning of future pressures and development in CS and could be achieved by developing temporal and spatial model scenarios and projections in a second phase of the project if funding is available.

3. Workshop # 3 (March 15th, 2023; IOMRC)

The objectives of the workshop were to present (1) results from the Conceptual, qualitative, and quantitative models; and (2) data limitations and data gaps of the Ecopath model.

These are some of the main discussion outcomes from the workshop:

- Positive feedback was stated for the breakdown of the lifecycle for seagrass and the asexual and sexual loops, which may be useful for other habitat models.

- It was noted that for the ‘fished species’ node, it should be updated to ‘fish’ species, and that not all species rely on seagrass in the same way

- It was highlighted that the node for management in the seagrass models is not specific to an organisation or type, rather it describes management in principle.

<u>Ecopath model results</u>

- Ecopath model outputs including ecological indicators, keystone species, prey overlap indexes, mixed trophic impacts, network analysis, Lindeman spine and biomass distribution were presented. All data available in the region and a summary of current knowledge of the biomass, consumption and production in the CS food web was integrated in the Ecopath model and presented.

Discussion outcomes

- It was highlighted that biomass data from trawl surveys would favour demersal species, and therefore pelagic species are not as well represented for the system.

- It was noted that data for seagrass biomass and phytoplankton biomass is being produced currently, and that adding these data may alter the sum of all production

- It was therefore stated that outputs of the present model may be viewed as preliminary, and can be updated as more data is made available

- It was noted the importance of integrating new WAMSI data into the Ecopath model in future stages, and that the reconstruction of past states of CS and developing temporal and spatial scenarios of the whole system to assess the impacts of dredging, habitat alteration (e.g. artificial habitats) and cumulative impacts would be an extremely valuable exercise.

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Final Report	15/2/2024

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