

**From Conceptual Diagrams To Semi-Quantitative Models Of
Social-Ecological Systems:
Exploring Fuzzy Cognitive Mapping
For A Coastal Fisheries System
In The Southern Cape, South Africa**

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Abstract

The world's oceans face growing threats, necessitating immediate and sustainable action. Disadvantaged coastal communities are especially vulnerable to global change and ongoing human pressures. Strengthening the resilience and adaptability of marine social-ecological systems is crucial for achieving long-term conservation success, necessitating systems-based, inclusive, and communicable approaches. Qualitative modelling, particularly fuzzy-logic cognitive mapping (FCM), offers a promising toolset in support of strategic decision-making.

This study builds on causal maps co-created with small-scale fishers from South Africa's southern Cape, integrating expert views and local knowledge through the use of FCM and a rapid prototyping approach. Iterative FCM application involved testing software suitability, refining prototypes, and co-creating scenarios to simulate outcomes and understand key drivers of change. Modifications to the *'fcm'* RStudio package addressed a critical limitation, enhancing the tool's capacity to analyse diverse scenarios effectively and reliably.

Findings highlight the significant vulnerabilities of small-scale fishing communities in the southern Cape, driven by economic, policy, and environmental stressors. The study highlights the importance of participatory approaches in identifying vulnerability drivers and enhancing understanding of system dynamics. By integrating local knowledge with FCM, this research advances tools for exploring resilience and vulnerability in these communities.

List of Acronyms

BBN	Bayesian Belief Networks
CLD	Causal Loop Diagram
CM	Cognitive Mapping
DFFE	Department of Forestry, Fisheries and the Environment
Eco-ACE	Ecosystem-based Adaptive Capacity through Community Engagement
FCM	Fuzzy Cognitive Mapping
GULLS	Global Learning for Local Solutions (Belmont Forum funded project, 2012 – 2015)
IUU	Illegal, Unreported, and Unregulated
MLRA	Marine Living Resources Act
OFAT	One-Factor-at-a-Time
POC	Proof-of-Concept
SCIFR	Southern Cape Interdisciplinary Fisheries Research (project of the SA Research Chair in Marine Ecology and Fisheries, 2012 – 2022)
SEN	Social-Ecological Network
SES	Social-Ecological Systems
SSF	Small-Scale Fisheries

1. Introduction

1.1 Background And Context

The condition of the world's oceans has become a critical concern as they provide a range of essential ecosystem services fundamental to humanity's well-being. Oceans contribute to nourishment and support economic, social, cultural, and spiritual resources. They play a crucial role in regulating the climate, sequestering carbon, controlling erosion, filtering waste, and providing recreational spaces, making them indispensable to both human and environmental health (Granek et al., 2010). Among these services, fishing stands out as a major source of food provision, crucial for global food security and the livelihoods of coastal communities that depend on fisheries as their primary resource (FAO, 2020). However, the sustainability of global fisheries is increasingly at risk due to stressors such as climate change, social-economic pressures, and regulatory challenges, all of which jeopardise the security of populations reliant on fisheries (Asad et al., 2024).

Nearly 40% of the global population resides within 100 kilometres of the coast, a figure expected to rise to 80% by mid-century (Hobday et al., 2016). Within these coastal zones, marine-dependent communities, particularly those engaged in small-scale fisheries (SSFs), are exceptionally vulnerable to environmental and economic changes. SSF communities heavily depend on fisheries for both income and food security, making the sustainability of these fisheries critical at both local and global scales. In many national economies, SSF act as a safety net for the world's most impoverished populations, providing income and food security during economic downturns (Teh and Sumaila, 2013). This social and economic significance is particularly notable in small-scale fishing villages, where fish is a primary source of sustenance and income (Bennett. A et al., 2018; Teh and Pauly, 2018).

Although "small-scale", SSF substantially impacts global employment, health, nutrition, poverty alleviation, and seafood markets. They employ more people than the industrial fishing, oil and gas, shipping, and tourism industries, with women comprising a substantial portion of the workforce (Mangubhai and Lawless, 2021). The fish caught in SSF are critical for subsistence and are highly traded on local and global markets, ranking among the most traded foods worldwide (World Health Organisation, 2018). This essential role underscores the urgency of reducing SSF vulnerabilities to environmental and social-economic stressors

(Saksono et al., 2023; Sowman and Rebelo, 2019). Local environmental stewardship, as defined by (Bennett. N. J et al., 2018), encompasses actions taken by individuals, groups, or networks to manage resources and achieve social and environmental outcomes sustainably. This framework aligns with this study's participatory approach, emphasising local actors' central role in fostering resilience within social-ecological systems. Adaptive approaches that engage fishers in identifying stressors and developing resilience strategies are essential to supporting the sustainability of these communities (Sowman and Rebelo, 2019).

South Africa's small-scale fishers face compounded vulnerabilities common to SSF worldwide. Constrained by social-economic barriers and climate variability, South Africa's SSF communities experience limited access to resources, education, and skills training, factors that hinder informed decision-making and diminish resilience (Gammage et al., 2017a; Hauck and Sowman, 2022). Despite their critical role in supporting coastal livelihoods, SSFs in South Africa are often overlooked in policy frameworks, leaving these communities increasingly exposed to environmental and economic challenges (Sowman et al., 2021). In South Africa, where the Benguela and Agulhas currents support biodiversity, fishing communities face unique pressures, including overfishing, illegal harvesting, and climate variability, which collectively threaten the sustainability of these fisheries and highlight the need for adaptive management (DFFE, 2023).

Fishers in the southern Cape have reported substantial changes in species abundance, particularly kob (*Argyrosomus inodorus*), which they attribute to environmental changes (Duggan et al., 2014). Coupled with social-economic pressures such as poverty and limited access to capital, overfishing (excessive pressure) continues to be problematic in the southern Cape (Winker et al., 2012).

As vulnerability research has evolved, definitions of vulnerability now consider social and economic dimensions beyond mere exposure to physical hazards. Vulnerability encompasses social and biophysical systems that determine a community's exposure, sensitivity, and capacity for adaptation (Turner et al., 2003). Social vulnerability, in particular, considers political, social-economic, cultural, and institutional influences on a community's resilience, emphasising the importance of human-environment interactions in vulnerability management (Adger et al., 2005). Existing vulnerability frameworks generally fall into three categories: risk-hazard approaches, biophysical perspectives, and ecological resilience

frameworks. For example, the risk-hazard approach evaluates vulnerability through biophysical threats (Eakin and Luers, 2008), while ecological resilience frameworks focus on the dynamics between human and environmental systems (Gumel, 2022).

This study adopts a contextual vulnerability approach, focusing on social vulnerability to explore the unique stressors affecting South Africa's small-scale fishers in the southern Cape (O'Brien et al., 2007). Contextual approaches concentrate on the many social, political, economic, institutional, and biophysical components that interact to produce vulnerability (Murphy et al., 2015). A contextual approach identifies differences in vulnerability at the local scale, which is relevant for this study, as it focuses on a coastal community. At the community level, a contextual approach can consider the desires of local citizens, nongovernmental organizations, and local governing bodies (Murphy et al., 2015). This study will focus on a contextual approach through a social-ecological lens. This approach addresses a critical gap in most existing research by integrating social-ecological perspectives, particularly local fishers' knowledge and insights, to comprehensively assess vulnerability and adaptive capacity. Participatory methods involving fishers in vulnerability modelling are valuable for crafting adaptive strategies suited to local needs.

An integrated methodological approach is essential to address these interacting components and provide actionable insight. Social-ecological systems are inherently complex, and assessing vulnerability requires tools to accommodate this complexity (Lauerburg et al., 2020). Modelling offers a valuable means of synthesising diverse sources of information, including qualitative local knowledge and quantitative data, to understand the dynamics underlying vulnerability (Röckmann et al., 2012).

Participatory approaches to modelling, such as Fuzzy Cognitive Mapping (FCM), are particularly suitable in this context. These methods enable the inclusion of diverse stakeholder perspectives, such as those of small-scale fishers, into the modelling process (Gray et al., 2017). By incorporating local knowledge into the analysis, FCM can offer a nuanced understanding of the social-ecological vulnerabilities and adaptation of these communities (Xu et al., 2023).

1.2 Thesis Focus

This thesis examines the application of Fuzzy Cognitive Mapping (FCM) to understand the complex dynamics within the small-scale fishery systems of South Africa's southern Cape. FCMs offer a framework that integrates qualitative and quantitative data, which is particularly useful in contexts where data may be complex or incomplete (Nair et al., 2020). Through participatory FCMs, local knowledge from fishers and other stakeholders is incorporated to develop a more nuanced understanding of the system's dynamics and stressors (Gray et al., 2017).

Specifically, this study focuses on converting and semi-quantifying the causal loop diagram developed by Gammage and Jarre (2020) into a fuzzy-logic cognitive model (FCM). This semi-quantification of the CLD enables stakeholders to identify direct and indirect influences within the system and assess the relative magnitude of those influences.

This research contributes to two major projects: the 'Ecosystem-based Adaptive Capacity through Community Engagement' (Eco-ACE) project ¹ and the 'Southern Cape Interdisciplinary Fisheries Research (SCIFR) project². Both projects emphasise the interconnected nature of natural and social marine systems, advocating for a holistic perspective that views these systems as integrated entities. SCIFR explores key questions related to the interactions within marine social-ecological systems in the southern Cape. These include examining how natural and social changes influence these systems, how specific natural resource users adapt to global changes while shaping regional transformations, and how insights into the current state of these systems can support the development of a more sustainable and resilient future. Building on this, while SCIFR emphasises these interconnections within fisheries, the Eco-ACE project focuses on strengthening the adaptive capacity of coastal communities by fostering knowledge-sharing and collaborative decision-making. By establishing and utilising an FCM, this thesis provides a tool and insights to support informed decision-

¹ <https://ecoaceproject.co.za/>

²

https://maris.uct.ac.za/sites/default/files/content_migration/maris_uct_ac_za/2080/files/SCIFR_overview_2021Aug_final.pdf

making and enhance the adaptive capacity of small-scale fishers in the southern Cape region.

1.3 Research Questions

This thesis examines FCMs as an analytical tool for understanding the dynamic complexities of small-scale fisheries, thereby facilitating scenario-based management approaches to address the challenges faced by these communities. It aims to advance the understanding of the southern Cape's small-scale linefishery systems through fuzzy cognitive mapping (FCM), building upon the foundational work of Gammage and Jarre (2020). The following objectives provide the research focus:

Question 1: How can a semi-quantitative FCM be constructed to effectively represent and possibly extend the conceptual model of the small-scale linefisheries system in the southern Cape in Gammage and Jarre (2020)?

- Question 1a: What are the most suitable methods for applying fuzzy cognitive modelling (FCM) to the small-scale linefisheries systems in the Southern Cape, and how do they impact the accuracy and robustness of the model?
- Question 1b: How can different bodies of knowledge be integrated to represent this fishery system synthetically?
- Question 1c: Which additional insights can be generated from the FCM compared to the qualitative approach? Specifically, which key drivers discussed in Gammage and Jarre (2020) (economic, policy, climate) contribute the most to the vulnerability of the communities in the southern Cape?

Question 2: How can the semi-quantitative FCM be utilised to match the scenario stories in Gammage et al. (2021) and to analyse them further?

1.4 Expected Outcomes

The expected outcomes of this research are threefold. First, the study aims to offer methodological insights into FCM semi-quantification using literature-based methods, examining various quantification strategies and reflecting on the model's iterative calibration and validation process. Second, the developed FCM will enhance understanding of the social-economic and environmental interactions affecting small-scale fisheries in the southern Cape, identifying the most influential factors driving community vulnerability and adaptive capacity. Finally, scenario analysis using the FCM will enable the evaluation of possible future trajectories for the fishery system under varying social, economic, and climatic conditions.

1.5 Thesis Structure

This thesis is organised into six chapters, each addressing key components of the study and contributing to a comprehensive understanding of the application of Fuzzy Cognitive Mapping (FCM) to small-scale fishery systems in South Africa. The first chapter introduces the significance of small-scale fisheries in the country, emphasising their critical role in livelihoods, food security, and cultural heritage. It outlines the motivation for using FCM as a participatory modelling tool to address the vulnerabilities faced by these fisheries. The research aims and objectives are established, alongside an overview of the key research questions and the thesis structure.

The second chapter provides a detailed review of the theoretical foundations of social-ecological systems (SES), focusing on the complex dynamics of small-scale fisheries and the socio-economic and environmental challenges they face. It examines the development of FCM, tracing its origins and discussing its applications and relevance for modelling the interactions within SES, emphasising the South African context.

The third chapter describes the methodological framework employed in the study. It outlines the process of adapting a causal loop diagram into a semi-quantitative FCM, explains the methods of semi-quantification, and discusses the choice of modelling tools, inference rules, and squashing functions. The chapter also emphasises the

participatory approach to integrating local knowledge into the model and iteratively refining its design.

The fourth chapter focuses on developing and testing the proof-of-concept model, which provides a foundational exploration of FCM's utility in capturing the dynamics of small-scale fisheries. It explains quantifying model connections, testing initial assumptions, and calibrating the model. This chapter lays the groundwork for the regional prototype model, offering valuable insights into system behaviour and key interactions.

The fifth chapter extends the analysis by introducing a regional prototype model incorporating broader socio-economic and environmental factors. The model is tested for robustness through sensitivity and scenario analyses, and critical drivers of vulnerability and adaptive capacity are identified. The chapter demonstrates the practical implications of FCM for fisheries management and policy, providing actionable insights into addressing the challenges faced by small-scale fisheries.

The final chapter synthesises the research findings, reflecting on the study's methodological contributions and practical implications. It discusses the strengths and limitations of FCM as a tool for understanding and managing complex social-ecological systems. Future research directions are proposed, including improvements in semi-quantification methods, the adoption of enhanced participatory approaches, and the exploration of FCM applications in other contexts. The chapter concludes by summarising the key findings and reinforcing the value of participatory FCM in engaging stakeholders, supporting adaptive management strategies, and addressing the vulnerabilities of small-scale fisheries in South Africa.

2. Literature Review

This literature review explores how coastal communities are integral to worldwide marine social-ecological systems (SES), focusing on small-scale fisheries. It reviews the theoretical foundations for understanding SES and highlights the critical contributions of small-scale fisheries to food security and livelihoods, especially in developing societies. The review then narrows its focus to South Africa, examining the challenges faced by small-scale fisheries along the west and south coasts, with particular attention to environmental changes and social-economic dynamics in the southern Cape. Additionally, it reviews Fuzzy Cognitive Mapping (FCM) as a tool for understanding and managing the complex dynamics within these systems, with a focus on its application in scenario testing and environmental modelling.

2.1 Marine Social-Ecological Systems: Fisheries And Coastal Communities In South Africa

This section will explore the foundational concepts of social-ecological systems (SES), providing a comprehensive overview of their definitions, components, and key dynamics. It will examine the intricate interactions between human and environmental subsystems, highlighting the importance of resilience and sustainability within these systems. The review will then shift to small-scale fisheries as a crucial example of SES, focusing on the challenges they face due to environmental, economic, and governance stressors. Specific emphasis will be placed on South Africa's coastal regions, exploring how ecological and social-economic factors impact local fisheries.

2.1.1 Social-Ecological Systems: Definitions And Concepts

The Social-ecological systems (SES) paradigm emphasises the need for mutual resilience between social and ecological components (Folke and Berkes, 1998). SES are complex, integrated systems comprising social (human) and ecological (biophysical) subsystems, which interact through feedback loops. This definition, articulated by Berkes (2011), is particularly relevant to research that aims to identify the environmental,

social, economic, and political stressors affecting coastal fishing communities at various scales. The Social-Ecological Network (SEN) approaches, as reviewed by Sayles et al. (2019), provide a valuable framework for disentangling the intricate interactions within SES by explicitly modelling relationships between social and ecological components. These approaches are particularly relevant to this study, as they enable the identification of relationships and feedback mechanisms that shape the resilience and adaptive capacity of coastal fishing communities. By examining how network structures influence system resilience, SEN frameworks offer novel insights into the environmental, social, economic, and political stressors affecting these communities, contributing to sustainability science.

The concentration of human settlements near coastlines poses substantial pressures on marine social-ecological systems (SES), influencing their dynamics and sustainability. Approximately 39% of the global population resides within 100 km of a coastline (Millennium Ecosystem Assessment (Program), 2005), leading to substantial direct and indirect impacts on aquatic and terrestrial coastal environments (Williams et al., 2015). These changes affect critical ecosystem services, influencing human well-being (e.g. Daw et al., 2016). Marine SESs are particularly vulnerable to a combination of anthropogenic and environmental stressors. Overfishing, habitat degradation, and pollution are among the well-documented anthropogenic stressors (Blamey et al., 2014; Cinner and Barnes, 2019). Environmental stressors, such as climate variability (Hobday et al., 2016) and change, changes in oxygen levels (e.g., Stramma et al., 2010), and ocean acidification (e.g., Doney et al., 2009), further exacerbate the impact of anthropogenic stressors. The cumulative effects of these stressors have led to a reduction in ecosystem services, including food security and livelihoods (FAO, 2012).

Human responses to stressors within marine social-ecological systems (SES) add another layer of complexity. These responses include alterations in market structures (e.g. Thorpe and Bennett (2001)) and policy adaptations (e.g. Richards and Maguire (1998)). The feedback loops created by these responses can exacerbate existing challenges, highlighting the need for an integrated management approach (Perry et al., 2010; Stephenson et al., 2021).

Traditionally, marine ecosystem-based management has been based on a siloed approach, where human stressors were viewed as external to the ecosystem (Tulloch et al., 2020). This approach overlooked the intricate connections between marine ecosystems and human societies, which are components of a single, complex SES with substantial feedback and interdependencies. The SES approach goes further than the ecosystem approach, recognising that ecosystem changes can influence human societies and vice versa (reviewed by Stephenson et al., 2021)). This integrated perspective is also being increasingly applied to management in marine SES (FAO et al., 2003; Stephenson et al., 2021).

2.1.2 Small-Scale Fisheries And Southern Cape Research Area

Small-scale fisheries represent a vital social-ecological system (SES), providing millions worldwide with food, livelihoods, and cultural identity. Despite their smaller economic footprint compared to industrial fisheries, they play a critical role in food security and employment (García-Lorenzo et al., 2024). Governing these fisheries involves a complex network of policies, institutions, and management systems that account for social-economic and ecological dynamics. Effective fisheries management requires an understanding of the relationships between fishery resources, fishing communities, and the broader ecological systems on which they depend (Berkes et al., 2001; Castilla and Defeo, 2005; Lindkvist et al., 2020). These fisheries are vulnerable to environmental changes, market fluctuations, and governance challenges, among other stressors (Garcia and Charles, 2008; Kooiman et al., 2005; McClanahan et al., 2009). Pittman and Armitage (2016) highlighted the complexity of governance across the land-sea interface, emphasising that effective governance requires overcoming challenges related to boundary determination, cross-scale coordination, and integrating diverse knowledge systems. Their systematic review identified ecosystem-based and integrated management approaches as critical for addressing these multifaceted challenges (Pittman and Armitage, 2016).

The southern Cape region exemplifies the complexities of managing small-scale fisheries amidst social-economic and ecological challenges. This region has been the focus of extensive research, highlighting the interdependencies between ecological

conditions, fishing practices, and the livelihoods of local communities (e.g. Aswani et al., 2019; Duggan et al., 2014; Duggan, 2018; Gammage et al., 2017a, 2019; Gammage and Jarre, 2020; Raemaekers and Sowman, 2015; Sowman and Raemaekers, 2018; Ward et al., 2021).

The interconnected marine social-ecological systems of South Africa's west and south coasts, influenced by the Benguela Current, are shaped by shared ecological and social-economic factors. The West Coast features cold, nutrient-rich waters that support key inshore species, such as the snoek (*Thyrsites atun*) and West Coast rock lobster (*Jasus lalandii*), which are crucial to the livelihoods of coastal communities. Fisheries in this region utilise low-technology gear and small boats, often family-run and heritage-based (Gardner, 2022; Hutchings et al., 2009; Isaacs et al., 2022). Conversely, the south coast's diverse ecosystem, also influenced by the warmer Agulhas Current, supports species such as hake (*Merluccius spp.*), silver kob (*Argyrosomus inodorus*) (Griffiths, 1997), carpenter (*Argyrozona argyrozona*), and red roman (*Chrysoblephus laticeps*), essential to the region's small-scale fisheries. Both coasts face challenges such as overfishing, illegal harvesting, and the impacts of climate variability, necessitating the development and implementation of adaptive strategies by resource managers, policymakers, and local communities to ensure the sustainable use and resilience of marine resources (Eggers et al., 2022; Isaacs et al., 2022; van der Lingen et al., 2006).

During periods of species scarcity, fishers switch to alternatives such as sharks and other linefish, reflecting the flexibility required for community survival under fluctuating fish stocks and market conditions (Allison and Ellis, 2001; Gammage et al., 2017a; Griffiths, 1997; Martins et al., 2019). The communities involved face social-economic challenges, including poverty, limited employment opportunities, and dependence on state grants (Gammage et al., 2017b).

This research builds on SCIFR's work, particularly Gammage and Jarre's (2020) causal loop diagram, to explore specific communities within the southern Cape: Mossel Bay, Gouritsmond/Bitouville, Melkhoutfontein, and Slangrivier (Figure 1), each contributing distinctly to the region's social-economic fabric. A pivotal aspect of this study involves the methodological innovations introduced by Gammage and Jarre (2020), who created a regional causal loop diagram (CLD) (Figure 2) that integrates the social-ecological

system of these four communities. This CLD was developed through a participatory process, wherein town-specific maps were initially created by presenting a base map to participants from each town. The town-specific maps were then amalgamated into a regional map, with the integration process involving the comparison of inputs from the towns and identifying commonalities in the wording of variables or connections among variables, ensuring the map's applicability to each town's context (Gammage and Jarre 2020). Mossel Bay, a critical economic and logistical hub, features a substantial port supporting commercial and small-scale fisheries and is a major tourist destination due to its historical sites and natural allure (Ward et al., 2022). Its diversified economy extends beyond fishing to include tourism and industrial activities linked to its commercial port. Gouritsmond/Bitouville is recognised for its dual role as a seasonal tourist destination and retirement community, with infrastructure supporting tourism and fishing activities. These communities face economic constraints due to their seasonally fluctuating populations, which impact the stability of local services and businesses (Gammage et al., 2023). Adjacent to the Goukou River and historically affected by Apartheid's spatial planning, Melkhoutfontein remains predominantly populated by communities of colour, grappling with enduring social-economic challenges. In Melkhoutfontein, fishing once played a substantial role, but agriculture and service industries, driven by Stilbaai's tourism and retirement economies, now dominate. Regulatory policies favouring recreational fishing have restricted access for local small-scale fishers (Ward et al., 2022). Meanwhile, cultural tourism projects have revitalised the local economy, creating new opportunities for community engagement and development. Slangrivier, a rural community with substantial employment and housing challenges, is primarily engaged in agriculture, with limited connections to coastal fishing activities due to its inland location. Local initiatives promoting sustainable agriculture and improved living conditions support the community's resilience and adaptability to social-economic challenges (Gammage et al., 2023).



Figure 1: Map of the study sites in the southern Cape (adopted from Gammage et al. (2021)). Red triangle highlights Melkhoutfontein, where Gammage et al. (2021) developed scenario stores with the fishing community.

The scenarios are developed around three main aspects: access to capital, access to marine resources (fishing rights), and the impact of climate change and the general productivity of marine ecosystems (Figure 3) because these factors critically influence the future social-economic conditions of the town over the next 30 years.

Participants in these scenario story development workshops included a diverse group of local fishers and community leaders, ensuring a wide range of local perspectives was considered. The second workshop involved interactive group discussions to effectively envision Melkhoutfontein's future based on the identified scenario spaces (Gammage et al., 2021). The third workshop developed and incorporated Bayesian Belief Networks (BBNs) results to include additional influences, such as climate change, thereby enhancing the scenarios' depth and relevance (Gammage and Jarre, 2020). Subsequent desktop analysis merged community input with scientific research on environmental and ecosystem changes to create the four final scenario stories.

The narrative of the first scenario, 'Nothing much has changed' (Figure 3), illustrates a deterioration of current challenges and the persistence of policy gaps in Melkhoutfontein. In this scenario, implementing the Small-Scale Fisheries Policy remains disorganised, resulting in small-scale fishers having limited access to marine resources. The government extends the interim relief policy, but obtaining permits remains difficult, leading to declining linefish catches. The climate has become increasingly dry, straining agriculture and the economy and limiting work opportunities outside fishing. Melkhoutfontein expands through government programmes, but low investment and social issues persist (Gammage et al., 2021).

In the second scenario, 'We will get there eventually' (Figure 3), a different future is envisioned where access to resources is improved. This scenario presents limited optimism, with implementing the Small-Scale Fisheries Policy leading to forming cooperatives despite initial economic challenges. Fishers lack the capital for necessary gear and, as a result, continue to crew on commercial boats with periodic catches. Slow economic growth, high unemployment, and social issues persist; however, small-scale fishers sustain their livelihoods, and Melkhoutfontein continues to grow with the necessary infrastructure (Gammage et al., 2021).

The last two scenarios, 'The going is good' and 'The future is bright' (Figure 3), portray more positive outcomes from successful policy implementation and adaptive community responses. Scenario 3, 'The going is good' (cold productive), highlighted successful policy implementation and increased upwelling, leading to abundant cooler-water species such as anchovy (*Engraulis capensis*) and sardine (*Sardinops sagax*) as important prey to linefish species and shallow-water hake (*Merluccius capensis*) and yellowtail (*Seriola lalandi*) as linefishery targets. Fishers find employment in the industrialised (now grown) offshore fishing sector. Economic growth reduces unemployment, and proactive government planning mitigates climate impacts. Melkhoutfontein urbanises, attracting tourism and improving social-economic conditions for fishers and the broader community (Gammage et al., 2021). Scenario 4, 'The future is bright' (warm productive), depicts substantial growth, prosperity, and personal satisfaction. Warm temperate fish species (e.g. geelbek, *Atractoscion aequidens*) whose populations have been rebuilt/restored are more abundant in the now subtropical waters of Melkhoutfontein, allowing fishers to shift from kob to geelbek without having to change craft. Proactive government support and successful policy implementation enable fishers to sustain and advance their livelihoods, accumulating wealth over 30 years. This leads to substantial economic growth, low unemployment, and proactive climate adaptation, which in turn fosters innovation and employment. Melkhoutfontein grows with improved infrastructure, attracting new residents and tourism, enhancing food security and well-being for the community (Gammage et al., 2021).

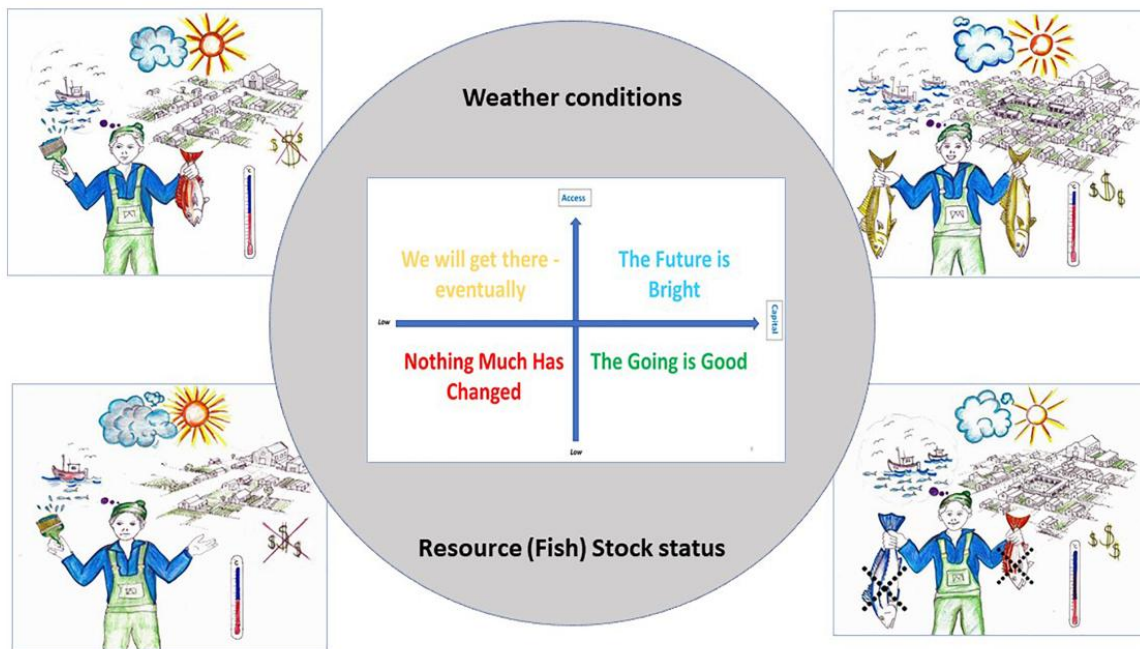


Figure 3: Depiction of scenario stories (adopted from Gammage et al. 2021).

2.2 Stressors Impacting Small-Scale Fisheries In The Southern Cape

This section reviews the various stressors affecting small-scale fisheries in the southern Cape, with a focus on the challenges posed by policy, economic, and climate-related factors. It begins by examining the policy and management stressors, highlighting the historical marginalisation of small-scale fishers and the ongoing governance challenges that affect resource access and sustainable livelihoods. Next, it considers the economic stressors that complicate fishers' ability to earn a living, such as rising operational costs and financial vulnerability. Finally, it explores the climate stressors, detailing how climatic fluctuations and environmental changes have impacted marine ecosystems and fish stocks, affecting fishing communities.

2.2.1 Policy/Management Stressors And Their Impact On Fisheries

Research in the southern Cape has consistently identified drivers of change across fishing-dependent communities, influenced by specific town contexts that affect their adaptive capacities (Gammage et al., 2017a, 2017b; Gammage and Jarre, 2020).

Historically, South African small-scale fisheries have supported coastal communities but were long marginalised in policy frameworks, including in the southern Cape (e.g. Visser, 2015). The Marine Living Resources Act (MLRA) of 1998 marked a step by legally recognising subsistence fishers and attempting to address their marginalisation (Government Gazette 19148, 1998). However, its narrow interpretation initially excluded many fishers, leading to community dissatisfaction (Isaacs and Hara, 2015; Sowman et al., 2014). The 2012 Policy for Small-Scale Fisheries introduced substantial shifts by formalising fishing rights for communities marginalised during Apartheid and the Individual Transferable Quotas continuing in the commercial handline fishery. These community rights aim to alleviate poverty, enhance food security, and promote social-economic growth in disadvantaged areas (Government Gazette 35455, 2012; Isaacs and Hara, 2015; Sowman et al., 2014).

The Marine Living Resources Amendment Act of 2014 sought to recognise and support small-scale fishers, providing a more comprehensive framework for further development (Government Gazette 37659, 2014). Despite these legal advances, slow implementation has perpetuated governance challenges such as illegal fishing and marginalisation in decision-making processes (Jarre et al., 2018; Sowman and Wynberg, 2014).

A major source of conflict in the region is the competition between inshore trawl and linefisheries, particularly over valuable fish species such as kob (*Agyrosomus inodorus*), which leads to overfishing and stock depletion (Winker et al., 2012). Government policies historically favouring the inshore trawl fishery have exacerbated tensions (Visser, 2015), marginalising handline fishers and leading to grievances about exclusion from resource management and decision-making (Gammage et al., 2017a). Additionally, trawling near coastal areas degrades crucial reef habitats (Atkinson et al., 2011; Currie et al., 2020) and contributes to illegal, unreported, and unregulated (IUU) fishing practices, intensifying economic hardships for linefishers reliant on kob and causing environmental damage (Attwood et al., 2011; Duggan, 2018).

Implementing the Small-Scale Fishing Policy effectively could enhance food security, improve livelihoods, and reduce conflicts over fishing rights, supporting a more sustainable and fairer fishery sector (Hiriart-Bertrand et al., 2020; Isaacs and Hara, 2015; Smythe, 2024; Sowman et al., 2014). However, a comprehensive approach to

management must address the social-economic and environmental challenges comprehensively (Duggan et al., 2014; Norton, 2014; Skein et al., 2022).

2.2.2 Economic Stressors Affecting Small-Scale Fisheries In The Southern Cape

Fishing plays a vital role in the economies of coastal communities, providing a crucial source of income and supporting fundamental needs in the southern Cape (Gammage et al., 2019; Ward et al., 2022). While skippers in these areas have diversified their income through skilled secondary activities, such as boat repairs, accommodation rentals, and beekeeping, many crew members, on the other hand, often lack the specialised skills required for these types of work. Instead, they are more likely to rely on lower-skilled, informal jobs, such as gardening or construction, which typically offer low incomes (Duggan et al., 2014; Gammage et al., 2017b; Kapembwa et al., 2021). Despite these alternative income sources, the overall economic context imposes constraints.

Rising fuel prices, increased living costs, and intermediary-determined pricing structures elevate operational costs, limiting fishers' ability to develop lucrative skills and establish sustainable income sources outside fishing (Duggan 2018; Gammage et al., 2017a, 2017b). Capital constraints affect disadvantaged fishers, hindering their ability to acquire essential equipment, such as suitable boats, for securing commercial linefish rights (Gammage et al., 2019; Xu et al., 2023). Their earnings further highlight the financial vulnerability of many fishers, often less than R5000 per month (Gammage, 2015), and the lack of financial safety nets, with over 60% having no access to reserves during fishing failures. This limited financial capacity restricts their ability to adapt to changes within the fishery, compelling them to persist with suboptimal coping strategies under continuous economic strain (Gammage et al., 2017b).

The situation can worsen during national economic downturns when consumer demand for fish decreases, leading to further reductions in fish prices by intermediaries who control the pricing rather than the fishers themselves (Gammage et al., 2017a). The price of kob can also decrease when landings increase, often due to the basic economic principle of supply and demand: as the supply of kob increases, the price per unit can decrease if demand does not rise proportionately (FAO et al., 2014). This dependency on

intermediaries for price setting exposes fishers to heightened vulnerability during economic recessions. Historical data and perceptions from fishers illustrate the profound impacts of economic downturns, stressing the critical importance of understanding economic pressures to grasp the broader challenges facing the fishery sector in the southern Cape (Gammage et al., 2017a; Duggan, 2018).

2.2.3 Climate Stressors And Their Impact On Fisheries

In recent decades, southern Benguela has undergone notable changes in sea surface temperature, sea level rise, rainfall, and primary production (DFFE, 2022; Polonsky and Serebrennikov, 2020; Reason, 2017). Warming rates differ spatially and seasonally, with the Agulhas Current showing consistent warming since the 1980s (Rouault et al., 2009; Sweijd and Smit, 2020). The upwelling system in the southern Benguela has displayed marked intensity and variability from the early 1980s to the 2000s (Blamey et al., 2012). Additionally, the region experienced an ecosystem regime shift in the late 1990s and early 2000s, which substantially affected the structure and function of marine ecosystems (Blamey et al., 2012; Watermeyer et al., 2016). Shifts in wind patterns have repercussions for marine conditions, affecting wave heights and complicating coastal fishing activities (Lyttle et al., 2021; Ward et al., 2021).

Lamont et al. (2018) also highlight inter-annual and decadal fluctuations in upwelling, particularly indicating an increase on the Agulhas Bank from 1979 to 2015. Fishers report that this has impacted local fisheries, influencing temperature-sensitive species such as kob, as these species tend to avoid the cooler, nutrient-dense waters brought about by upwelling, affecting their feeding habits and, thus, commercial yields (Duggan, 2012; Gammage et al., 2017b). A vulnerability assessment has identified the small pelagics and linefish sectors as the most susceptible to climate change, with a particular emphasis on the vulnerability of small boats, small-scale, and net fisheries. In contrast, aquaculture is seen as moderately vulnerable (Andra, 2022; Gammage et al., 2017a; Martins et al., 2019).

Integrating scientific and local ecological knowledge has been shown to provide critical insights into the impacts of climate change on small-scale fisheries, supporting the

development of adaptive strategies that address both biophysical and social dimensions of vulnerability (Gianelli et al., 2021). This approach enables communities to navigate rapid environmental changes through informed decision-making and co-management practices (Gianelli et al., 2021).

2.3 The Modelling Process And Rapid Prototyping

In this section, the focus will be on the interdisciplinary modelling process and its significance in environmental systems research, particularly in the context of fisheries. The discussion will begin by outlining the essential steps in developing a simplified 'model world' based on real-world observations, as introduced in Starfield and Jarre (2011). The process of participatory modelling, which emphasises stakeholder engagement and the integration of diverse knowledge systems, will be introduced, highlighting its role in fostering collaboration and addressing complex environmental issues. The benefits and challenges of rapid prototyping and proof-of-concept (POC) models will be examined, emphasising their practical application in refining and validating theoretical ideas.

2.3.1 The Modelling Process And Its Importance

An interdisciplinary modelling process, as outlined by Starfield and Jarre (2011) (Figure 4), begins with an exploration of the 'real world' to be represented. The initial step is to create a 'model world', a deliberately simplified version of reality. Defining the model's purpose is essential, as this guides the entire process. The design phase involves formulating a list of assumptions and preferences that align with the study's objectives, ensuring that the model includes only pertinent elements while intentionally excluding irrelevant aspects (Starfield and Jarre, 2011). The construction and coding of the model leverage the expertise of both disciplinary and non-academic experts. Once operational, the model requires real-world data for initial parameterisation and calibration. Best estimates from other sources or general ecological theory are used in the absence of specific data. A participatory modelling or collaborative approach uses stakeholder consultations to co-design and parameterise the model, integrating diverse knowledge

systems. The model is then executed to generate outputs, which must be translated and interpreted back into the real world, considering the model's assumptions and the quality of its parameterisation (Starfield and Jarre 2011). Sensitivity and assumption tests are conducted on the model's inputs and assumptions to identify these weaknesses. Sensitivity analysis involves expressing all model parameters with upper and lower error bounds and testing the model's response to these variations. Assumption analysis involves modifying the model structure to assess the impact of each assumption on the model's results (Starfield and Jarre, 2011).

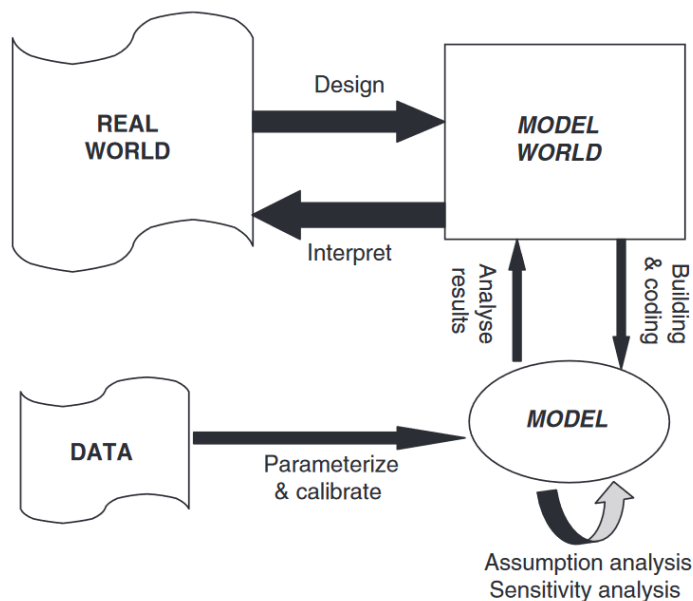


Figure 4: The modelling process (Adopted from Starfield and Jarre (2011)).

Participatory modelling is a form of interdisciplinary modelling that integrates scientific methods with stakeholder engagement, allowing for diverse input that helps understand complex issues across various fields. This method has been advanced by researchers who have emphasised the importance of accessible interfaces for collaborative efforts (Gammage and Jarre, 2020; Gray et al., 2017; Van den Belt, 2004; Voinov and Bousquet, 2010; Voinov and Gaddis, 2008). The process involves stakeholders from the outset, with activities ranging from identifying relevant participants to applying the model in practical scenarios (Dreyer and Renn, 2011). Workshops are key to participatory modelling, providing active engagement and discussion platforms. These online or in-person sessions are designed to be inclusive and accommodating to all participants, ensuring a

productive environment (Freebairn et al., 2022). Despite its advantages in fostering collaboration and enhancing decision-making, participatory modelling can be challenging due to time constraints and the complexity of managing diverse inputs (Röckmann et al., 2012; Van den Belt, 2004). Nonetheless, it remains a valuable tool in environmental assessment, community planning, and other fields where collective understanding and engagement are key.

2.3.2 Rapid Prototyping And Proof-Of-Concept Models

ii) Rapid Prototyping

As Starfield and Jarre (2011) highlight, rapid prototyping is a practical approach to modelling involving creating a series of prototypes. This method begins with the objectives of the model, which are defined by the real-world problem it aims to address. The modeller designs and builds the simplest possible model (Prototype 1) using available data, making educated guesses for any missing data regarding parameterisation. The model is quickly run to test its viability, and subsequent prototypes refine the model as necessary, always keeping its purpose in mind.

Each prototype builds on prior versions, integrating fresh insights and data to enhance the model's utility and applicability rather than simply striving for accuracy. Starfield and Jarre (2011) emphasise that rapid prototyping in interdisciplinary contexts prioritises functional simplicity and flexibility over exhaustive precision, which fosters a system-focused perspective crucial for complex social-ecological systems. This approach accelerates initial model development, allowing flaws to be identified and refinements to be made early on.

Despite its benefits, rapid prototyping has limitations, particularly the risk of oversimplification that can obscure system intricacies (Starfield and Jarre, 2011). Early models may exclude critical elements, resulting in provisional representations that guide further inquiry rather than definitive conclusions. Moreover, maintaining iterative stakeholder engagement can be challenging, especially if priorities shift with new data inputs. While the iterative nature allows for adaptability, it can demand substantial

resources, necessitating ongoing adjustments that may impact time and budget (Starfield and Jarre, 2011).

iii) Proof-Of-Concept Models

Proof-of-concept (POC) models are used across various scientific disciplines as a form of rapid prototyping to validate and explore theoretical ideas or hypotheses (Elliott, 2021; Neto et al., 2018; Servedio et al., 2014). These models demonstrate whether an idea can work in practice by creating simplified models, prototypes, or simulations (Neto et al., 2018). This initial testing confirms the feasibility of the idea and enhances understanding of the underlying concepts (Neto et al., 2018).

In fields such as evolutionary biology, POC models are instrumental in elucidating complex theories and pinpointing assumptions that may not be immediately obvious (Servedio et al., 2014). These models often employ mathematical simulations to test explicit assumptions and derive outcomes based on logical principles, a process comparable to experimental methods (Kokko, 2007; Servedio et al., 2014).

In SES modelling, such as for the southern Cape linefishery system, employing a *POC model* may focus more on testing methodologies or foundational assumptions rather than fully demonstrating feasibility. This early-stage testing, often referred to as a pre-prototype phase, is crucial for refining data collection and analysis techniques. This application of *POC models* facilitates a preliminary exploration of tools and approaches, ensuring their suitability for capturing the necessary system dynamics before advancing to more detailed and comprehensive model development.

2.4 Fuzzy Cognitive Modelling

In this section, the review will focus on Fuzzy Cognitive Modelling (FCM), a widely used methodology for analysing complex systems by representing causal relationships through a combination of cognitive mapping and fuzzy logic. The review will begin with the historical development of FCMs, tracing their origins in cognitive psychology and their advancement through various academic disciplines. Next, the advantages and disadvantages of FCMs will be explored, particularly their ability to incorporate qualitative and quantitative data, making them valuable in participatory settings and decision-making processes. The review will then cover graphical and mathematical representation of FCMs, providing insights into how these models visually depict system dynamics. Methods for semi-quantifying FCMs, including participatory approaches and literature-based strategies, will also be introduced, highlighting how these techniques facilitate the integration of diverse knowledge systems. Finally, key technical elements such as inference rules, squashing functions, scenario testing, and sensitivity analysis will be reviewed, ensuring a thorough overview of FCM applications, especially in modelling SES.

2.4.1 History Of Fuzzy Cognitive Maps

The theoretical foundation for capturing human knowledge using Fuzzy Cognitive Maps (FCMs) lies in constructivist psychology, which suggests that individuals organise knowledge and information into mental representations to comprehend their surroundings (Craik, 1967; Gray et al., 2015; Voinov and Bousquet, 2010). These mental models can be visually depicted as cognitive maps (Giabbanelli, 2024).

The semiquantitative representation of a system originates from graph theory, formulated by Euler in 1736 and has been developed by mathematicians since (Ławniczak et al., 2021). Tolman (1948) originally coined cognitive mapping (CM). A political scientist, Robert Axelrod, further developed the concept in 1976 to illustrate decision-makers' reasoning regarding social and political systems (Axelrod, 1976). Axelrod's concept aligns with how Gammage's causal loop diagram (Gammage and

Jarre, 2020) maps out key feedback loops and drivers of change between the fishery system's social, political, biophysical, and economic components. Cognitive mapping extends beyond a simple listing of ideas by organising them into a map that shows the interactions between these ideas (Mendoza and Prabhu, 2005). However, cognitive mapping can result in large and incomprehensible models that are difficult to analyse and do not account for indirect variables and feedback loops (Jetter and Schweinfert, 2011).

Building upon this, Kosko developed "Fuzzy" Cognitive Maps (FCM) in 1986 (Kosko, 1986). Unlike Axelrod's cognitive maps, where relationships are described by discrete values (0 or 1), the strengths of causal relationships in Kosko's FCM are fuzzy and range between -1 and 1 (Barbrook-Johnson and Penn, 2022). This modification enables the study of feedback loops within a system, extending beyond traditional CLDs by incorporating the quantitative aspects characteristic of FCMs (Mendoza and Prabhu 2005). The evolution of cognitive mapping into Fuzzy Cognitive Maps has provided a better tool for understanding complex systems by incorporating the uncertainty inherent in human reasoning, thus offering a framework for analysing feedback loops and causal relationships within these systems.

2.4.2 Advantages And Disadvantages Of FCM

Fuzzy Cognitive Maps (FCMs) offer several advantages when modelling complex systems. First, FCMs do not require hard data, quantitative, measurable, and verifiable information, to create and analyse models. This feature allows researchers to include qualitative knowledge in (semi-) quantifying relationships between components, making FCMs particularly valuable in contexts where quantitative information is scarce (Nair et al., 2020).

FCMs are extensively employed in participatory settings, involving stakeholders with in-depth system knowledge. Workshops and collaborative sessions enable the co-creation of models, allowing for parameterisation to be performed quickly and effectively through stakeholder consensus (Barbrook-Johnson and Penn, 2022). Engaging multiple stakeholders is particularly beneficial, as it facilitates dialogue, knowledge sharing, and

collaborative problem-solving. This participatory approach enhances a model's relevance and accuracy by integrating diverse perspectives into the decision-making process. Including local, expert, and non-expert knowledge is essential when modelling systems with social or behavioural components. Local perceptions and tacit knowledge often play a critical role in shaping real-world actions (Barbrook-Johnson and Penn, 2022).

Another advantage of FCMs is the ease with which their outputs can be understood. FCMs offer a straightforward and intuitive representation of complex systems, making them accessible to even non-experts (Koutsellis et al., 2022). Their transparency and causal nature further enhance their utility in decision-making processes (Nápoles et al., 2018). FCMs have been successfully applied in various domains, such as municipal governance (Parreño and Pablo-Martí, 2024), medicine (Apostolopoulos et al., 2024), and information technology (Hajek et al., 2017), where they have proven effective in identifying patterns that traditional methods may overlook (Navas de Maya and Kurt, 2022). They are also valuable when direct causality between components is difficult to define due to system complexity or data limitations (Kokkinos et al., 2018).

However, FCMs have notable limitations. The reliance on expert opinion can introduce uncertainty in parameterisation through incomplete knowledge (Navas de Maya and Kurt, 2022). While the participatory approach can help address this issue by incorporating diverse perspectives, it can also be time-consuming and complex, especially when dealing with stakeholders unfamiliar with the modelling process (Gray et al., 2017). Furthermore, environmental and social issues often involve stakeholders with conflicting interests, making consensus-building difficult in widely diverse groups (Barbrook-Johnson and Penn, 2022). Additionally, the subjective and qualitative nature of FCMs can lead to ambiguous outcomes when parameter changes result in non-convergence or chaotic behaviour (Koutsellis et al., 2022). Although more expert involvement can mitigate subjectivity, these challenges must be considered when interpreting results (Gray et al., 2017).

Despite their broad applicability and alignment with good modelling practice, FCMs must be tested before their conclusions can be reliably applied to real-world problems. Furthermore, while FCMs are helpful for engaging stakeholders, the simplicity of the

models can sometimes concern technical experts, who may feel that participatory results are less precise (Gray et al., 2012; Mendoza and Prabhu, 2005). Another challenge is the absence of a universally agreed-upon methodology for developing FCMs, as using different algorithms can result in inconsistent outputs, complicating cross-study comparisons (Parreño and Pablo-Martí, 2024).

The lack of a clear temporal dimension can pose issues. The values of components after iterations cannot be directly converted into time steps, complicating time-dependent analysis (Barbrook-Johnson and Penn, 2022). Similar to static ecosystem models such as EcoPath (<https://ecopath.org/>), they allow for exploring what-if scenarios.

In summary, FCMs are a valuable tool for modelling complex systems, offering flexibility, stakeholder engagement, and the ability to work with qualitative and quantitative data. However, they also present challenges, particularly regarding the subjectivity of input data, methodological inconsistencies, and (as in any model) the need for testing before applying findings to real-world situations. These advantages and limitations must be carefully considered when deciding whether to use FCMs in a particular research context, and in any case, it is important to follow good modelling practice.

2.4.3 Causal And Dynamic Approaches

Fuzzy Cognitive Mapping (FCM) is a method used to represent system components and their relationships through a structured graph (Gray et al., 2017). In these directed graphs, nodes symbolise the system components, while their connections depict the relationships or interactions (Kosko, 1986; Malek, 2017). These connections are directional, indicating causal sequences, and carry a positive or negative sign to show whether the effect results in an increase or decrease. Additionally, they can be weighted to reflect the magnitude of the effect (Giabbanelli, 2024).

The causal approach to FCM analysis, grounded in the method's original mathematical formulation, emphasises the certainty of causal relationships within a system (Barbrook-Johnson and Penn, 2020). In this approach, the strength of connections between components represents the degree of certainty that one component causes or suppresses another. Component values in the model are generally constrained between

0 and 1, indicating the certainty level regarding whether a component is activated or influenced by others (Barbrook-Johnson and Penn, 2022). While less common, these values may also range from -1 to 1, reflecting positive and negative influences within the system (Barbrook-Johnson and Penn, 2022). The primary output of a causal FCM analysis is a ranked list of components illustrating the extent to which changes within the model influence each component. Adjustments in model parameters or relationships are standard in modelling and are used to explore potential impacts on a system. While made within the model framework, these modifications provide insights into how similar changes might affect actual system components or outcomes in the real world. This approach is particularly beneficial for understanding the implications of such changes, as it highlights which components may be influenced, even if the precise magnitude of the effects is not quantifiable (Barbrook-Johnson and Penn, 2022).

In contrast, the dynamic approach to FCM analysis emphasises the propagation of effects, such as adjustments in model parameters or relationships, through a system and the relative magnitude of changes in component values over iterations (Barbrook-Johnson and Penn, 2022). This approach is more intuitive, allowing for the dynamic exploration of how changes in one component influence others across iterations. In this context, component values can take any real number, representing the size or magnitude of changes rather than indicating certainty as in the causal approach (Barbrook-Johnson and Penn, 2022). The dynamic approach is particularly valuable for identifying which components are most influential or impacted within a system, providing a visual and quantitative representation of how changes in component values might dynamically unfold (Barbrook-Johnson and Penn, 2022). However, interpreting these outputs requires caution, as there is a risk of misinterpreting the dynamical FCM as a simulation, potentially leading to incorrect conclusions about system behaviour (Barbrook-Johnson and Penn, 2022). For example, in the context of fisheries, if an FCM model indicates that a reduction in fishing effort leads to a higher fish stock over time, interpreting this as a simulation might lead to the conclusion that reducing effort by a certain amount will directly result in stock recovery by another certain amount. The model, however, is not quantitative in this sense and does not necessarily account for ecological complexities,

such as predator-prey relationships or changes in habitat, which could alter the actual outcome.

Barbrook-Johnson and Penn (2022) are among the few who discuss the different approaches to constructing and analysing FCMs, highlighting the causal and dynamic approaches. Most studies, however, employ a hybrid approach, where squashing functions are included, but quantification is interpreted as a measure of strength. While Barbrook-Johnson and Penn (2022) discuss these different approaches in detail, most studies employ a hybrid approach that integrates aspects of both but do not directly state their approach. In this study, the causal approach is employed because squashing functions are not utilised in the dynamical approach. Nevertheless, the connections are (semi-)quantified (categorised) based on the strength of the interaction rather than causal certainty.

2.4.5 Fuzzy Cognitive Maps: Mathematical Representation, Software Tools, Squashing Functions, Inference Rules And Sensitivity Testing

The mathematical representation of an FCM is expressed through numerical values assigned to components and connections, as well as FCM matrix calculations (van Vliet et al., 2010). Components and connections have numerical values ranging from -1 to 1, illustrating the strength and direction of causal relationships (Gray et al., 2017). Positive relationships indicate that an increase (or decrease) in one component will lead to an increase (or decrease) in another, whereas negative relationships imply the opposite (Gray et al., 2017). For better participant understanding, most studies use a range of Likert categories with strengths assigned to them (e.g. low, medium, high) to semi-quantify the FCM connections. Some research on Likert scoring categories has been done to aid in choosing the number of categories necessary (e.g. Aybek and Toraman, 2022; Setiadi et al., 2020; Visscher and Yengo, 2023); however, none of these are FCM-specific.

FCM matrices have an equal number of columns and rows corresponding to the number of components in the model. The values of the connections are represented in the matrix. Analysis of the matrix provides information about the system and its interactions.

Similarly, the number of non-zero matrix elements highlights the degree of interaction within the system, where a higher number signifies more connectivity (Özesmi and Özesmi, 2004).

The model's components can be categorised into three types based on their functions. *Transmitter* or driver components solely exert influence on other system components without being affected themselves, reflecting their role in driving changes within the system (Eden et al., 1992). On the other hand, *receiver* components are influenced by other components but do not exert any influence, indicating their role as endpoints in the model's causal chains (Eden et al., 1992). *Ordinary* components serve a dual function, both influencing and being influenced by other components, representing a more interconnected and dynamic role within the system (Eden et al., 1992).

Centrality, calculated as the ratio of the *receiver* to *transmitter* components, indicates the importance of all components or the individual weight of a component in the overall model (Gray et al., 2017). A higher *Centrality* value suggests that a component or set of components plays a crucial role within the model.

Together, these indices provide a comprehensive view of the system's structure, highlighting areas of influence and interaction, which can inform what-if questions based on the relationships between components within the model.

iv) Software

Several software packages are available for designing and creating Fuzzy Cognitive Maps (FCMs), differing in complexity. Some packages feature user-friendly interfaces facilitating stakeholder engagement, while others offer advanced functionalities. For instance, *FCM Expert* (Nápoles et al., 2018) provides scenario analysis, pattern classification, and machine learning algorithms to optimise models, making it a versatile option for novice users and more complex analytical tasks. However, while *FCM Expert* is designed to have a user-friendly interface, configuring specific parameters and using advanced algorithms may require higher expertise, which can be a barrier for some users. *FCM-Analyst* facilitates model construction and computation with a user-friendly interface (Margaritis et al., 2002). *FCM Wizard*, an open-source tool, facilitates the

construction, analysis, and visualisation of FCMs, making it accessible to both experts and non-experts for informed decision-making (Papageorgiou et al., 2018). Koutsellis et al. (2023) used *In-cognitive*, a web-based interactive application designed to create, visualise, and compute FCMs built using Python (Koutsellis et al., 2023). However, Python has a steep learning curve.

Mental Modeler (<https://www.mentalmodeler.com/>) has primarily been used for environmental purposes and is advantageous for participatory modelling, allowing users to create semi-quantitative models collaboratively and combining a user-friendly interface with advanced features to facilitate active stakeholder participation (Gray and Cox, 2013). It offers features such as scenario analysis and network structure indices to enhance its functionality (Singer et al., 2017).

Among the available software, *R* with the '*fcm*' package (Dikopoulou and Papageorgiou, 2017) stands out for its transparency and lack of computational constraints, making it a preferred choice over other tools. It enables many users to perform FCM inference without requiring advanced *R* skills (Dikopoulou et al., 2018). Users can choose from six different inference rules or four squashing functions, providing flexibility for visualising weighted matrices as fuzzy cognitive maps and simulating various scenarios (Deviney et al., 2024; Dikopoulou et al., 2018). Moreover, the '*fcm*' package in *R*, being open-source, allows researchers to experiment with various fuzzy inference methods, enhancing research transparency and reproducibility (Agostinho et al., 2023; Dikopoulou, 2021; Dikopoulou et al., 2023; Parisi, 2024).

v) *Fuzzy Cognitive Map Squashing Functions*

In Fuzzy Cognitive Maps (FCMs), a squashing function is necessary to normalise the values of components and ensure that they remain within a defined range, typically between 0 and 1 or -1 and 1. This prevents values from growing indefinitely during iterations and stabilises the model's behaviour. The choice of squashing function is crucial in determining FCM performance and outcomes. Commonly used squashing functions include *Bivalent*, *Trivalent*, *Sigmoid*, and *Hyperbolic Tangent Functions*, each serving different modelling purposes (Dikopoulou et al., 2018; Tsadiras, 2008). The

sigmoid and *Hyperbolic Tangent Functions* (Table 1) are the most frequently employed (Kokkinos et al., 2018).

The *Hyperbolic Tangent Function* (Table 1) is widely recognised for converting input values into a range between -1 and 1, making it suitable for modelling system dynamics. Nair et al. (2020), in their study with experts from various Civil Society Organisations in Kampala, Uganda, chose the *Hyperbolic Tangent Function* due to its common usage in FCMs. Similarly, Alipour et al. (2019), who developed an FCM using knowledge from experts in the Renewable Energy and Energy Efficiency Organization in Iran, selected this function for its strength in highlighting the extent or degree of interactions, as recommended by Jetter and Schweinfort (2011). Van Vliet et al. (2010) also emphasise the significance of the *Hyperbolic Tangent Function* in maintaining the stability and interpretability of FCMs. This function's ability to prevent chaotic behaviour and provide clear differentiation between node values makes it a preferred choice in many studies.

However, the *Sigmoid Function* (Table 1), known for its distinctive S-shaped curve, is a widely used squashing function in FCM modelling. It maps any input value to a range between 0 and 1, making it a popular choice in studies utilising *Mental Modeler* for scenario analysis (Gray et al., 2015; Halbrendt et al., 2014; Singer et al., 2017). Despite its frequent application, many of these studies do not explicitly discuss the choice of the squashing function or the potential impact of using alternative functions. Some exceptions include the work of Koutsellis et al. (2022), who explored the limitations of both the sigmoid and *Hyperbolic Tangent Functions* in FCMs of the energy sector in Greece. They emphasised that while both functions can yield clear final states, the *Hyperbolic Tangent Function* effectively avoids chaotic behaviours and provides better contrast in node values. Lavin (2018) further supported the use of the *Hyperbolic Tangent Function* over the *Sigmoid Function*, noting its ability to maintain convergence values within the range of (-1, 1), thus allowing for more detailed modelling of changes in system dynamics.

Papageorgiou et al. (2020) employed the *Sigmoid Function*, noting that it is suitable for models with positive semi-quantifications, where interactions only contribute positively. In contrast, the *Hyperbolic Tangent Function* is often used when both positive and negative connection strengths need to be modelled, allowing for the representation of

inhibitory and enhancing effects. The importance of selecting an appropriate squashing function is further highlighted in the work of Penn et al. (2013). Their sensitivity analysis of FCM outputs using sigmoidal squashing functions demonstrated that the choice of function could lead to substantial differences in model behaviour and outcomes, influencing the understanding of system dynamics. The selection process is not merely about choosing between positive and negative connection strengths but also involves considering the broader behaviour of the system, the nature of the relationships between components, and how sensitive the model is to varying degrees of influence. Penn et al. (2013) suggest that comparing outputs generated by various squashing functions can be valuable for model validation, as each function may highlight various aspects of the system. Their analysis showed that slight changes in the squashing function led to shifts in the ranking of components, which could influence the interpretation of critical drivers or outcomes in the model. Therefore, consistently examining top-ranked or bottom-ranked components across different functions helps identify the most elements of the model, while variations in rankings may indicate components more sensitive to the choice of squashing function. This underscores the need to carefully consider the model's characteristics and goals when selecting a function, as the choice can affect the reliability of conclusions drawn from the FCM.

Table 1: FCM squashing functions where x is the value of a model component at the convergence point, λ is lambda, and e is Euler's number (approximately equal to 2.71828).

Squashing function name	Squashing function equation	Reference
Sigmoid squashing	$\sigma(x) = \frac{1}{1 + e^{-\lambda x}}$	Mitchell (1997)
Hyperbolic tangent	$\text{tanhtanh}(x) = \frac{e^{\lambda x} - e^{-\lambda x}}{e^{\lambda x} + e^{-\lambda x}}$	Mitchell (1997)

vi) Fuzzy Cognitive Map Inference Rules

After selecting the software and squashing function, the next critical step in Fuzzy Cognitive Maps (FCMs) is choosing the appropriate inference rule. Each component's value is updated through an inference function based on the strengths of the connections that link it to other components (Lavin, 2018). Inference rules are fundamental to fuzzy inference systems and FCMs, as they govern the flow of information between components (Sujamol et al., 2018). The resulting output indicates the degree of increase or decrease in the FCM's components (Dikopoulou et al., 2018). The most commonly employed inference rules in FCMs include the *Kosko Inference Rule*, the *Modified Kosko Inference Rule*, and the *Rescaled Kosko Inference Rule*, each of which contributes differently to the overall input-output mapping of the model (Kokkinos et al., 2018; Sujamol et al., 2018; see

Table 2 for the corresponding equations).

The *Kosko Inference Rule* (

Table 2) is widely recognised for its simplicity, making it a popular choice in FCM modelling. This rule is particularly valuable for researchers seeking a straightforward and reliable mechanism for inferring changes within the system (Dikopoulou et al., 2018). Sujamol et al. (2018) emphasise the efficiency of the *Kosko* rule in converging to a stable state quickly, known as a fixed-point attractor, which is essential for ensuring consistent outcomes in complex models. Similarly, Arji et al. (2019) found that the *Kosko* rule demonstrated substantial representation capabilities and converged effectively during the modelling of complex medical data, further establishing its utility in various fields.

In contrast, the *Modified Kosko Inference Rule* (

Table 2) combines the original component value with the magnitude of change, thus providing an overall measure of change for each component (Lavin 2018). However, in their comparative study, Arji et al. (2019) noted that while the *Modified Kosko* rule provided a comprehensive measure of change, it did not substantially outperform the *Kosko* rule in terms of convergence during their medical data modelling study, suggesting that the benefits of the *Modified Kosko* rule might be context-dependent.

The Rescaled Kosko Inference Rule (

Table 2) addresses the potential issue of over-activation of components, which can lead to excessive influence of uncertain aspects on decision-making processes (Dikopoulou et al., 2018; Sujamol et al., 2018). The Rescaled Kosko rule is described in Fuzzy Cognitive Maps (FCMs) as a method used when the initial values of concepts are not known (Sujamol et al., 2018). However, as highlighted by Sujamol et al. (2018), a substantial limitation of this rule is that it does not always guarantee system convergence. This lack of guaranteed convergence could pose challenges in applications where consistent and stable outcomes are crucial.

Table 2: FCM Inference Rules where κ (Greek letter Kappa) is the interaction index at every computation step, $f(\cdot)$ is the threshold (squashing) function, $C_j(\kappa)$ is the value of component C_j at the computation step κ , w_{ji} is the strength of the connection between component C_i and component C_j , $C_i(\kappa+1)$ is the value of component C_i at computation step $\kappa + 1$ (Dikopoulou et al., 2018; Kosko, 1986).

Inference Rule Name	Inference Rule Equation	Reference
<i>Kosko Inference Rule</i>	$C_i^{(\kappa+1)} = f\left(\sum_{j=1, j \neq i}^n W_{ji} \times C_j^{(\kappa)}\right)$	(Kosko, 1986)
<i>Modified Kosko Inference Rule</i>	$C_i^{(\kappa+1)} = f\left(C_i^{(\kappa)} + \left(\sum_{j=1, j \neq i}^n W_{ji} \times C_j^{(\kappa)}\right)\right)$	(Dikopoulou et al., 2018)
<i>Rescaled Kosko Inference Rule</i>	$C_i^{(\kappa+1)} = f\left((2 \times C_i^{(\kappa)} - 1) + \sum_{j=1, j \neq i}^n W_{ji} \times (2 \times C_j^{(\kappa)} - 1)\right)$	(Dikopoulou et al., 2018)

vii) Lambda Parameter Within The Squashing Function

The *Lambda*(λ) parameter plays a critical role in shaping the steepness of the squashing function near zero, which directly impacts the stability and interpretability of Fuzzy Cognitive Maps (FCMs). Carefully selecting the λ value is essential, as it determines how the squashing function behaves under different conditions. Alipour et al. (2019) highlighted the significance of selecting an appropriate *Lambda*(λ) value, indicating that a small λ makes the squashing function too flat, leading to indistinguishable node values. In contrast, a large λ can transform the function into a step function, resulting in chaotic or cyclic behaviours.

Koutsellis et al. (2022) analyse the impact of the *Lambda Parameter* on the sigmoid and hyperbolic tangent transfer functions in FCMs. They propose specific bounds for the *Lambda* values to ensure that the FCM operates within the "almost linear" region of the transfer functions, which is critical for avoiding chaotic or cyclic behaviours and ensuring convergence to a fixed point. The *Lambda Parameter* should be less than or equal to 0.927 for the *log-Sigmoid Function*, while for the *Hyperbolic Tangent Function*, *Lambda* should be less than or equal to 0.421. These bounds help maintain the linearity and stability of the transfer functions, thereby producing more reliable and interpretable results. Despite this recommendation, this study utilised a default λ value of 1 due to its widespread use and acceptance in numerous studies, as indicated by Dikopoulou et al. (2018). Several studies also use a λ value of 1 (Alipour et al., 2019; Kokkinos et al., 2018; Meechang and Watanabe, 2023; Nápoles et al., 2023). These studies do not offer a detailed explanation for this choice, merely noting that it is the standard default value.

viii) Scenario Testing

The next step in utilising an FCM is to develop and test various combinations of inputs ("scenarios") to understand how they affect the FCM components. Several factors may influence the behaviour of an FCM: 1) squashing function and its parameter(s); 2) elements (strengths) of the strength matrix and the design of the model; 3) initial state vector (Harmati and Koczy, 2019).

An *activation vector* is always required in FCM modelling, as it defines the initial values for each component in the system. These initial values represent the starting conditions of the model and are crucial for simulating how influences propagate through the network. Without the activation vector, the model would lack a defined starting point, making it impossible to observe how changes in one component affect the others. Components in the activation vector are set to 0 when their state remains unchanged or clamped (as explained in the following paragraph), while they are assigned a value between -1 and 1 (e.g. Henly-Shepard et al., 2015; Kokkinos et al., 2018) when they are deactivated or activated, representing the degree of influence for each component. Standard activation methods typically set component values to 1 (e.g., Alipour et al., 2019; Banini and Bearman, 1998; Freitag et al., 2019; Kokkinos et al., 2018; Osoba and Kosko, 2019; Özesmi and Özesmi, 2004; Papageorgiou et al., 2018, 2020; Sarkar et al., 2022; Tsadiras, 2008). While some studies activate components at values other than 1, none provide a clear rationale for this choice (e.g., Henly-Shepard et al., 2015; Kontogianni et al., 2012; Koutsellis et al., 2022; Murungweni et al., 2011; Navas de Maya and Kurt, 2022; Sujamol et al., 2018)

This activation vector is the starting point for computation, encapsulating the system's initial conditions (Gray et al., 2012). Each scenario represents a unique starting condition of the system, allowing the FCM to test various hypotheses and explore diverse possibilities. The scenario setup involves applying various activation vectors, each representing a distinct set of initial conditions (Gray et al., 2017).

The FCM is then processed through multiple iterative steps. During each step, the values of the components are updated based on their interactions as defined by the FCM matrix. This process involves multiplying the activation vector by the FCM matrix of the intended FCM, resulting in an output vector that reflects the updated state of the system (Gray et al., 2012).

Next, the chosen FCM inference rule is applied to the new vector (e.g. Kosko, Modified-Kosko, Rescaled). This iterative process continues through multiple steps, allowing the model to evolve and capture the dynamic interactions within the system until convergence (Gray et al., 2017). The FCM inference rules are discussed in Section 2.4.5

iii.

Squashing functions are applied to ensure realism and control the influence of each component within the model. Depending on the specific requirements, these functions constrain the updated component values to a standard range between -1 and 1. This prevents extreme output values that could potentially distort the model. The application of FCM squashing functions is further discussed in Section 2.4.5 ii.

A new vector is produced at each iteration, depicting the updated activation levels of the components based on the previous vector, the chosen inference rule, and the selected squashing function. The convergence point is reached when an FCM produces one of the following long-term behaviours through iterations: 1) It reaches a fixed point, so the state vector stabilises after a certain number of iterations (Harmati and Koczy, 2019), 2) It produces limit cycles, meaning several consecutive state vectors turn up repeatedly (Dikopoulou et al., 2018), and 3) It may show chaotic behaviour, where the activation vector never stabilises, and there is no convergence (Giabbanelli et al., 2024).

In the model, *clamping* refers to fixing component values during iterations of FCM calculations. Kosko (1986) introduced this approach to compute different scenarios by holding the chosen values of activated or deactivated components constant in the activation vector during each time step. By clamping selected components, the model enables researchers to observe how it behaves under specific conditions where a component maintains its set activation state. During matrix multiplication, the clamped components remain fixed at each iteration, helping to analyse how changes in other parts of the model propagate. This process facilitates understanding potential impacts in real-world systems (Kosko, 1986) where specific components are maintained as fixed.

ix) Sensitivity And Assumption Testing In Fuzzy Cognitive Maps

To effectively highlight the importance of sensitivity and assumption analysis in Fuzzy Cognitive Maps (FCMs), it is essential to contextualise these practices within the broader framework of best modelling practices. Sensitivity and assumption analysis are crucial for ensuring that FCMs produce reliable and accurate outcomes, particularly given the inherent complexities of modelling systems with quantitative and qualitative inputs.

The accuracy of FCMs heavily relies on connection strengths, which are often determined based on expert knowledge. However, slight variations in these strengths can affect computation outcomes (Hatwagner et al., 2018). The importance of sensitivity analysis in FCMs is further highlighted by Murungweni et al. (2011), who describe an approach where the connection strengths in FCM matrices are randomly varied within a 20% range. This method ensures that slight changes do not overly influence the model's outcomes in parameter values, thus increasing the robustness of the FCM (Murungweni et al., 2011). Helfgott et al. (2015) also emphasise that without comprehensive sensitivity analysis, FCM results, or the inferences drawn should be interpreted cautiously. There is a risk of producing misleading conclusions or adjusting the map to fit pre-existing assumptions or desired outcomes (Helfgott et al., 2015).

Mehryar et al. (2019) employ the One-Factor-at-a-Time (OFAT) sensitivity analysis, which examines how individual changes in connection strengths will influence model outputs by varying one parameter at a time while holding others constant. This approach is particularly valuable in FCMs, where even minor adjustments in a single connection can create effects throughout the network, impacting the overall dynamics of the system. By isolating these changes, OFAT helps identify the most influential connections and ensures that a single parameter does not disproportionately affect the model's behaviour.

x) Methods For Semi-Quantifying Fuzzy Cognitive Maps

There are two primary techniques for semi-quantifying the connections in a fuzzy cognitive map (FCM): one involves the modeller consulting experts or stakeholders to gather connection strengths, while the other relies on the literature analysis to derive these strengths (Jetter and Kok, 2014). Each method offers unique advantages and presents specific challenges in the semi-quantification process of FCMs, which will be further explored in the following section.

a) Participatory Approach

Creating a Fuzzy Cognitive Map (FCM) can be a participatory process involving the direct engagement of experts or stakeholders to synthesise and formalise their knowledge and experience (Gray et al., 2017). The participatory approach ensures that the components and their interrelationships reflect the practical insights and lived realities of those connected to the system through knowledge extraction. This process typically involves interviews, group sessions, questionnaires, and/or document analysis (Ülengin and Topçu, 1997).

In contrast, co-creation goes a step further by involving stakeholders in the contribution of knowledge and in developing and refining the FCM itself. In co-creation, participants actively shape the structure, adjust relationships, and influence model outcomes, making them co-designers of the final map. This collaborative approach leads to a deeper level of ownership and relevance, as the stakeholders are integral in defining the system and analysing its dynamics (Gray et al., 2015).

The co-creative approach emphasises the inclusion of stakeholders, such as fishers, policymakers, and local communities, directly in the model-building process (Knox et al., 2024). This engagement captures the context-specific knowledge of these groups, which is often absent from the broader literature. This approach was pursued by Louise Gammage in her PhD research, which included qualitative causal loop diagrams (Gammage and Jarre, 2020), on which this research is based.

Traditionally, expertise has been associated with individuals possessing extensive specialised training and experience. However, in the context of FCM projects, this

definition is broadened to include traditional or local experts who offer invaluable insights through their lived experiences (Giabbanelli et al., 2024). This inclusive approach promotes the integration of diverse knowledge systems, ensuring that local and experiential knowledge is given equal weight alongside formal scientific expertise. Ward (2021) emphasises the importance of this integration, highlighting how placing local knowledge from farmers and fishers alongside scientific observations enhances the understanding of climate variability in the southern Cape. More informed and context-relevant decision-making strategies can be developed by revealing synergies and disconnects between these knowledge systems. Tengö et al. (2014) underscore the importance of integrating Indigenous, local, and scientific knowledge on an equal and transparent platform, ensuring that each system contributes meaningfully without being overshadowed by others. Notably, Aminpour et al. (2020) demonstrated the value of integrating different bodies of expertise by co-creating FCMs with various fishery stakeholders, including recreational anglers, commercial fishers, and policymakers, to understand the ecological and economic impacts of rising ocean temperatures on the striped bass fishery off the Massachusetts coast.

b) Literature Search Approach And Knowledge Integration

While participatory approaches incorporate direct input from stakeholders such as fishers, this study takes a literature-based approach. This method thoroughly analyses existing research, theories, and data to quantify model connections, primarily drawing on secondary data sources, including academic articles, reports, and previous studies. One key advantage of the literature approach is that it leverages established studies, ensuring the model's semi-quantifications are built on well-documented knowledge (Gray et al., 2015). However, a notable limitation is that it may not reflect recent changes in the field or capture the nuanced, context-specific insights that participatory methods might reveal (Gray et al., 2012). Additionally, this approach may lack multi-stakeholder perspectives, as it relies on what is already available in the literature.

While adopting a literature-based approach, this study builds on published results from the Southern Cape Interdisciplinary Fisheries Research (SCIFR) project. The SCIFR

project was conceived to understand better the southern Cape region's social-ecological systems (SES). Therefore, the starting point for this research includes an established causal diagram from the SCIFR project (Gammage and Jarre, 2020). This diagram focuses on the period from 2012 to 2017, a time characterised by multiple stressors, including severe scarcity of kob, limited alternative employment opportunities, and the absence of the implementation of the Small-Scale Fisheries Policy (SSFP) in the southern Cape.

Combining local knowledge from fishers with scientific studies provides a comprehensive understanding of key stressors and dynamics. Studies underscore the importance of integrating multiple knowledge sources to improve fisheries management. For example, Peixoto et al. (2022) found that combining fishers' knowledge with scientific data filled critical gaps in the Azores Archipelago's fish stock assessments. Similarly, Kelly et al. (2022) demonstrated that integrating local and scientific knowledge in Norway's Fishguider decision support system enhanced fisheries management, while Ainsworth et al. (2020) showed similar benefits in Scotland, resolving conservation conflicts through multi-perspective approaches.

The participatory-based literature enriches fisheries models by incorporating fishers' experiential insights, which can highlight localised stressors such as changing sea conditions and external impacts such as weather and safety. In Sweden, Wijermans et al. (2020) showed that diverse fishing behaviours, when incorporated, improved fisheries management outcomes by considering social and behavioural dynamics. In South Africa, Rivers et al. (2023) argued that integrating diverse knowledge in Algoa Bay would lead to better legislative transparency. Ward et al. (2021) found both synergies and disconnects in knowledge integration within the southern Cape, illustrating inherent challenges and opportunities.

Gammage and Jarre (2020) and Halbrendt et al. (2014) stress the value of participatory approaches for a dynamic understanding that local knowledge offers as structured decision-making tools. Gammage and Jarre (2021) demonstrate that these help capture uncertainties and foster communication across management scales. Duggan (2012) emphasised that scientific frameworks without local insights may overlook critical, context-specific information.

In summary, while this study employs a literature-based approach grounded in past SCIFR project findings, it acknowledges the proven benefits of integrating fishers' knowledge as reflected in the underlying literature. Studies consistently highlight that models enriched by diverse knowledge sources yield more comprehensive, realistic, and adaptable fisheries management input.

3. From Causal Diagram To Fuzzy Cognitive Model: Sign Re-Evaluation And Proof-Of-Concept Model

In this section, the methods and results used to address Research Question 1a, "What are the most suitable methods for applying fuzzy cognitive modelling (FCM) to the hand linefisheries system in the southern Cape, and how do they impact the accuracy and robustness of the model?" are presented. The section begins by outlining the development of the Proof-of-Concept (POC) model, which captures key components influencing fishers' ability to secure a sustainable livelihood. It explains the methodology employed to quantify relationships between components using a combination of risk assessment and literature-based approaches. Additionally, modelling tools such as Vensim™ and RStudio's 'fcm' package are explored, focusing on conducting sensitivity and assumption testing. The selection of squashing functions and inference rules is examined to assess their impact on the model's accuracy and robustness, offering insights into the application of FCM to small-scale fisheries in the southern Cape.

The *POC model*, designed to capture essential elements affecting the fishers' 'Ability to secure a sustainable livelihood,' was developed by selecting a few key components and connections from the larger causal loop diagram (CLD) and converting this smaller diagram into an FCM. The *POC model* also informed decisions on the choice of software and parameters for output generation in the Regional prototype model.

3.1 Causal Loop Diagram Sign Re-evaluation

The CLD, developed by Gammage and Jarre (2020), served the purpose of understanding and analysing the complex social-ecological systems (SES) within South Africa's southern Cape small-scale commercial linefishery communities. This CLD differed from an FCM. In the CLD, connections between components were labelled as negative (-) when the conceptual effect was negative or harmful, aggravating vulnerability, and vice versa for positive (+) effects. However, in FCMs, the positive/negative label depends on the interaction between components, where positive indicates that one component increases when the other increases (amplifying), and negative indicates that one

component increases when the other decreases (dampening). This difference in the interpretation of the connections necessitated a re-evaluation of all the connections in the CLD developed by Gammage and Jarre (2020). The re-evaluation involved determining whether each component's relationship was amplifying or dampening based on their interactions, per FCM principles. This step was crucial to ensure the internal coherence of the FCM.

Table 3 shows the results of the CLD sign re-evaluation for those components where the sign was changed. 20 out of 54 connection signs were changed. All 64 connections were re-evaluated, and 25 signs were altered. Before re-evaluation, there were 21 dampening connections, 29 amplifying connections, and 14 uncertain connections. After re-evaluation, there were 22 dampening connections, 32 amplifying connections, and 10 uncertain connections.

Table 3: Sign re-evaluation between the causal loop diagram of Gammage and Jarre 2020 and the fuzzy cognitive model in this study for those components where the sign was changed. 20 out of 54 connection signs were changed.

Outgoing component	Incoming component	CLD (Old sign)	FCM (New sign)
'Access to rights'	'Uncertainty'	?	-
'Available sea days'	'Fish (Kob) catches'	?	+
'Change in prevailing winds (direction, strength and seasonality)'	'Fish (Kob) catches'	+	-
'Deterioration in sea state'	'Unsafe operating conditions'	-	+
'External economic pressures'	'Input costs (running costs and equipment)'	-	+
'Implementation of sector-specific policy and implementation'	'Uncertainty'	+	-
'Inshore trawl: illegal fishery practices (fishing too close to coast, targeting and dumping of bycatch)'	'Ecosystem health'	+	-
'Inshore trawl: illegal fishery practices (fishing too close to coast, targeting and dumping of bycatch)'	'Kob abundance'	+	-
'Inshore trawl: illegal fishery practices (fishing too close to coast, targeting and dumping of bycatch)'	'Conflict between inshore trawl and linefishery'	-	+
'Inshore trawl: illegal fishery practices (fishing too close to coast, targeting and dumping of bycatch)'	'Inshore trawl: effect on reef (habitat degradation)'	?	+
'Physical navigation dangers (river mouths)'	'Unsafe operating conditions'	-	+
'Policy and regulation'	'Inshore trawl: illegal fishery practices (fishing too close to coast, targeting and dumping of bycatch)'	?	-
'Policy and regulation'	'Access to rights'	-	+
'Policy and regulation'	'Implementation of sector-specific policy and implementation'	?	+
'Price of Kob and other target species'	'Income (fishing and other sources)'	-	+
'Risk of injury (compromises ability to fish)'	'Fish (Kob) catches'	+	-
'Risk of injury (compromises ability to fish)'	'Ability to secure a sustainable livelihood (put food on the table)'	+	-
'SSFP regulations & implementation'	'Uncertainty'	?	-
'Uncertainty'	'Ability to secure a sustainable livelihood (put food on the table)'	+	-
Alternative employment opportunities'	'Income (fishing and other sources)'	-	+

3.2 Building The Proof-Of-Concept Model

In a small example, the *POC model* outputs explain how modifications to the chosen model components affect the target component 'Ability to secure a sustainable livelihood'. Six components with eight connections were chosen to keep the *POC model* small and straightforward (Figure 5). Each component represents an important aspect of the fishers' livelihood and challenges.

- 'Risk of injury': The risk of personal injury or severe and frequent injury that compromises the fishers' ability to engage in fishing activities.
- 'Unsafe operating conditions': Conditions that may lead to boat damage or injuries, such as rough seas or faulty equipment.
- 'Deterioration in sea state': The prevailing wind conditions that deteriorate the conditions for fishing, reducing the number of available fishing days and injuring fishers.
- 'Fish catches': All fisheries products taken for commercial reasons. The quantity of fish caught, directly contributing to the fishers' Income.
- 'Income (fishing and other sources)': The money received by the fishers for their labour, including earnings from fishing activities and other sources of Income.
- 'Ability to secure a sustainable livelihood': The capacity to obtain a stable and long-term income or resources allowing fishers and their households to meet their basic needs, including accessing food and sustaining their way of life.

The Vensim™ (Personal Learning Edition) software was used to depict the model (Figure 5). The *POC model* focuses on six specific components with eight connections.

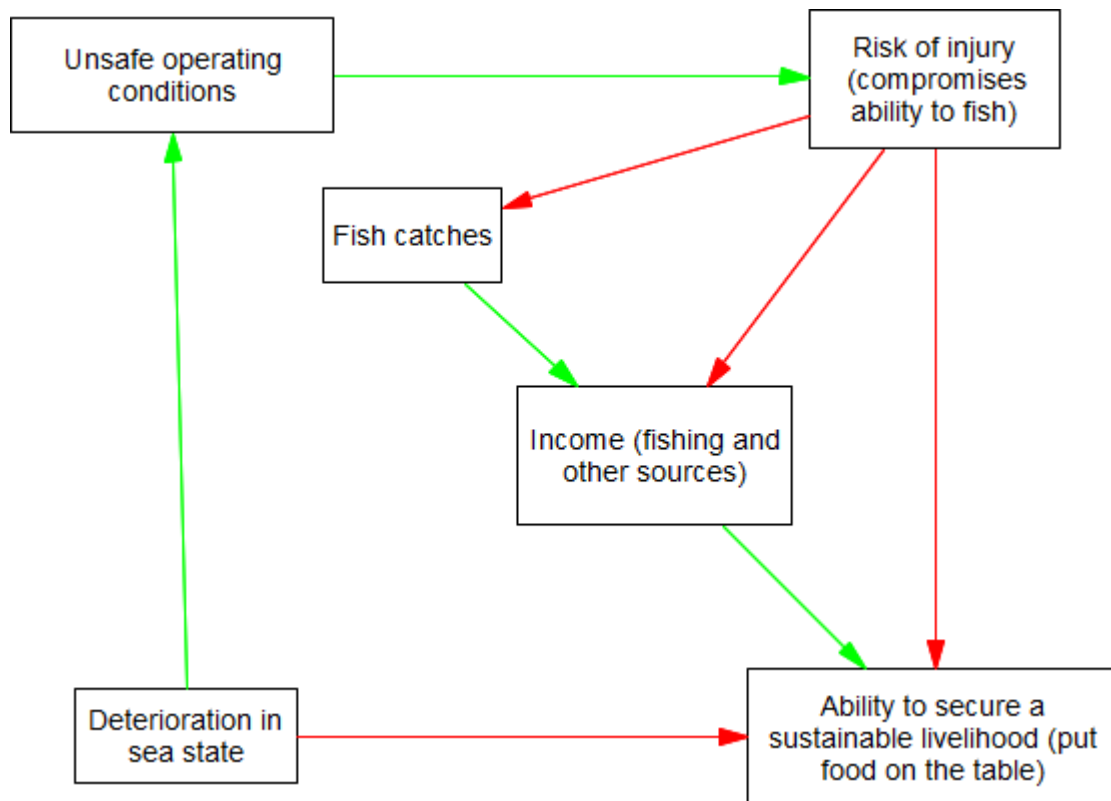


Figure 5: POC design showing how key stressors identified by fishers and sea state stressors interact and affect fishers' Ability to put food on the table. Red arrow: Dampening connection, Green arrow: Amplifying connection. Note the absence of feedback loops.

3.3 Quantification Of Proof-Of-Concept Model Connections

After the *POC model* had been designed, the connections between components needed to be quantified. This meant assigning an amplifying (+) or dampening (-) strength between -1 and 1 to each connection.

A comprehensive literature search used low, medium, and high categories to quantify the *POC model* connections. The desktop literature search followed the methodology outlined below:

A thorough search strategy was developed to identify relevant literature. The literature search incorporated outputs from the SCIFR and Global learning for local solutions (GULLS) projects first (Duggan, 2018; Gammage et al., 2021, 2019, 2017a, 2017b; Gammage and Jarre, 2021, 2020; Jarre et al., 2018; Lyttle et al., 2021; Martins et al., 2019;

Norton, 2014; Ward et al., 2021). If these papers did not provide the necessary information to quantify the connection, other peer-reviewed publications and grey literature specifically focused on environmental, political, and economic aspects related to coastal communities in the southern Benguela were consulted. The necessary literature was compiled using Google Scholar. The articles on the quantified connections were selected for further examination and data extraction. The reference lists of these chosen articles were also reviewed to identify additional relevant sources.

A template was used to record the literature search findings in Excel systematically. The template stored the relationship strength, category quantification, references, and data quality. Categorising and quantifying relationships within a Fuzzy Cognitive Map (FCM) is inherently complex and often requires subjective judgments. In such a situation, it thus becomes essential to adopt a consistent quantification system to manage complexity effectively (Fletcher, 2015, 2005). In FCMs, where the strengths of interactions between system components are often uncertain, applying risk analysis methods provides a structured approach to evaluating these relationships. Although FCMs primarily focus on the consequences of interactions rather than their likelihood, leveraging risk assessment principles allows researchers to assess the potential impact of various interactions systematically (Fletcher 2015). This approach facilitates a more objective semi-quantification of the strengths of relationships, enhancing the model's ability to capture the relative importance of each interaction. Adapting Fletcher's qualitative risk assessment method is driven by its comprehensive and structured approach to prioritising issues. By incorporating this method, the uncertainty of connections in the FCM can be better represented, enhancing the model's accuracy. Adapting Fletcher's (2005) approach to this study, a qualitative risk assessment technique involved assigning scores to consequence and likelihood levels to determine a risk category for each relationship in the *POC model*. There were six ordinal levels of impact for consequence and likelihood, ranging from negligible to catastrophic (0 to 5) for unfavourable consequence (Table 5) and from remote to likely (1 to 6) for likelihood (Table 4), adapting Fletcher's (2005) approach to this study. Favourable consequence ordinal levels (Table 4), ranging from negligible to optimal (0-5), were created to be used where a relationship had a 'favourable' consequence rather than 'unfavourable'. The total score for each

connection was calculated by multiplying the consequence and likelihood scores (Fletcher, 2005).

The relationship category was determined based on the total score, with ranges from 0 to 10 defined as Low, 11 to 20 for Medium, and 21 to 30 as High. This categorisation describes the degree of impact one component has on another, effectively communicating relationship strengths to stakeholders. Specific numerical values were chosen for the Relationship Strength categories to demarcate different relationship levels without overlap or ambiguity. Whole numbers and decimals (-1.0, -0.7, -0.3, 0.3, 0.7, and 1.0) provide a linear progression from highly negative to highly positive relationships (Table 6). Using 0.5 for the medium categories was avoided because it would necessitate using 0 for the low category, which was problematic. A value of 0 would have implied that the relationship did not exist, contradicting the model's purpose. Therefore, using 0.3 and 0.7 ensured that all categories were meaningful and relevant, effectively capturing the strengths of the relationship.

Data quality was assessed on a scale of 1 to 4, with 1 indicating very low confidence, 2 indicating expert judgement, 3 indicating general literature support (this includes international peer-reviewed and grey literature), and 4 indicating data support (this includes local data for the Benguela current system and local peer-reviewed or grey literature). Data quality scores were not used in the analysis, as the focus was on testing components with high *Centrality* scores rather than those with low data quality. An extended sensitivity analysis accounting for these data quality scores is recommended; however, this was beyond the scope of the present study."

To aid in interpreting convergence values within the model, qualitative ranges were established to represent varying degrees of impact (Table 7). These ranges are designed to simplify the understanding and discussion of results, providing a structured yet accessible framework for assessing outcomes. Although the boundaries of these qualitative ranges are sharply defined, their interpretation within the analysis is applied with a degree of flexibility. This allows slight deviations from strict cutoffs to be considered in the discussion, accommodating data nuances and contextual factors that

may influence results. This approach acknowledges the inherent complexity of modelling systems, where exact numerical thresholds may not fully capture the subtleties of real-world implications. These qualitative ranges indicate whether an effect is favourable or unfavourable and the strength of the impact on the 'Ability to secure a sustainable livelihood'. Categorising convergence values enables the analysis to highlight whether an outcome points to a substantial threat, positive change, or more moderate effects, such as a challenge or a slight boost. This method enhances the model's interpretability, clarifying how different scenarios or variables influence the overarching goal of achieving sustainable livelihoods.

Table 4: Likelihood score scale definitions sourced from Fletcher (2005).

Likelihood Score
1 - Remote: It was expected to occur
2 - Rare: May occur sometimes
3 - Unlikely: Some evidence to suggest this was possible here
4 - Possible: Uncommon, but has been known to occur elsewhere
5 - Occasional: May occur in exceptional circumstances
6 - Likely: Never heard of, but not impossible

Table 5: Unfavourable and favourable consequence score scales. The definitions for unfavourable consequences were sourced from Fletcher (2005), while those for favourable consequences were derived based on the corresponding definitions of negative consequences.

Unfavourable Consequence Score	Favourable Consequence Score
0-Negligible: No recovery time needed	0-Negligible: No noticeable positive impact
1-Minor: Rapid recovery would occur if stopped - measured in months	1-Minor: Positive impacts are evident and occur within months
2-Moderate: Recovery measured in months to years if activity stopped	2-Moderate: Positive impacts are evident and occur within months to years
3-Severe: Recovery measured in years if stopped	3-Substantial: Positive impacts are considerable and occur within years
4-Major: Recovery period measured in years to decades if stopped	4-Major: Positive impacts are extensive and occur over years to decades
5-Catastrophic: Long-term recovery period to acceptable levels will be greater than decades or never, even if stopped	5-Optimal: Positive impacts are profound and have long-term benefits, lasting decades or more

Table 6: Relationship Strength Categories Used to Quantify the Strength of Connections in the Southern Cape Fishery System.

Category	Relationship Strength
High Negative	-1.0
Medium Negative	-0.7
Low Negative	-0.3
Low Positive	0.3
Medium Positive	0.7
High Positive	1.0

Table 7: Convergence value ranges and their corresponding qualitative interpretations.

Convergence value range		Unfavourable Impact	Favourable Impact
Greater than 0.8	Less than -0.8	Substantial Threat	Substantial Positive Change
0.7 to 0.8 (inclusive)	-0.7 to -0.8 (inclusive)	Very Challenging	Meaningful Improvement
0.5 to 0.7 (exclusive 0.7)	-0.5 to -0.7 (exclusive -0.7)	Challenging	Notable Boost
0.3 to 0.5 (exclusive 0.5)	-0.3 to -0.5 (exclusive -0.5)	Somewhat Challenging	Slight Boost
0.0 to 0.3 (inclusive 0.0, exclusive 0.3)	0.0 to -0.3 (inclusive 0.0, exclusive -0.3)	Neither Challenging nor Favourable	Neither Challenging nor Favourable

Table 8 shows the results of the desktop literature search, including the relationships that had been quantified, the quantification given, and the data quality score. The supporting evidence for the quantifications can be found in Appendix A1.

Table 8: Overview of all eight relationships within the *POC model*. These had been classified into three relationship categories: Low, Medium, and High.

Relationship	+/-	Relationship Category	Relationship	Data Quality (1-4)
'Risk of injury' -> 'Fish catches'	-	Medium	0.7	3
'Risk of injury' -> 'Income'	-	Medium	0.7	3
'Risk of injury' -> 'Ability to secure a sustainable livelihood'	-	Medium	0.7	3
'Unsafe operating conditions' -> 'Risk of injury'	+	Low	0.3	4
'Deterioration in sea state' -> 'Unsafe operating conditions'	+	Medium	0.7	3
'Deterioration in sea state' -> 'Ability to secure a sustainable livelihood'	-	Low	0.3	2
'Fish catches' -> 'Income'	+	Medium	0.7	3
'Income' -> 'Ability to secure a sustainable livelihood'	+	High	1	3

3.4 Deciding Which Software, Squashing Function, Inference Rule And *Lambda* Parameter To Use While Conducting Tests On Proof-Of-Concept Model

This section aims to select the appropriate software, squashing function, inference rule, and *Lambda Parameter* to perform sensitivity and assumption analyses on a fuzzy-logic cognitive model (FCM). The *Mental Modeler* software (Gray and Cox, 2013) and the R Language with *RStudio* (R Core Team 2023), specifically the '*fcm*' (Dikopoulou and Papageorgiou, 2017) package, were tested. To make a meaningful choice, it was crucial to investigate the available inference rules and squashing functions in both software alternatives to enhance the accuracy and reliability of sensitivity and assumption analyses to be conducted on the FCM.

Proof-Of-Concept Model: Software And Squashing Functions

xi) Proof-Of-Concept Model: Mental Modeler Tests

Mental Modeler was used to conduct a sensitivity analysis, evaluating the outputs of using the sigmoid and *Hyperbolic Tangent Functions* on the *POC model* shown in Figure 5. The *Kosko Inference Rule* was the default inference rule used for all calculations within *Mental Modeler*. The sensitivity tests were conducted by activating the 'Deterioration in sea state' component and evaluating the outputs using the *Sigmoid Function* first and then the *Hyperbolic Tangent Function*. A component was activated by changing the component's value from 0 to 1 and keeping all deactivated components at 0. Two tests were conducted (one for each squashing function). Figure 6 displays the model's outcomes when the 'Deterioration in sea state' component was fully activated.

Using the *Sigmoid Function* resulted in noticeable (>10%) changes in the components 'Unsafe operating conditions' and 'Ability to put food on the table' (Figure 6). The 'Risk of injury' component was also minimally affected despite being the second highest convergence value from the fully activated component 'Deterioration in sea state'. The direct connection from the fully activated component influenced the final output, 'Ability to put food on the table'. The results indicated that using the *Sigmoid Function* dampened all indirect relationships beyond one intermediate step more than using the *Hyperbolic Tangent Function*. The convergence value, 'Ability to put food on the table',

using the *Hyperbolic Tangent Function*, was 62% larger than that obtained using the *Sigmoid Function*. The dampening effect observed when using the *Sigmoid Function* was not evident when using the *Hyperbolic Tangent Function*. The latter produced changes in all system components (except for 'Deterioration in sea state') and demonstrated how change propagated across the system (Figure 6).

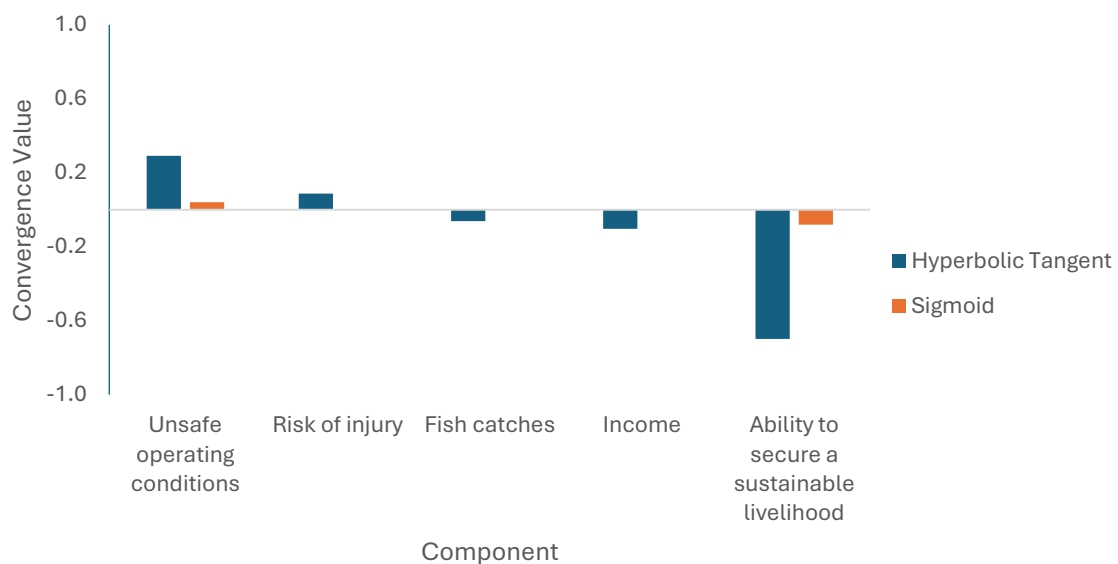


Figure 6: Convergence value of components of the POC model with 'Deterioration in sea state' component fully activated, using the *Kosko Inference Rule* in Mental Modeler and the hyperbolic tangent (blue) and sigmoid (orange) squashing functions.

When another model was created by isolating the 'Deterioration in sea state' and 'Ability to secure a sustainable livelihood' components, with a connection between them, and the 'Deterioration in sea state' component was fully activated, the output value remained the same using the *Sigmoid Function*, while it changed by 10% using the *Hyperbolic Tangent Function*. This observation indicated that using the *Sigmoid Function* exhibited low sensitivity to changes in the model structure when calculating outputs for direct connections. Several sensitivity tests also revealed that using the *Sigmoid Function* did not produce noticeable output changes unless a component was activated by 60% or more. Upon manual calculation, it was found that the Mental Modeler was generating inaccurate outputs when using the *Sigmoid Function*. In contrast, the *Hyperbolic Tangent Function* generated outputs even with component activation as low as 1%.

xii) Proof-Of-Concept Model: Rstudio (The 'fcm' Package) Tests

Due to the uncertainties surrounding the calculations that used the *Sigmoid Function* in *Mental Modeler*, it was decided to assess the use of the sigmoid and *Hyperbolic Tangent Functions* on the *POC model* using the 'fcm' package in *RStudio* and using the *Kosko Inference Rule*. The purpose was to compare the results with those obtained from *the Mental Modeler*, who also used the *Kosko Inference Rule*. The sensitivity tests were conducted by activating the 'Deterioration in sea state' component and evaluating the outputs using the *Sigmoid Function* first and then the *Hyperbolic Tangent Function*. Two tests were conducted (one for each squashing function). The model's outcomes, when the 'Deterioration in sea state' component was fully activated, are depicted in Figure 7.

When running the *POC model* with the 'fcm' package, the outcomes were the values at convergence (i.e., when they start forming a repeating cycle). The convergence values obtained using the *Hyperbolic Tangent Function* with the 'fcm' package (Figure 7) match those from *Mental Modeler* (Figure 6). However, there were differences between *Mental Modeler* and 'fcm' package outputs when using the *Sigmoid Function*, including a change in the sign of the convergence value. Activating 'Deterioration in sea state' using the *Sigmoid Function* in the 'fcm' package resulted in noticeable (>10%) changes in all model components. Unlike *Mental Modeler*, the 'fcm' package does not dampen indirect relationships beyond one intermediate step using the *Sigmoid Function*, allowing the change from the activated component to propagate throughout the system.

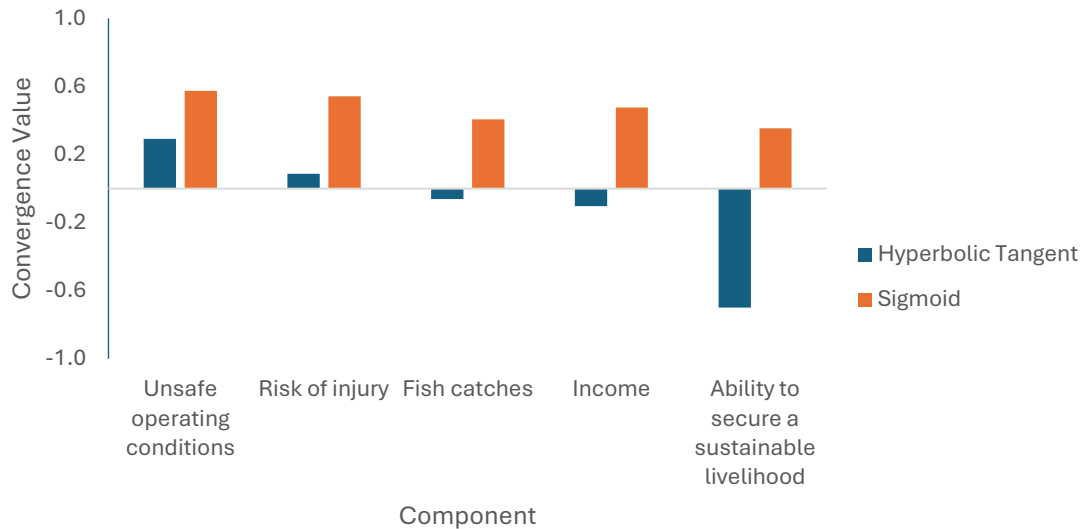


Figure 7: Convergence value for POC model components when the 'Deterioration in sea state' component was fully activated, using the *Kosko Inference Rule* in the 'fcm' package and the sigmoid or *Hyperbolic Tangent Functions*.

When assessing the outputs of FCM inference using the *Hyperbolic Tangent Function*, the sign indicates whether the change was a decrease or an increase from the baseline. Focusing on the change in the component only and not the direction of the response when the 'Deterioration in sea state' component was fully activated, the three components with the highest changes in convergence values using the *Hyperbolic Tangent Function* were 'Ability to secure a sustainable livelihood,' 'Unsafe operating conditions,' and 'Income,' listed in descending order of change (Figure 7). Conversely, with the *Sigmoid Function*, the three components with the highest changes were 'Unsafe operating conditions,' 'Risk of injury,' and 'Income,' listed in descending order of change (Figure 7).

Examining the direct connections illustrated in the model helped to understand these findings better. Figure 5 shows direct connections between the driving component 'Deterioration in sea state' and 'Unsafe operating conditions' and 'Ability to secure a sustainable livelihood.' Therefore, activating 'Deterioration in sea state' was expected to have a more substantial impact on these two target components than the other components in the model. Furthermore, the change should propagate through the

model, gradually decreasing as it moves away from the activated component. The outcomes obtained using the *Hyperbolic Tangent Function* align with these expectations. The *Sigmoid Function* results did not correspond to what was expected.

It was suspected that the sign (+/-) of the connections affected the propagation of the effect through the model when different signs were used since the *Sigmoid Function* outputs only positive values. To test for this, quantifying the relationship between 'Deterioration in sea state' and 'Ability to obtain a sustainable livelihood' was changed from '-0.7' to '+0.7' to check if positive and negative connections were mapped differently using the *Sigmoid Function*. Subsequently, the sigmoid outputs listed 'Ability to secure a sustainable livelihood,' 'Unsafe operating conditions,' and 'Risk of injury' in descending order of change. These results aligned with expectations since the abovementioned components were directly connected to the activated or indirect components with high quantifications. Additional tests were conducted by activating each component of the *POC model*, one at a time, and ensuring the outgoing connection from the activated component was negative. Then, the convergence values were calculated to check if the *Sigmoid Function* attenuated dampening connections. In all cases, the outcomes indicated that the *Sigmoid Function* attenuated the effects of dampening connections. This attenuation occurs because negative inputs are mapped to negative values when using the *Hyperbolic Tangent Function*, whereas, with the *Sigmoid Function*, negative inputs are mapped to values close to zero (Figure 8). Positive inputs had a small difference in output value using the sigmoid and *Hyperbolic Tangent Functions*, so the attenuation does not occur with positive inputs. This attenuation of negative inputs using the *Sigmoid Function* affected the final convergence values and the conclusions drawn from the model outputs.

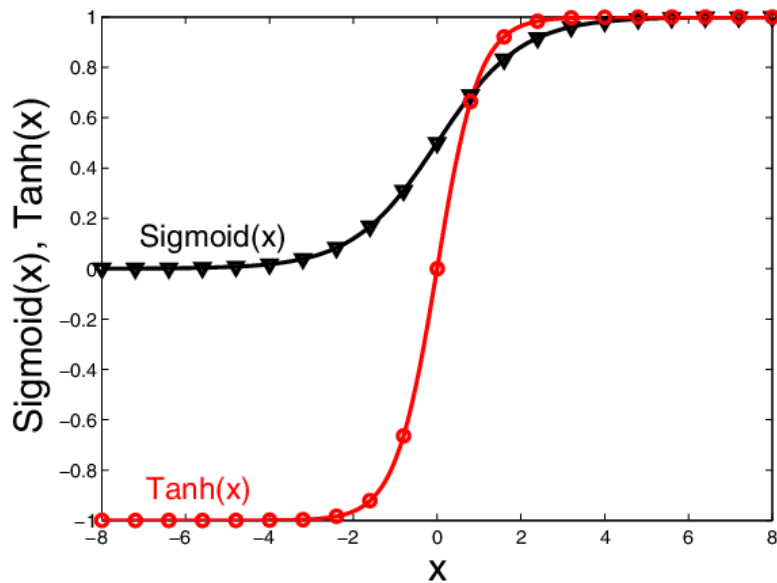


Figure 8: Hyperbolic Tangent ($\text{Tanh}(x)$) and Sigmoid ($\text{Sigmoid}(x)$) Squashing Functions (adopted from Namin et al., 2009).

xiii) Proof-Of-Concept Model: Squashing Function Conclusion

Based on Penn et al.'s (2013) recommendation, tests were conducted on implementing the sigmoid and *Hyperbolic Tangent Functions* in *Mental Modeler* and the 'fcm' package. Based on previous studies and sensitivity tests performed on the *POC model*, it was observed that the choice of squashing function impacts the outputs of the model and could alter the understanding of outputs, thus influencing decision-making based on those outputs. Based on the literature and the tests conducted on the *POC model*, the decision was made to apply the *Hyperbolic Tangent Function* to constrain the component values using the 'fcm' package for analysis. The 'fcm' package was chosen over *Mental Modeler* because it provides greater transparency regarding its functioning and calculation processes. It allows for tracing the calculations performed using the sigmoid and *Hyperbolic Tangent Functions*, demonstrating how changes propagate through the model. The *Hyperbolic Tangent Function* was chosen because this function does not dampen the effects of dampening connections as strongly as the *Sigmoid Function*.

3.4.2 Proof-Of-Concept Model: Inference Rules

After the *RStudio* 'fcm' package and the *Hyperbolic Tangent Function* had been chosen, the subsequent step was to select which inference rule would be used for data analysis. The 'fcm' package provided a choice between three inference rules: *Kosko*, *Modified Kosko*, and *Rescaled*, whereas *Mental Modeler* was limited to using only the *Kosko Inference Rule*.

When the *Rescaled Kosko* rule constrains the over-activation of components, thereby preventing an excessive influence of uncertain aspects on decision-making processes (Dikopoulou et al., 2018; Sujamol et al., 2018). However, it is essential to note that using the *Rescaled Kosko* rule does not always guarantee model convergence (Sujamol et al., 2018). Even though using this rule in the *POC model* produced convergence values (Figure 9), this may not be true for subsequent prototypes. Furthermore, when the 'Deterioration in sea state' component was fully activated on the *POC model* using the *Hyperbolic Tangent Function*, output values were close to the limit (+/-1) and showed opposite signs to the results obtained when using the other inference rules (Figure 9). Consequently, a decision was made to choose either the *Kosko Inference Rule* or the *Modified Kosko Inference Rule*.

A sensitivity test was conducted to determine which inference rule to use by activating the 'Deterioration in sea state' component and evaluating the outputs using the *Kosko Inference Rule* and the *Modified Kosko Inference Rule*, with a separate test conducted for each inference rule.

The *Kosko Inference Rule* represents the magnitude of change in component values, whereas the *Modified Kosko Inference Rule* combines the original component value with the magnitude of change to provide an overall measure of change for each component (Sujamol et al., 2018). The test indicated that the outcomes obtained using the *Modified Kosko Inference Rule* were larger than those obtained using the *Kosko Inference Rule* (Figure 9). For instance, using the *Modified Kosko Inference Rule*, the 'Income' and 'Ability to secure a sustainable livelihood' components resulted in values close to one. A limitation of employing the *Modified Kosko Inference Rule* was that since the *Hyperbolic Tangent Function* guaranteed that output values stayed within the range of -1 to 1, even if there was a substantial change in a convergence value that exceeds these limits, the

resulting value will be capped at -1 or 1. Figure 9 reveals only a 2.5% difference between 'Income' and 'Ability to secure a sustainable livelihood' when using the *Modified Kosko Inference Rule*. However, considering that 'Ability to secure a sustainable livelihood' cannot be less than -1, the difference between these two components might be more substantial since the difference between 'Income' and 'Ability to secure a sustainable livelihood' using the *Kosko Inference Rule* was larger. This strong squashing effect on the convergence value was not evident when using the *Kosko Inference Rule*, as Figure 9 indicates a 59.5% difference between 'Income' and 'Ability to secure a sustainable livelihood'.

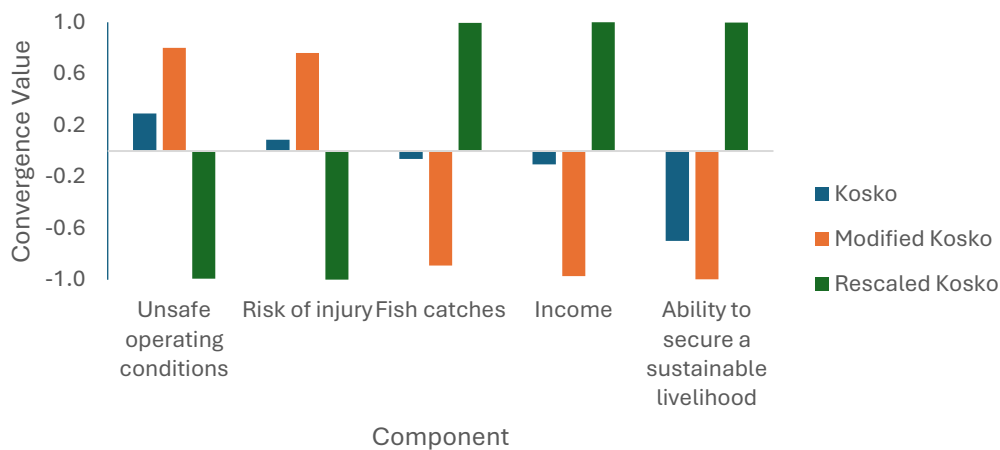


Figure 9: Convergence value for components in the POC model when the 'Deterioration in sea state' component was fully activated, using the Kosko, Modified-Kosko, and Rescale Inferences rules, with the *Hyperbolic Tangent Function*.

i) Proof-Of-Concept Model: Inference Rule Conclusion

Tests were conducted to implement the Kosko, Modified Kosko, and Rescaled *Kosko Inference Rules* using the 'fcm' package. Based on the literature and the tests performed on the prototype, the *Kosko Inference Rule* for analysis appears to be the most suitable for this project. This decision was made because applying the Rescaled *Kosko Inference Rule* reversed the output's sign (+/-), and some studies indicated that this rule does not consistently reach convergence. The *Modified Kosko Inference Rule* reduced the

convergence values due to the limiting effect of the squashing function on the maximum convergence value.

3.4.3 Proof-Of-Concept Model: Lambda Parameter

Regarding the *Lambda Parameter*, which influences the steepness of the *Hyperbolic Tangent Function* near zero, tests were conducted with values ranging from 1 to 3. A default value of 1 was chosen based on its balanced representation of model changes without exaggerating slight changes, aligning with previous findings in the literature (Dikopoulou et al., 2018).

Tests with different λ values (1, 2, and 3) revealed that increasing λ beyond 3 resulted in output convergence values equalling 1, which was illogical and did not account for the uncertainty in the interaction of model components. Specifically, when λ was set to 2, the 'Ability to secure a sustainable livelihood' reached its maximum value of -1 and stayed constant even as λ increased to three, illustrating that higher λ values lead to extreme and unrealistic convergence values. The comparative analysis of convergence values under different λ settings (Table 9) demonstrated that $\lambda = 1$ provided a more balanced outcome, reflecting the system's understanding more accurately. While convergence values increased with higher λ values, the output for 'Ability to secure a sustainable livelihood' at $\lambda = 2$ and 3 were excessively high, indicating a disconnect with the logical understanding of the system's dynamics. Hence, $\lambda = 1$ was deemed appropriate for all runs in this study, providing standardisation and facilitating easier comparison of results across different research publications.

Table 9: Convergence values in the *POC model* when setting the *Lambda Parameter* at 1, 2, and 3.

Component Name	Convergence Value		
	<i>Lambda</i> = 1	<i>Lambda</i> = 2	<i>Lambda</i> = 3
Ability to secure a sustainable livelihood	-0.698	-1	-1
Fish catches	-0.061	-0.41	-0.83
Income	-0.103	-0.77	-0.99
Risk of injury	0.087	0.31	0.57
Unsafe operating conditions	0.291	0.54	0.72

3.5 Testing The Proof-Of-Concept Prototype Model

With the Proof-of-concept (POC) model constructed and parameterised and the squashing function and inference rules for analysis selected, the next step involved subjecting the *POC model* to sensitivity and assumption testing. The following section focuses firstly on sensitivity analysis, which assesses the importance of quantification values and the model's tolerance to quantification variations. Next, assumption analysis was presented, where key assumptions were tested by modifying the model.

3.5.1 Proof-Of-Concept Model: Sensitivity Testing Of Connection Strengths

This section presents the changes in convergence values from the baseline when connection quantifications were altered by one (*Table 10*) and two-category (*Table 11*) category increments, noting that most changes were below 0.1 (10%). The 'Deterioration in sea state' component was activated in five tests since it was the driving component of the POC model. To activate a component, the starting value must be changed from 0 to 1, while the remaining 'deactivated' components remain at 0. To evaluate the sensitivity of the POC model to inputs, two groups of tests were conducted: 1) modifying the quantification of connections by one category increment at a time, and 2) modifying the quantification by two category increments. Positive numbers were reduced (e.g., a connection strength of 0.7 was changed to 0.3, and in two-category tests, 0.7 was

changed to 0.1 and 1.0 to 0.3), while negative numbers were increased (e.g., -0.7 was changed to -0.3, and in two-category tests, -1.0 was changed to -0.3). Connections with a strength of ± 0.3 were left unchanged in both tests to avoid altering their sign.

Starting with the 'Ability to secure a sustainable livelihood', the baseline value was -0.698 (very challenging) when 'Deterioration in sea state' was activated. When the connection quantifications were reduced by one category, the strongest positive change occurred with the connection between the 'Deterioration in sea state' and the 'Ability to secure a sustainable livelihood', showing a substantial increase of +0.265 in 'Ability to secure a sustainable livelihood' from the baseline. Other connections, such as the 'Risk of injury' to 'Fish catches' and 'Income(fishing)', showed minor positive changes ranging from +0.013 to +0.018, indicating stable impacts under the sensitivity test. When the quantification was altered by two categories, the connection between 'Deterioration in sea state' and the 'Ability to secure a sustainable livelihood' showed a dramatic increase in 'Ability to secure a sustainable livelihood' of +0.440, suggesting even greater sensitivity. Other connections showed slightly higher changes than in the one-category test, with increases of +0.019 to +0.028.

For 'Income (fishing)', with a baseline value of -0.103 (Neither challenging nor favourable), the most notable positive change in the one-category test was observed in the connection between 'Unsafe operating conditions' and the 'Risk of injury', which increased by +0.069. In the two-category test, the strongest positive change was in the connection between the 'Risk of injury' and 'Income (fishing)', increasing by +0.042. Connections involving the 'Ability to secure a sustainable livelihood' showed no change in both tests. The connection between the 'Risk of injury' and 'Fish catches' showed a positive change of +0.024 in the one-category test and +0.036 in the two-category test, indicating moderate sensitivity.

'Fish catches' had a baseline value of -0.061 (Neither challenging nor favourable). In the one-category test, the strongest positive change in this category was associated with the connection between 'Unsafe operating conditions' and the 'Risk of injury', which increased by +0.041. In the two-category test, the most substantial change was in the connection between the 'Risk of injury' and 'Fish catches', which increased by +0.052, indicating even greater sensitivity. Other connections, including those with 'Income

(fishing)' and the 'Ability to secure a sustainable livelihood', remained unchanged in both tests, reflecting stability in their impacts.

Regarding the 'Risk of injury', the baseline value was 0.087 (Neither challenging nor favourable). In the one-category test, slight decreases were seen in the connections involving 'Unsafe operating conditions' (-0.058) and 'Deterioration in sea state' (-0.057). In the two-category test, all connections remain unchanged from baseline.

For 'Unsafe operating conditions', with a baseline value of 0.291 (Somewhat challenging), the most substantial negative change in the one-category test was observed in the connection between 'Deterioration in sea state' and 'Unsafe operating conditions', which decreased by -0.192. In the two-category test, all connections remained unchanged from baseline.

Overall, most of the changes from baseline were below 0.1 (10%), indicating that altering individual connection quantifications does not generally impact the convergence values; however, this depends on which connections are being altered. For example, the sensitivity analysis highlights the influence of the 'Deterioration in sea state' on the 'Ability to secure a sustainable livelihood' due to the direct connection between the two components, with the change from baseline becoming even more pronounced in the two-category test (+0.440 compared to +0.265 change from baseline). It also highlights the considerable impact of the 'Risk of injury' on 'Income (fishing)' and 'Fish catches', with slightly higher changes observed in the two-category test. This highlights that awareness of direct vs indirect connections in the model was necessary before making changes and should be considered when working on the larger regional prototype model.

Table 10: Convergence values when connection quantifications from the POC model were altered by one category increment compared to the baseline.

	Convergence Value																
	Baseline	Risk of injury (compromises ability to fish) -> Fish (Kob) catches	Change from baseline	Risk of injury (compromises ability to fish) -> Income (fishing and other sources)	Change from baseline	Risk of injury (compromises ability to fish) -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline	Unsafe operating conditions -> Risk of injury (compromises ability to fish)	Change from baseline	Deterioration in sea state -> Unsafe operating conditions	Change from baseline	Deterioration in sea state -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline	Fish (Kob) catches -> Income (fishing and other sources)	Change from baseline	Income (fishing and other sources) -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline
Ability to secure a sustainable livelihood	-0.698	-0.686	0.013	-0.680	0.018	-0.680	0.018	-0.638	0.060	-0.639	0.059	-0.434	0.265	-0.686	0.013	-0.682	0.016
Income	-0.103	-0.079	0.024	-0.069	0.035	-0.103	0.000	-0.035	0.069	-0.036	0.068	-0.103	0.000	-0.079	0.024	-0.103	0.000
Fish catches	-0.061	-0.026	0.035	-0.061	0.000	-0.061	0.000	-0.020	0.041	-0.021	0.040	-0.061	0.000	-0.061	0.000	-0.061	0.000
Risk of injury	0.087	0.087	0.000	0.087	0.000	0.087	0.000	0.029	-0.058	0.030	-0.057	0.087	0.000	0.087	0.000	0.087	0.000
Unsafe operating conditions	0.291	0.291	0.000	0.291	0.000	0.291	0.000	0.291	0.000	0.100	-0.192	0.291	0.000	0.291	0.000	0.291	0.000

Table 11: Convergence values when connection quantifications from the POC model were altered by two category increments compared to the baseline.

	Convergence Value												
	Baseline	Risk of injury (compromises ability to fish) -> Fish (Kob) catches	Change from baseline	Risk of injury (compromises ability to fish) -> Income (fishing and other sources)	Change from baseline	Risk of injury (compromises ability to fish) -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline	Deterioration in sea state -> Unsafe operating conditions	Change from baseline	Fish (Kob) catches -> Income (fishing and other sources)	Change from baseline	Income (fishing and other sources) -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline
Ability to secure a sustainable livelihood	-0.698	-0.679	0.019	-0.671	0.028	-0.671	0.028	-0.258	0.440	-0.679	0.019	-0.660	0.039
Income	-0.103	-0.067	0.036	-0.061	0.042	-0.103	0.000	-0.103	0.000	-0.067	0.036	-0.103	0.000
Fish catches	-0.061	-0.009	0.052	-0.051	0.010	-0.061	0.000	-0.061	0.000	-0.061	0.000	-0.061	0.000
Risk of injury	0.087	0.087	0.000	0.087	0.000	0.087	0.000	0.087	0.000	0.087	0.000	0.087	0.000
Unsafe operating conditions	0.291	0.291	0.000	0.291	0.000	0.291	0.000	0.291	0.000	0.291	0.000	0.291	0.000

3.5.2 Proof-Of-Concept Model: Sensitivity Analysis Of The Activation Values

In this section, activation values are tested across a broader range (-1 to 1) to reflect better realistic conditions within the small-scale fisheries of the southern Cape. This contrasts with standard activation methods, which typically set component values to 1. While some studies activate components at values other than 1, none provide a clear rationale for this choice. Refer to Section 2.4.5 on scenario testing for a list of these studies.

This section applies sensitivity analysis to the activation values within the Proof-of-Concept (POC) model. To ensure consistency, the 'Deterioration in sea state' transmitting component was systematically adjusted to activation values of -1, -0.7, -0.3, 0.3, 0.7, and 1, one at a time. This approach allows for examining how varying activation values impact the model's outputs, offering insights into the model's behaviour under different conditions.

The initial scenario tests revealed an issue with the function (Refer to Appendix A2 for the convergence values). Upon examining the source code of the 'fcm.infer' function used to calculate convergence values, it was found that the function only recognised and clamped an activated component if it equalled 1. After contacting the 'fcm' package developers, the code was modified to ensure all non-zero values were activated and clamped in each iteration. The altered function, 'fcm.infer2', was tested to ensure it produced the same results as the original when 'Deterioration in sea state' was activated to 1, which it did.

The scenario tests were redone using the modified 'fcm.infer2' function, and the results were presented in Table 12. The component convergence values remained consistent with the activation values and were correctly clamped for all activation values. Consequently, 'fcm.infer2' was used to perform scenario testing in this study.

Table 12 reveals that when 'Deterioration in sea state' was deactivated or activated by the same magnitude, the convergence value of the components remained the same but changed sign (+/-). For example, when the 'Deterioration in sea state' was activated (+1) or deactivated (-1), the 'Ability to secure a sustainable livelihood' component converged at -0.698 and +0.698, respectively. Notably, the 'Ability to secure a sustainable livelihood'

component showed the strongest changes, followed by 'Unsafe operating conditions', 'Income', 'Risk of injury', and 'Fish catches'. Convergence values for 'Unsafe operating conditions' ranged from -0.291 to +0.291, underscoring the direct impact of sea conditions on operational safety. Other components, such as 'Fish catches' and 'Income', showed minor changes, with convergence values ranging from +0.061 to -0.061 and +0.103 to -0.103, respectively, indicating smaller impacts (Table 12). The 'Risk of injury' displayed a negative relationship with 'Deterioration in sea state', where deteriorating conditions increased the risk of injury, and improving conditions decreased it.

Table 12: Convergence values in the POC model when using the 'fcm.infer2' function and activating 'Deterioration in sea state' to -1,-0.7,-0.3,0,0.3,0.7, and 1.

Component Name	'Deterioration in sea state' activation value and corresponding convergence values in model components						
	-1	-0.7	-0.3	0	0.3	0.7	1
Ability to secure a sustainable livelihood	0.698	0.542	0.255	0	-0.255	-0.542	-0.698
Deterioration in sea state	-1.000	-0.700	-0.300	0	0.300	0.700	1.000
Fish catches	0.061	0.043	0.019	0	-0.019	-0.043	-0.061
Income	0.103	0.074	0.032	0	-0.032	-0.074	-0.103
Risk of injury	-0.087	-0.062	-0.027	0	0.027	0.062	0.087
Unsafe operating conditions	-0.291	-0.207	-0.090	0	0.090	0.207	0.291

3.5.3 Proof-Of-Concept Model: Assumption Testing Of Connection Strengths

This section presents the changes in convergence values from the baseline when connections were removed (Table 13), noting that most changes were below 0.1 (10%). Key assumptions were tested by modifying the model and observing the resulting changes in output. The 'Deterioration in sea state' component was activated in all tests as a driving component of the *POC model*. To evaluate the *POC model's* assumptions, connections were removed one at a time to test if the initial assumptions of the inserted connections were important.

Starting with the 'Ability to secure a sustainable livelihood', the baseline value was -0.698. When certain connections were removed, the strongest positive change

occurred with removing the connection between the 'Deterioration in sea state' and the 'Ability to secure a sustainable livelihood', showing a substantial increase of +0.536 from the baseline. Other connections, such as the 'Risk of injury' to 'Fish catches' and 'Income (fishing)', show positive changes of +0.022 and +0.032, respectively. Removing the connection between 'Unsafe operating conditions' and the 'Ability to secure a sustainable livelihood' resulted in a positive change of +0.094.

For 'Income (fishing)', with a baseline value of -0.103, the most notable positive change was observed by removing the connection between 'Unsafe operating conditions' and 'Risk of injury', which increased by +0.103. Connections involving the 'Ability to secure a sustainable livelihood' show a stable baseline with no change. Removing the connection between the 'Risk of injury' and 'Income (fishing)' shows a positive change of +0.042.

'Fish catches' had a baseline value of -0.061. The strongest positive change in this category was associated with removing the connection between the 'Risk of injury' and 'Fish catches', which increased by +0.061. Other connections remain unchanged, including those with 'Income (fishing)' and the 'Ability to secure a sustainable livelihood'.

Regarding the 'Risk of injury', the baseline value was 0.087. Removing the connection involving 'Unsafe operating conditions' results in a substantial negative change of -0.087. All other connections, such as those with 'Fish catches', 'Income (fishing)', and the 'Ability to secure a sustainable livelihood', remain unchanged.

For 'Unsafe operating conditions', with a baseline value of 0.291, removing the connection between the 'Deterioration in sea state' and 'Unsafe operating conditions' results in a negative change of -0.291. Other connections remain unchanged.

Most changes from the baseline convergence values were under 0.1 (or 10%), suggesting that removing individual connections had minimal impact. However, the influence varied based on which connections were removed. Notably, the assumption analysis underscored the substantial role of the direct connection between 'Deterioration in sea state' and 'Ability to secure a sustainable livelihood,' where removal resulted in a +0.536 shift in convergence. This effect arises from the direct relationship between these two components, highlighting the importance of understanding model dynamics and their

specific interactions before making adjustments. Such considerations are essential when working towards a more comprehensive regional prototype model.

Table 13: Convergence values when connection quantifications from the POC model were removed compared to the baseline.

Component affected when the connection was removed	Convergence Value																
	Baseline	Risk of injury (compromises ability to fish) -> Fish (Kob) catches	Change from baseline	Risk of injury (compromises ability to fish) -> Income (fishing and other sources)	Change from baseline	Risk of injury (compromises ability to fish) -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline	Unsafe operating conditions -> Risk of injury (compromises ability to fish)	Change from baseline	Deterioration in sea state -> Unsafe operating conditions	Change from baseline	Deterioration in sea state -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline	Fish (Kob) catches -> Income (fishing and other sources)	Change from baseline	Income (fishing and other sources) -> Ability to secure a sustainable livelihood (put food on the table)	Change from baseline
Ability to secure a sustainable livelihood	-0.698	-0.676	0.022	-0.666	0.032	-0.666	0.033	-0.604	0.094	-0.604	0.094	-0.163	0.536	-0.676	0.022	-0.642	0.057
Income	-0.103	-0.061	0.042	-0.061	0.042	-0.103	0.000	0.000	0.103	0.000	0.103	-0.103	0.000	-0.061	0.042	-0.103	0.000
Fish catches	-0.061	0.000	0.061	-0.043	0.018	-0.061	0.000	0.000	0.061	0.000	0.061	-0.061	0.000	-0.061	0.000	-0.061	0.000
Risk of injury	0.087	0.087	0.000	0.087	0.000	0.087	0.000	0.000	-0.087	0.000	-0.087	0.087	0.000	0.087	0.000	0.087	0.000
Unsafe operating conditions	0.291	0.291	0.000	0.291	0.000	0.291	0.000	0.291	0.000	0.000	-0.291	0.291	0.000	0.291	0.000	0.291	0.000

3.5.4 Testing The Proof-Of-Concept Prototype Model: Conclusion

The sensitivity tests conducted on the Proof-of-Concept (POC) model provided critical insights into the model's responsiveness to changes in connection quantifications. Most changes from the baseline were below 0.1 (10%), indicating that individual connection quantifications did not impact convergence values. However, notable exceptions were observed in key areas, such as the substantial influence of the 'Deterioration in sea state' on the 'Ability to secure a sustainable livelihood', particularly when two-category increments altered quantifications. This underscored the importance of understanding specific component interactions within the model.

The assumption testing revealed that removing certain connections could lead to changes in convergence values, emphasising the necessity of carefully considering the inclusion of connections in the model. For instance, removing the direct connection between 'Deterioration in sea state' and 'Ability to secure a sustainable livelihood' resulted in a notable increase from the baseline, highlighting this connection's critical role. Connections were categorised as direct, one alternative, and two alternative pathways to understand these dynamics better. Direct connections such as that between 'Deterioration in sea state' and 'Ability to secure a sustainable livelihood' are primary linkages where removal has an immediate and substantial impact on convergence values, underscoring their fundamental influence on the model's balance. One alternative pathway connection has a single backup connection, so their removal causes moderate shifts in convergence values, revealing how the remaining pathway can only partially mitigate the loss of a direct connection. However, two alternative pathway connections show minimal change in convergence values upon removal due to multiple paths, indicating a built-in resilience stabilising the model in the face of changes. This classification underscores the importance of each connection type, with direct connections proving critical and alternative pathways providing valuable insights into the model's adaptive capacity. This nuanced approach to categorising connections allows for a clearer understanding of pathway significance and system stability, which is crucial for interpreting the results from assumption testing in base run 2.

Additionally, sensitivity analysis of the activation values using the modified 'fcm.infer2' function showed that the model's components responded consistently with activation

values, ensuring accurate clamping and reflecting the expected behaviour. This analysis confirmed that components such as 'Ability to secure a sustainable livelihood' and 'Unsafe operating conditions' were sensitive to changes in 'Deterioration in sea state,' likely due to their direct connections. Meanwhile, components such as 'Fish catches' and 'Income' exhibited only minor changes, suggesting that indirect connections may have limited influence in these cases. This could imply that, while direct connections are critical in determining immediate impacts on convergence values, indirect connections may contribute less to system sensitivity, especially where alternative pathways are absent. Consequently, while indirect connections need not be entirely disregarded, they may be prioritised less in sensitivity analyses focused on key outcomes such as livelihood security and operating safety.

These analyses demonstrated that in the POC model, adjustments in connection quantifications, the presence or absence of key connections, and activation values directly influenced specific outputs, such as convergence rates and sensitivity of certain components. This highlights the importance of calibrating connection strengths and validating component activation thresholds to represent influence pathways in the larger model accurately. Consequently, these learnings will be applied to enhance the larger model, notably by refining sensitivity thresholds and prioritising high-impact connections identified in the POC model.

4. Regional Prototype Model

This section provides an in-depth analysis of the restructuring and quantification of the Regional Prototype Model. Due to the semi-quantitative nature of Fuzzy Cognitive Maps (FCMs), it was essential to re-evaluate the model's structure before parameterising the connections. The model was then built and calibrated. Sensitivity analysis was carried out to understand better the influence of specific connections and parameters on overall model behaviour, providing insight into which components impacted the modelled system's dynamics.

4.1 Regional Prototype Model Restructuring And Quantification

Due to the semi-quantitative nature of FCMs, it was necessary to re-evaluate the structure of the Regional prototype model before parameterising the model connections. This was done by carefully considering every component and connection in the model and determining if clarification in the component name was needed, if the connection could be quantified based on the current data or knowledge of the system, or if a component/connection needed to be added to better show the structure of the system. The structural changes included adding, removing, and clarifying the names of components. The outcome of the structural changes in the Regional Prototype model can be found in Appendix B1.

The model connections were quantified using a desktop literature search (see Section 3.3 for the procedure). Gammage and Jarre (2020) categorised the model components into seven distinct groups: 'Key stressor (theme) identified by fishers,' 'Biophysical stressors', 'Biophysical: other fisheries', 'Social Networks', 'Social & Economic', 'Regulation/Management,' and 'Sea State'. The connections in each model component group were quantified, one group at a time. For example, all the connections in the 'Biophysical stressors' group were quantified, followed by the 'Social & Economic' group, and so on, until all connections were quantified. Table 14 presents the results of this parameterisation. Refer to Appendix B2 for the reasoning behind each relationship's quantification. Figure 10 depicts a representation of the FCM after quantification.

Table 14: Overview of all 57 relationships within the Regional prototype model, classified into relationship categories: Low, Medium, and High. Group colour coding: White = Key stressor, Orange = Biophysical stressor, Yellow = Biophysical stressor: other fisheries, Blue = Social stressor, Green = Economic stressor, Purple = Regulation/Management stressor.

Relationship Group	Relationship number	Relationship	+ /-	Relationship Category
Sea state	1	Deterioration in sea state -> Available sea days	-	Medium
	2	Deterioration in sea state -> Unsafe operating conditions	+	Low
	3	Injury at sea -> Commercial alternative landings	-	Medium
	4	Injury at sea -> Commercial kob landings	-	Medium
	5	Injury at sea -> Income (other sources)	-	Medium
	6	Unsafe operating conditions -> Injury at sea	+	Low
Key Components	7	Available sea days -> Commercial alternative landings	+	High
	8	Available sea days -> Commercial kob landings	+	High
	Removed during later calibration	Commercial alternative landings -> Ability to secure a sustainable livelihood	+	Low
	9	Commercial alternative landings -> Income (fishing)	+	Medium
	10	Commercial alternative landings -> Price of kob and other target species (price setting by fish mongers), Add a dampening connection of low strength	-	Low
	11	Commercial kob landings -> Commercial alternative landings	-	Medium
	12	Commercial kob landings -> Income (fishing)	+	High
	Relationship number	Relationship	+ /-	Relationship Category

	13	Commercial kob landings -> Kob abundance	-	High
	14	Commercial kob landings -> Price of kob and other target species (price setting by fish mongers)	-	Low
	15	Ecosystem health -> Commercial alternative landings	-	Low
	16	Ecosystem health -> Kob abundance	+	Medium
	17	Income (fishing) -> Ability to secure a sustainable livelihood	+	High
	18	Income (other sources) -> Ability to secure a sustainable livelihood	+	High
	19	Kob abundance -> Commercial kob landings	+	High
	20	Kob abundance -> Ecosystem health	+	Medium
	21	Sector-specific policy implementation -> Access to rights	+	Medium
	22	Sector-specific policy implementation -> Conflict between inshore trawl and linefishery	-	High
	23	Sector-specific policy implementation -> Minimum catch (size) limits for kob	+	Low
	24	Sector-specific policy implementation -> Surveillance (patrol vessel/aerial)	+	High
	25	Sector-specific policy implementation-> Access to DFFE (Department of Forestry, Fisheries and the Environment)	+	Medium
	Removed during later calibration	Sector-specific policy regulation -> Minimum catch (size) limits for kob	+	Medium
	Regulation/ Management	26	Minimum catch (size) limits for kob -> Commercial kob landings	+
27		Surveillance (patrol vessel/aerial) -> Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading)	-	Medium
Biophysical stressor	28	Current strength -> Deterioration in sea state	+	Low
	Relationship number	Relationship	+ /-	Relationship Category

	29	Duration of fishing season -> Commercial alternative landings	+	Medium
	30	Duration of fishing season -> Commercial kob landings	+	Medium
	31	Physical navigation dangers (river mouths) -> Unsafe operating conditions	+	Medium
	32	Prevailing sea surface temperature range -> Commercial alternative landings	-	High
	33	Prevailing sea surface temperature range -> Commercial kob landings	-	High
	34	Prevailing sea surface temperature range -> Kob abundance	-	Medium
	35	Variability in rainfall patterns -> Physical navigation dangers (river mouths)	+	Low
	36	Wave height -> Deterioration in sea state	+	Medium
	37	Wind events that drive upwelling-> Duration of fishing season	+	Medium
	38	Wind strength -> Current strength	+	Low
	39	Wind strength-> Wave Height	+	Medium
Biophysical stressor: other fisheries	40	Inshore trawl: effect on reef (habitat degradation) -> Ecosystem health	-	Medium
	41	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Conflict between inshore trawl and linefishery	+	High
	Removed during later calibration	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Ecosystem health	-	Medium
	42	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Inshore trawl: effect on reef (habitat degradation)	+	Medium
	43	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Kob abundance	-	Medium
	Relationship number	Relationship	+ /-	Relationship Category

	44	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Surveillance (patrol vessel/aerial)	+	Medium
Economic	45	Access to capital (savings/investments/ retirement income/loans) -> Access to craft	+	Medium
	46	Access to craft -> Commercial alternative landings	+	High
	47	Access to craft -> Commercial kob landings	+	High
	48	Alternative employment opportunities -> Income (other sources)	+	Medium
	49	External economic pressures -> Alternative employment opportunities	-	Medium
	50	External economic pressures -> Input costs (running costs and equipment for fishing)	+	High
	51	External economic pressures -> Price of kob and other target species (price setting by fish mongers)	-	Medium
	52	Input costs (running costs and equipment for fishing) -> Income (fishing)	-	Medium
	53	Price of kob and other target species (price setting by fish mongers)-> Income (fishing)	+	Medium
	54	Specific financial management skills -> Access to capital (savings/investments/ retirement income/loans)	+	Medium
Social	55	Access to DFFE -> Sector-specific policy implementation	+	Medium
	56	Access to rights -> Access to craft	+	High
	57	Conflict between inshore trawl and linefishery -> Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading)	+	Low
	Removed during later calibration	Conflict between inshore trawl and linefishery -> Sector-specific policy regulation	+	Low

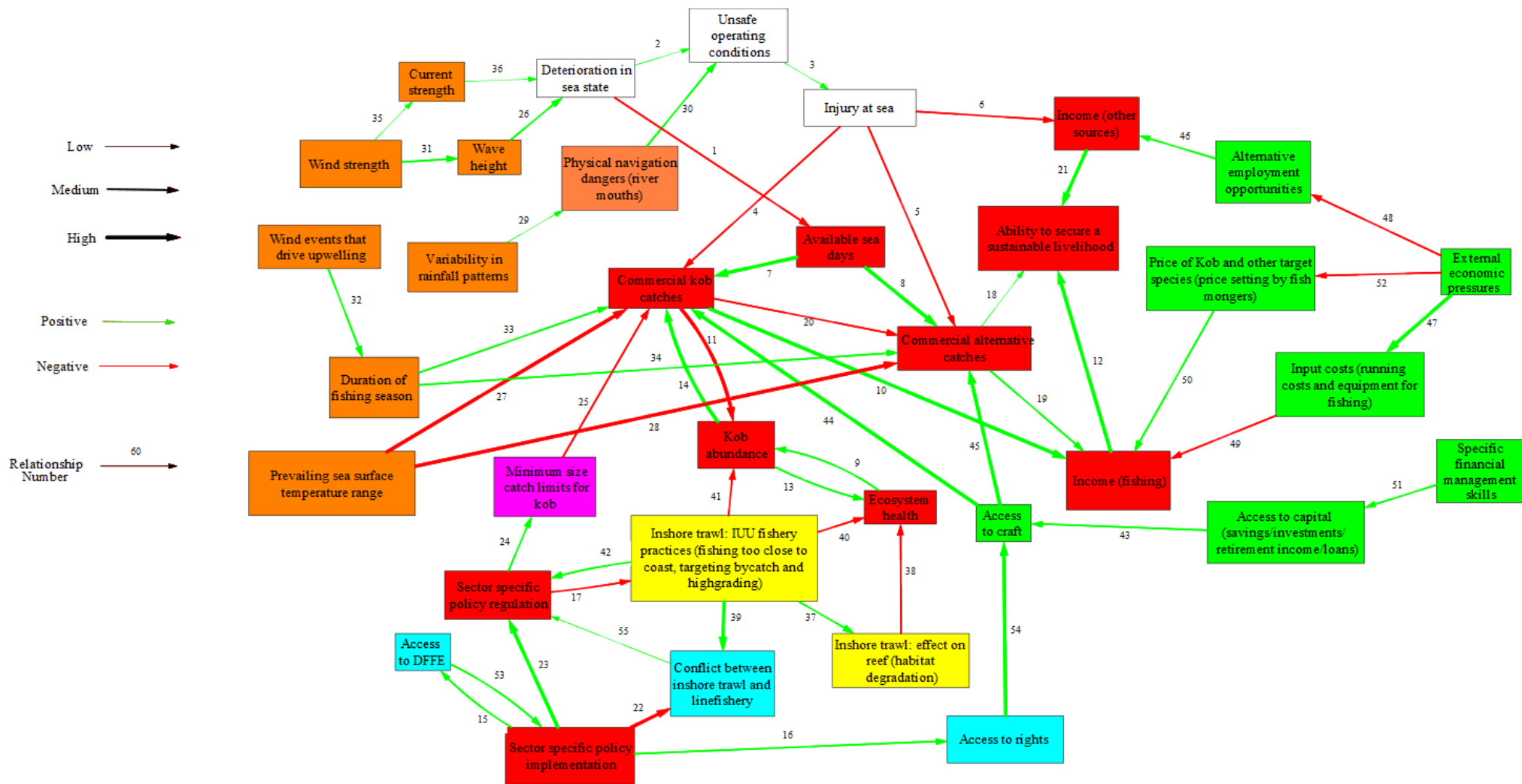


Figure 10: Graphical representation of the Regional prototype model after quantification. Refer to Appendix B2 for colour coding and arrow numbers.

4.2 Regional Prototype Model Output Analysis

Once the Regional prototype model was restructured and the connections were quantified, the 'fcm.infer2' function in the 'fcm' package in R was used to compile a Base Model. The results of the Base Model were analysed, and the model was calibrated based on this analysis. This resulted in a second Base Model that yielded sensible outputs after calibration. The following section details these steps.

4.2.1 Regional Prototype Model Base Model 1

This section covers a series of tests to determine baseline model convergence values and component interrelationships. Initial attempts to establish baseline convergence values involved setting all components in the activation vector to either 0 or 1 with no clamping, in line with Murungweni et al. (2011), Gray et al. (2015), Alipour et al. (2019), Alonso-Garcia et al. (2021), and Sarkar et al. (2022). Changing all component values to zero and running the code did not reach convergence, while changing to 1 converged at the 37th iteration; however, all components eventually converged to zero. This indicates that the software's mathematics played a role. Subsequent testing with the *Sigmoid Function* and *Modified Kosko Inference Rule* produced non-zero outputs. However, these options were not chosen due to the specific limitations mentioned in Section 4.3.1 on choosing the squashing function for the 'fcm.infer' function.

After unsuccessful attempts with the initial approach, two sets of tests were conducted using the baseline matrix, clamping only specific components to 1. First, the *Transmitter* components were 'activated' (clamped at 1) one at a time. Next, the components with the top six highest *Centrality* scores were 'activated' (clamped at 1) one at a time. Refer to Section 2.4.5 for the definition of transmitting components and *Centrality* scores and Appendix B3 for the *Centrality* scores on which the chosen components for Base Model 1 testing were based.

i) Base Model 1: Transmitter Components Activated

The *Transmitter* components were 'External economic pressures', 'Prevailing sea surface temperature range', 'Wind strength', 'Specific financial management skills', 'Wind events that drive upwelling', and 'Variability in rainfall patterns'.

The convergence values for the Regional prototype model across several tests are shown in Table 15. Firstly, several notable changes occurred when 'External economic pressures' was clamped at 1. 'Input costs' exhibited the strongest change, considerably increasing to 0.762 (very challenging) following the direct positive connection. One notable result was the substantial decrease to -0.815 (very challenging) in the 'Ability to secure a sustainable livelihood'. This decline could be attributed to the amplifying high-strength connections from 'Income (fishing)' and 'Income (other sources)' to 'Ability to secure a sustainable livelihood'. Additionally, the unexpectedly lower negative value in 'Alternative employment opportunities' at -0.604 (Challenging) compared to 'Income (other sources)' at -0.4 (somewhat challenging) highlighted a discrepancy that required attention. This difference was influenced by the direct connection from 'External economic pressures' to 'Alternative employment opportunities', indirectly impacting 'Income (other sources)'.

In the test where 'Prevailing sea surface temperature range' was clamped at 1, unexpected negative convergence values for 'Ability to secure a sustainable livelihood' at -0.699 (very challenging) and 'Income (fishing)' at -0.679 (very challenging) highlighted potential flaws in representing these relationships in the model. The amplifying effect of connections from 'Commercial kob catches' to both 'Commercial alternative catches' and 'Income (fishing)' suggested re-evaluating these connections to better align with our understanding of the system.

Similarly, in the test where 'Wind events that drive upwelling' was clamped at 1, the disproportionately high convergence value for 'Income (fishing)' at 0.349 (somewhat challenging) indicated a potential problem in the parameterisation of this relationship in the model, influenced by the amplifying effect of 'Commercial kob catches'. Further investigation into these connections was warranted to improve model accuracy.

Lastly, the convergence values aligned with expectations when 'Specific financial management skills' and 'Variability in rainfall patterns' were clamped at 1. Next, the components with the top six highest *Centrality* scores in Base Model 1 needed to be individually activated.

Table 15: Convergence values for the Regional prototype model when transmitting components were clamped at 1 (fully activated).

Component name	Convergence Value					
	External economic pressures' fully activated	Wind Strength' fully activated	Specific financial management skills' fully activated	Prevailing sea surface temperature range' fully activated	Wind events that drive upwelling' fully activated	Variability in rainfall patterns' fully activated
Ability to secure a sustainable livelihood	-0.815	-0.379	0.397	-0.699	0.416	-0.089
Access to capital (savings/investments/retirement income/loans)	0	0	0.604	0	0	0
Access to craft	0	0	0	0	0	0
Alternative employment opportunities	-0.604	0	0	0	0	0
Available sea days	0	-0.318	0	0	0	0
Commercial alternative catches	0	-0.257	0.293	-0.619	0.308	-0.032
Commercial kob catches	0	-0.120	0.139	-0.395	0.148	-0.014
Current strength	0	0.291	0	0	0	0
Deterioration in sea state	0	0.470	0	0	0	0
Duration of fishing season	0	0	0	0	0.604	0
Ecosystem health	0	0.157	-0.180	0.387	-0.189	0.020
Income (fishing)	-0.743	-0.291	0.332	-0.679	0.349	-0.036

Component name	External economic pressures' fully activated	Wind Strength' fully activated	Specific financial management skills' fully activated	Prevailing sea surface temperature range' fully activated	Wind events that drive upwelling' fully activated	Variability in rainfall patterns' fully activated
Income (other sources)	-0.400	-0.029	0	0	0	-0.042
Injury at sea	0	0.042	0	0	0	0.060
Input costs (running costs and equipment for fishing)	0.762	0	0	0	0	0
Kob abundance	0	0.226	-0.259	0.582	-0.274	0.028
Physical navigation dangers (river mouths)	0	0	0	0	0	0.291
Price of kob and other target species (price setting by fishmongers)	-0.604	0	0	0	0	0
Unsafe operating conditions	0	0.140	0	0	0	0.201
Wave height	0	0.604	0	0	0	0

ii) Base Model 1: Highest Centrality Scores Components Activated

The top six highest *Centrality* components were 'Commercial kob catches', 'Commercial alternative catches', 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)', 'Income (fishing)', 'Kob abundance', and 'Sector specific policy implementation'.

The convergence values for the FCM across several tests are shown in Table 16, which revealed several noteworthy observations and highlighted areas that required attention and further investigation. For instance, during the activation of 'Commercial kob catches', the convergence values suggested that 'Income (fishing)' at 0.520 (notable boost) and 'Kob abundance' at -0.882 (substantial threat) were highly affected. However, an unexpected increase in 'Income (fishing)' was noted despite a decrease in 'Kob abundance', indicating a potential problem in the model representation of this relationship.

Similarly, when 'Commercial alternative catches' were activated, the convergence values for 'Ability to secure a sustainable livelihood' at 0.718 (meaningful improvement) and 'Income (fishing)' at 0.604 (notable boost) were higher than anticipated. This discrepancy was attributed to the direct amplifying low-strength connection from 'Commercial alternative catches' to 'Ability to secure a sustainable livelihood', suggesting a potential oversimplification in the model.

During the activation of 'Inshore Trawl: IUU Fishery Practices', the unexpectedly high convergence value for 'Ecosystem health' at -0.907 (substantial threat) suggested a complex interaction between the activated component and other variables, including feedback connections. Additionally, unexpected increases in 'Sector-specific policy regulation' at 0.730 (meaningful improvement) and 'Minimum catch (size) limits for kob' at 0.471 (notable boost) indicated a need to reassess their relationships within the model parameterisation.

Similarly, during the activation of 'Kob abundance', while the expected relationship between 'Kob abundance' and 'Commercial kob catches' was observed, the model failed to reflect the anticipated impact on the 'Price of kob and other target species (price

setting by fish mongers)', signalling a potential oversight in representing market dynamics.

Finally, when 'Sector-specific policy implementation' was activated, the unexpected high increase in 'Access to DFFE' at 0.604 (notable boost) highlighted a considerable influence from the activated component. However, the discrepancy in the convergence values for 'Sector-specific policy regulation' at 0.474 (notable boost) and 'Conflict between inshore trawl and linefishery' at -0.867 (substantial positive change) underscored the importance of indirect connections in shaping model results.

Table 16: Convergence values for the Regional prototype model when the components with the highest *Centrality* scores were clamped at 1 (fully activated).

Component name	Convergence Value					
	Commercial kob catches' fully activated	Commercial alternative catches' fully activated	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated	Income (fishing) fully activated	Kob abundance' fully activated	Sector-specific policy implementation fully activated
Ability to secure a sustainable livelihood	0.327	0.718	-0.228	0.762	0.246	0.553
Access to craft	0	0	0	0	0	0.540
Access to DFFE	0	0	0	0	0	0.604
Access to rights	0	0	0	0	0	0.604
Commercial alternative catches	-0.604	0	0.459	0	-0.488	0.150
Commercial kob catches	0	0	-0.709	0	0.762	0.556
Conflict between inshore trawl and linefishery	0	0	0.762	0	0	-0.867
Ecosystem health	-0.549	0	-0.907	0	0.604	0.275
Income (fishing)	0.520	0.604	-0.369	0	0.397	0.579
Inshore trawl: effect on reef (habitat degradation)	0	0	0.604	0	0	-0.220

Component name	Commercial kob catches' fully activated	Commercial alternative catches' fully activated	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated	Income (fishing) fully activated	Kob abundance' fully activated	Sector-specific policy implementation fully activated
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0	0	0	0	0	-0.321
Kob abundance	-0.882	0	-0.555	0	0	-0.138
Minimum catch (size) limits for kob	0	0	0.471	0	0	0.321
Sector-specific policy regulation	0	0	0.730	0	0	0.474

iii) Base Model 1: Comparison Of 'Ability To Secure A Sustainable Livelihood' Convergence Values

Based on the convergence values of the first run (Figure 11), the activated components could be ranked in terms of their influence on the 'Ability to secure a sustainable livelihood' component. This ranking highlights the relative importance, in terms of absolute value, of each activated component in influencing the 'Ability to secure a sustainable livelihood', with higher-ranked components exerting a greater influence.

1. External economic pressures (-0.815, very challenging)
2. Income (fishing) (0.762, meaningful improvement)
3. Commercial alternative catches (0.718, meaningful improvement)
4. Prevailing sea surface temperature range (-0.699, very challenging)
5. Sector-specific policy implementation (0.553, notable boost)
6. Wind events that drive upwelling (0.416, slight boost)
7. Specific financial management skills (0.397, slight boost)
8. Wind strength (-0.379, somewhat challenging)
9. Commercial kob catches (0.327, slight boost)
10. Kob abundance (0.246, neither challenging nor favourable)
11. Inshore trawl: IUU fishery practices (-0.228, neither challenging nor favourable)
12. Variability in rainfall patterns (-0.089, neither challenging nor favourable)

Upon analysis, several components affecting the 'Ability to secure a sustainable livelihood' convergence values deserve attention for potential adjustments:

- Activated Commercial Alternative Catches: The 'Ability to Secure a Sustainable Livelihood' convergence value appears inflated due to the direct connection from 'Commercial alternative catches' to 'Ability to Secure a Sustainable Livelihood'.
- Activated Commercial Kob Catches: While expected to result in a higher convergence value for the 'Ability to Secure a Sustainable Livelihood' than for 'Commercial Alternative catches' because the primary target species was kob, it was attenuated by the direct dampening connection from 'Commercial Alternative Catches' to 'Ability to Secure a Sustainable Livelihood'.

- Activated Kob Abundance: The low 'Ability to Secure a Sustainable Livelihood' convergence value may stem from the two-way feedback loops between 'Commercial Kob Catches' and 'Kob Abundance'. Additionally, upon convergence, 'Commercial Alternative Catches' decreased by -49% and was directly connected to 'Ability to Secure a Sustainable Livelihood', indicating a complex relationship that requires further examination.
- Activated Prevailing Sea Surface Temperature Range: The high negative 'Ability to Secure a Sustainable Livelihood' convergence value results from the dampening high-strength connections from 'Prevailing Sea Surface Temperature Range' to both 'Commercial kob catches' and 'Commercial alternative catches'. The strongly decreased 'Commercial alternative catches' was directly connected to 'Ability to Secure a Sustainable Livelihood'.

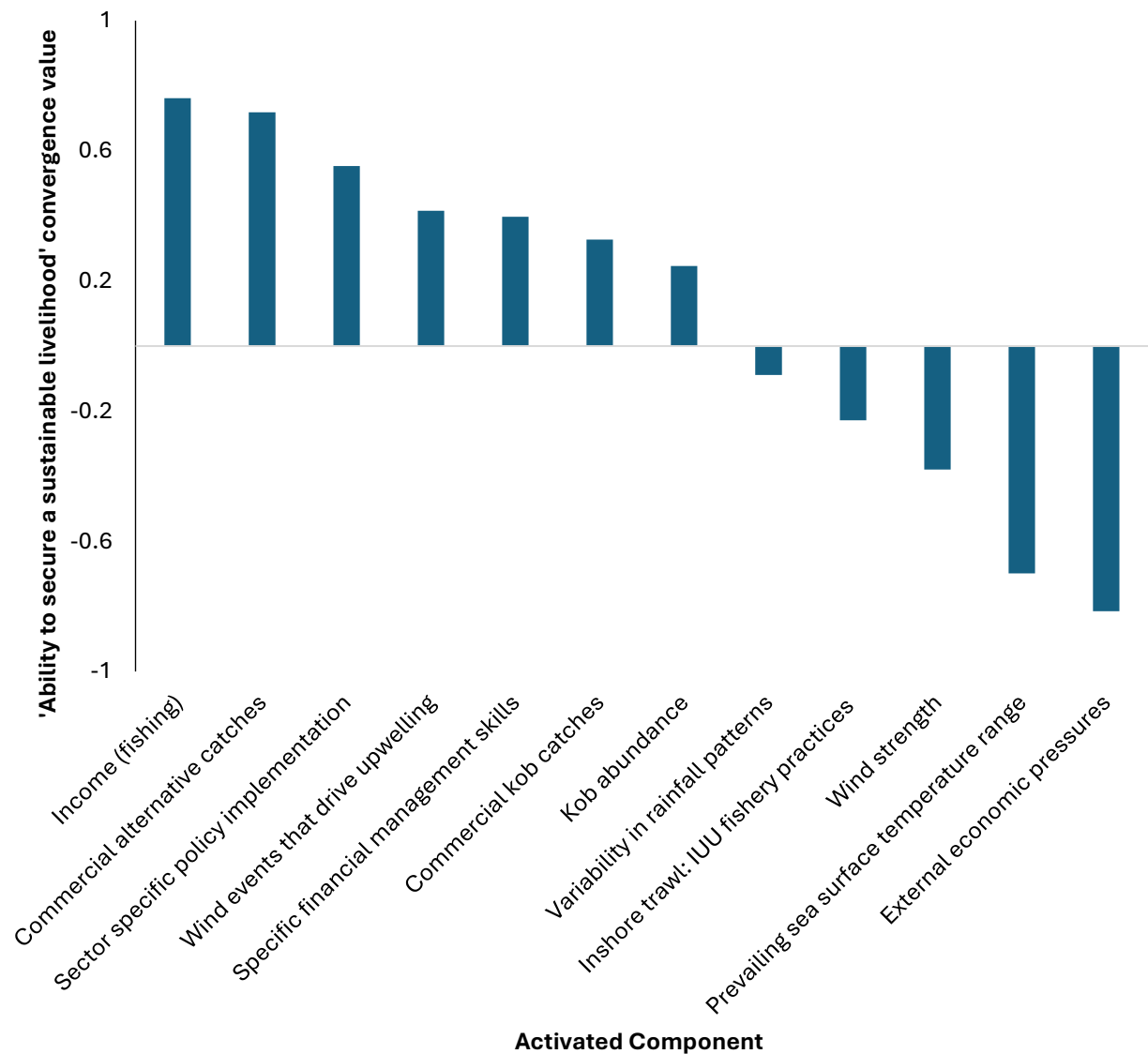


Figure 11: Results of Base Run 1: ‘Ability to secure a sustainable livelihood’ convergence values when fully activating the transmitting components and components with the top six highest *Centrality* scores after Base Model 1. Transmitters = ‘External economic pressures’, ‘Wind strength’, ‘Prevailing sea surface temperature range’, ‘Wind events that drive upwelling’, ‘Specific financial management skills’, ‘Variability in rainfall patterns’. High *Centrality* = ‘Commercial kob catches’, ‘Commercial alternative catches’, ‘Inshore trawl: IUU fishery practices’, ‘Income (fishing)’, ‘Kob abundance’, ‘Sector specific policy implementation’.

iv) Base Model 1: Lessons Learnt And Calibration Suggestions

In the FCM approach, connections can be direct (immediate cause and effect) or indirect (involving intermediate pathways). Distinguishing between these connections helps identify how changes propagate through the system. It was important to note that as the number of pathways extending sequentially from the activated component grows, one leading to another and then another, the influence of a change diminishes. For example, starting with 'Commercial kob catches' and its impact on 'Commercial alternative catches,' the convergence value was -0.604 (challenging). This indicates that an increase in 'Commercial kob catches' leads to a decrease in 'Commercial alternative catches.' Next, 'Commercial alternative catches' and 'Commercial kob catches' affect 'Income (fishing)' with a convergence value of 0.520 (notable boost). Finally, 'Income (fishing)' influences the 'Ability to secure a sustainable livelihood' with a convergence value of 0.327 (slight boost).

The strength of connections between components, whether low, medium, or high, plays a pivotal role in influencing the Regional prototype model's outputs. Interestingly, even connections classified as low strength can substantially affect system dynamics, while medium and high-strength connections have progressively larger impacts, often driving key behavioural changes within the system. This suggests that all connection strengths contribute meaningfully to the model's overall behaviour, underscoring the importance of accurately quantifying these relationships when simulating complex systems. Table 17 summarises the calibration suggestions based on the results of *Base Model 1*.

Table 17: Suggestions for further model calibration based on *Base Model 1* results.

Activated component	Problem identified	Change to be tested
<p>Prevailing sea surface temperature range</p>	<p>'Kob abundance' should not increase since an elevated temperature should deter kob from the fishing grounds. This had happened because 'Prevailing sea surface temperature range' was dampening 'Commercial kob catches', which in turn increases 'Kob abundance'.</p>	<ul style="list-style-type: none"> • Prevailing sea surface temperature range -> Commercial kob catches, Change strength of the connection to dampening medium strength connection. • Prevailing sea surface temperature range -> Commercial alternative catches, Change strength of the connection to dampening medium strength connection. • Prevailing sea surface temperature range -> Kob abundance, Add dampening high strength connection. High strength because the connection to 'Commercial kob catches' was medium strength.
<p>Specific financial management skills</p>	<p>'Income (fishing)' should be stronger than 'Ability to secure a sustainable livelihood'. However, the 'Commercial alternative catches' connection contributes to 'Ability to secure a sustainable livelihood', elevating its Convergence value.</p>	<ul style="list-style-type: none"> • Commercial alternative catches -> Ability to secure a sustainable livelihood, Remove connection
<p>Commercial alternative catches</p>	<p>Values for 'Income (fishing)' and 'Ability to secure a sustainable livelihood' should be stronger when 'Commercial kob catches' was fully activated than when 'Commercial alternative catches' was fully activated, considering that alternative species were typically less lucrative and not the primary target of the fishery.</p>	<ul style="list-style-type: none"> • Commercial alternative catches -> Ability to secure a sustainable livelihood, Remove connection

<p>Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)</p>	<p>'Ecosystem health' should not decrease so strongly and should not be stronger than 'Inshore trawl: effect on reef (habitat degradation)'. This was because of the direct connection from the fully activated component.</p>	<ul style="list-style-type: none"> • Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Ecosystem health, Remove connection because there was already a connection from 'Inshore trawl: IUU fishery practices' to 'Inshore trawl: Habitat degradation' and then to 'Ecosystem health'. • Ecosystem health -> Alternative catches, Add dampening low strength connection to account for the influence of 'Ecosystem health' on 'Commercial alternative catches,' which was not adequately represented. This adjustment was warranted because the connection from 'Ecosystem health' to 'Kob abundance' was of medium strength, followed by a high-strength connection to 'Commercial kob catches.' Therefore, to align the direct connection to 'Commercial alternative catches,' it should be of low strength.
	<p>'Minimum catch (size) limits for kob' should not be affected since increased regulation should result in sending out more patrol vessels, not increasing the minimum size limit. This was attributed to the direct medium-strength connection to 'Sector-specific policy regulation', which was then connected to the fully activated component.</p>	<ul style="list-style-type: none"> • Change 'Sector specific policy regulation' to 'Surveillance (patrol vessels/aerial)' • Remove connection from 'Patrol Vessels' to 'Minimum size'. • Add amplifying low strength connection from 'Sector specific policy implementation' to 'Minimum size'.

		<ul style="list-style-type: none"> • Add amplifying low strength connection from 'Conflict between inshore trawl and linefishery' to 'Inshore trawl: IUU fishery practices'
Kob abundance	'Income(fishing)' was too weak due to the connection from 'Commercial alternative catches', which had been dampened by 'Commercial kob catches'.	<ul style="list-style-type: none"> • Commercial kob catches -> Commercial alternative catches. Change the connection to low strength to increase the impact of commercial kob catches on commercial alternative catches
	Changes in 'Kob abundance' should affect 'Price of kob and other target species (price setting by fish mongers)' since typically, an increase in kob abundance would lead to more supply in the market, potentially decreasing the Price paid to fishers.	<ul style="list-style-type: none"> • Commercial kob catches -> Price of kob and other target species (price setting by fish mongers), Add dampening low strength connection. • Commercial alternative catches -> Price of kob and other target species (price setting by fish mongers), Add a dampening connection of low strength, Add dampening low strength connection.
Sector-specific policy implementation	'Ability to secure a sustainable livelihood' was too strong due to the direct connection to 'Commercial alternative catches'.	<ul style="list-style-type: none"> • Commercial alternative catches -> Ability to secure a sustainable livelihood, Remove connection
	'Access to DFFE' was affected too strongly due to a direct medium-strength connection to the fully activated component.	<ul style="list-style-type: none"> • Sector-specific policy implementation-> Access to DFFE. Change the connection to low strength to reduce the impact.

4.2.2 Regional Prototype Model Calibration

The next step involved making changes to the model based on the suggestions provided in Table 17. This calibration process involved adjustment of connection quantifications, addressing one flagged problem at a time. Detailed results can be found in Appendix B4.

In activating the 'Prevailing sea surface temperature range' component, the identified problem was that 'Kob abundance' increased when it should have decreased due to elevated temperatures deterring kob from the fishing grounds. This was because the 'Prevailing sea surface temperature range' was dampening 'Commercial kob catches,' inadvertently increasing 'Kob abundance.' To resolve this, the connection from 'Prevailing sea surface temperature range' to 'Commercial kob catches' and 'Commercial alternative catches' was changed to a low-strength dampening connection, and a medium-strength dampening connection was added to 'Kob abundance.' The updated convergence values indicate a decrease in 'Kob abundance,' confirming that the issue has been fixed. This change ensures that the model more accurately reflects the expected ecological response to changes in sea surface temperature.

In activating the 'Specific financial management skills' component, the identified problem was that 'Income (fishing)' should have been stronger than 'Ability to secure a sustainable livelihood.' The connection from 'Commercial alternative catches' elevated the convergence value for 'Ability to secure a sustainable livelihood.' The connection between 'Commercial alternative catches' and 'Ability to secure a sustainable livelihood' was removed to address this. The updated convergence values show that 'Income (fishing)' was now stronger than 'Ability to secure a sustainable livelihood,' confirming the issue has been resolved. This adjustment ensures that the model accurately reflects the importance of financial management skills in enhancing fishing income.

In activating the 'Commercial alternative catches' component, the identified problem was that the values for 'Income (fishing)' and 'Ability to secure a sustainable livelihood' were too strong compared to when 'Commercial kob catches' were activated. This discrepancy arose because alternative species were typically less lucrative and not the primary target of the fishery. The connection between 'Commercial alternative catches' and 'Ability to secure a sustainable livelihood' was removed to fix this. The new convergence values indicate that the values are now appropriately higher for

'Commercial kob catches,' confirming that the issue has been corrected. This change ensured that the model reflected the economic reality of the target species' higher value than alternative catches. These insights, gained during assumption testing in Section 3.5.3, highlight the importance of understanding how single and multiple pathways influence the model.

In the activation of the 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' component, the identified problem was that 'Ecosystem health' decreased too strongly and was stronger than 'Inshore trawl: effect on reef (habitat degradation).' This issue stems from the direct relationship between these two components, underscoring the importance of understanding model dynamics and specific interactions before implementing adjustments. These insights, gained during assumption testing in Section 3.5.3, are crucial for advancing toward a more comprehensive regional prototype model. The connection from 'Inshore trawl: IUU fishery practices' to 'Ecosystem health' was removed, and a dampening low-strength connection was added from 'Ecosystem health' to 'Commercial alternative catches.' The updated convergence values show that 'Ecosystem health' decreased moderately and was not stronger than 'Inshore trawl: effect on reef (habitat degradation),' resolving the issue. This adjustment improved the model's representation of the indirect effects of IUU practices on ecosystem health.

In activating the 'Kob abundance' component, the identified problem was that 'Income (fishing)' was too weak due to the dampening connection from 'Commercial alternative catches.' To address this, the connection from 'Commercial kob catches' to 'Commercial alternative catches' was changed to low strength. The updated convergence values indicate a stronger 'Income (fishing),' confirming that the issue has been resolved. Additionally, 'Kob abundance' changes were needed to affect the 'Price of kob and other target species (price setting by fish mongers).' To fix this, dampening low-strength connections were added from 'Commercial kob catches' and 'Commercial alternative catches' to 'Price of kob and other target species.' The updated convergence values show that the price setting is now appropriately affected by changes in 'Kob abundance,' confirming that the issue has been fixed. These changes ensured that the

model accurately captures the economic relationship between kob abundance and price setting.

In activating the 'Sector-specific policy implementation' component, the identified problem was that 'Ability to secure a sustainable livelihood' was too strong due to the direct connection to 'Commercial alternative catches.' The connection between 'Commercial alternative catches' and 'Ability to secure a sustainable livelihood' was removed to address this. The updated convergence values confirm that 'Ability to secure a sustainable livelihood' was weaker, resolving the issue. Additionally, 'Access to DFFE' was affected too strongly due to a direct medium-strength connection. The connection from 'Sector-specific policy implementation' to 'Access to DFFE' was changed to low strength to reduce the impact. The updated convergence values show that 'Access to DFFE' is weaker, effectively fixing the problem. These adjustments ensure that the model accurately reflects the impacts of sector-specific policy implementation on various components.

4.2.3 Regional Prototype Model Base Model 2

The following section details the outcomes of *Base Model 2*, which utilised the same set of tests as *Base Model 1* but incorporated the adjustments based on calibration results described in the previous section. The difference between this section and the earlier ‘calibration’ section (Section 4.2.2) was that all modifications were included simultaneously. Figure 13 depicts the Regional prototype model after calibration.

i) Base Model 2: Regional prototype Model Metrics

Following the calibration of the model, the 'FCMapper' (Turney and Bachhofer, 2016) routine, an open-source tool in the *R* language, was used to calculate the components' *Indegree*, *Outdegree*, and *Centrality* results based on the quantified connections. 'Sector specific policy implementation', 'Inshore trawl: IUU fishery practices', and 'Commercial kob landings' had the highest *Outdegree* values of 3.4, 3.1 and 2.6, respectively (Figure 12). 'Commercial kob landings', 'Commercial alternative landings', and 'Kob abundance' had the highest *Indegree* values of 5.4, 4.3 and 3.1, respectively (Figure 12). 'Commercial kob landings', 'Commercial alternative landings', and 'Kob abundance' had the highest *Centrality* scores of 8, 5.3 and 4.8, respectively (Figure 12).

Among the bio-physical components group components, 'Wind events driving upwelling', 'Current strength', 'Wind strength', and 'Variability in rainfall patterns' emerge with the lowest *Centrality* scores. These low scores indicate that the biophysical components were perceived as less important within the model than other groups, reflecting the fishers' practical experience and priorities within the fishing context.

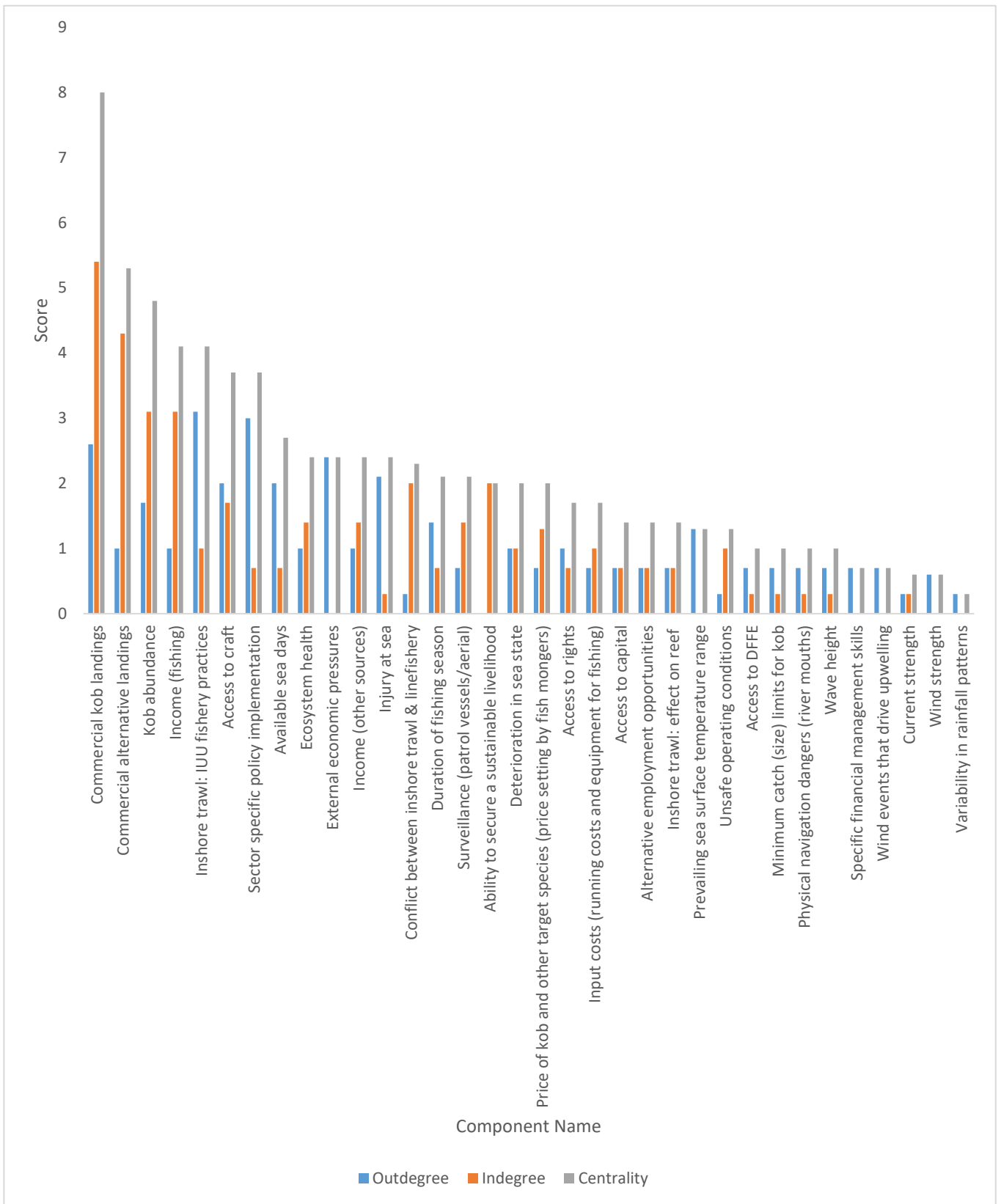


Figure 12: Outdegree, Indegree, and Centrality scores for Base Model 2.

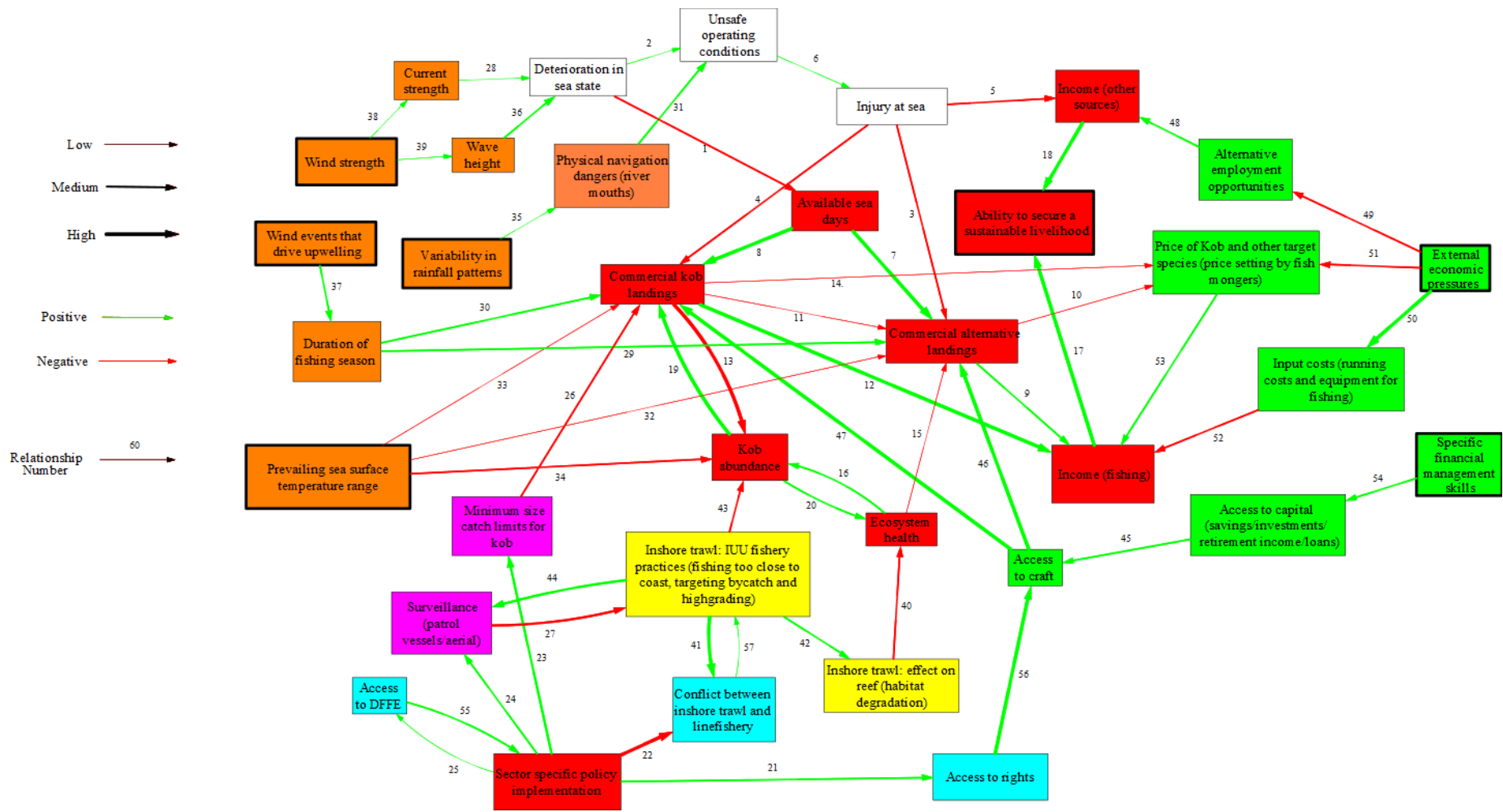


Figure 13: Graphical representation of the Regional prototype Base Model 2 after calibration. Refer to Appendix B2 for colour coding, arrow numbers and related descriptions. Transmitting and receiving components are emphasised with a thick box border.

ii) Base Model 2: Transmitting Components

Table 18 presents the convergence values for the Regional prototype model across several tests activating *transmitter* components and illustrates the convergence values for the FCM when 'Wind Strength' was clamped at 1. In *Base Model 1*, the primary problem was the inadequate representation of the influence of 'Wind Strength' on related components such as 'Wave height' and 'Current strength'. During calibration, the connections were adjusted to reflect these influences better, resulting in an amplifying low-strength connection to 'Current strength' and a medium-strength connection to 'Wave height'. The output values for 'Ability to secure a sustainable livelihood' and 'Income (fishing)' improved by 0.2, aligning with expectations and indicating satisfactory calibration results.

In *Base Model 1*, the 'Prevailing sea surface temperature range' did not substantially impact 'Kob abundance' and 'Ecosystem health' as expected. Table 18 shows that high-strength dampening connections were added during calibration to capture these relationships better. Consequently, 'Kob abundance' and 'Ecosystem health' decreased appropriately, while 'Ability to secure a sustainable livelihood' and 'Commercial alternative landings' increased by more than 0.3. These changes corrected the previously overly negative values and yielded satisfactory results, indicating effective calibration.

Table 18: Convergence values for the Regional prototype model when *transmitter* components were clamped at 1.

Component Affected	Convergence Value					
	External economic pressures' fully activated	Wind Strength' fully activated	Prevailing sea surface temperature range' fully activated	Wind events that drive upwelling' fully activated	Specific financial management skills' fully activated	Variability in rainfall patterns' fully activated
Ability to secure a sustainable livelihood	-0.815	-0.153	-0.447	0.258	0.245	-0.069
Access to capital (savings/investments/retirement income/loans)	0	0	0	0	0.604	0
Access to craft	0	0	0	0	0.400	0
Alternative employment opportunities	-0.604	0	0	0	0	0
Available sea days	0	-0.196	0	0	0	0
Commercial alternative landings	0	-0.161	-0.198	0.311	0.295	-0.032
Commercial kob landings	0	-0.073	-0.536	0.148	0.139	-0.014
Current strength	0	0.291	0	0	0	0

Component Affected	External economic pressures' fully activated	Wind Strength' fully activated	Prevailing sea surface temperature range' fully activated	Wind events that drive upwelling' fully activated	Specific financial management skills' fully activated	Variability in rainfall patterns' fully activated
Deterioration in sea state	0	0.283	0	0	0	0
Duration of fishing season	0	0	0	0.604	0	0
Ecosystem health	0	0.098	-0.206	-0.189	-0.180	0.020
Income (fishing)	-0.743	-0.135	-0.480	0.263	0.249	-0.027
Income (other sources)	-0.4	-0.018	0	0	0	-0.042
Injury at sea	0	0.025	0	0	0	0.060
Input costs (running costs and equipment for fishing)	0.762	0	0	0	0	0
Kob abundance	0	0.140	-0.299	-0.274	-0.259	0.028
Physical navigation dangers (river mouths)	0	0	0	0	0	0.291
Price of kob and other target species (price setting by fishmongers)	-0.604	0.070	0.217	-0.137	-0.129	0.014
Unsafe operating conditions	0	0.085	0	0	0	0.201
Wave height	0	0.291	0	0	0	0

iii) Base Model 2: Full Activation Of The Components With The Highest Centrality Scores

Table 19 displays the convergence values for the Regional prototype model across several tests. Activation of 'Commercial kob landings' and 'Income (fishing)' did not change output convergence values by more than 0.3 compared to Base Model 1, despite calibration adjustments.

Base Model 1 showed that 'Commercial alternative landings' had minimal influence on 'Ability to secure a sustainable livelihood' and 'Income (fishing)'. Calibration introduced amplifying connections to these components, resulting in weaker values than 'Commercial kob landings'. As shown in Table 19, these adjustments decreased the 'Price of kob and other target species' by -0.3. These changes aligned with expectations and indicated satisfactory calibration results.

For 'Inshore trawl: IUU fishery practices', *Base Model 1* did not adequately reflect the negative impact on 'Ecosystem health' and other related components. Calibration introduced dampening medium-strength connections and adjusted amplifying connections. Table 19 shows that 'Ecosystem health' improved by 0.2, aligning better with expected outcomes. The calibration effectively corrected the previously unfavourable trends, resulting in satisfactory outcomes.

In *Base Model 1*, the impact of 'Kob abundance' on 'Income (fishing)' and 'Commercial alternative landings' was too weak. Calibration introduced stronger connections to capture these relationships better. As shown in Table 19, 'Income (fishing)' increased slightly and 'Commercial alternative landings' became a weaker negative, aligning with expectations and resulting in satisfactory calibration outcomes.

For 'Sector-specific policy implementation', *Base Model 1* did not adequately capture the relationships with 'Access to rights' and 'Conflict between inshore trawl and linefishery'. Calibration introduced amplifying and dampening connections to reflect these relationships better. Table 19 shows that 'Access to DFFE' decreased by 0.3, aligning more closely with model expectations. These adjustments indicate that the calibration was adequate and the results were satisfactory.

Table 19: Convergence values for the Base Model 2 of the Regional prototype model when the top 6 highest *Centrality* components were clamped at 1, one by one.

Component Affected	Convergence Value					
	Commercial kob landings' fully activated	Commercial alternative landings' fully activated	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated	Income (fishing)' fully activated	Kob abundance' fully activated	Sector-specific policy implementation' fully activated
Ability to secure a sustainable livelihood	0.479	0.429	-0.388	0.762	0.480	0.472
Access to craft	0	0	0	0	0	0.540
Access to DFFE	0	0	0	0	0	0.291
Access to rights	0	0	0	0	0	0.604
Commercial alternative landings	-0.434	0	-0.048	0	-0.047	0.464
Commercial kob landings	0	0	-0.519	0	0.762	0.423
Conflict between inshore trawl and linefishery	0	0	0.762	0	0	-0.901
Ecosystem health	-0.549	0	-0.678	0	0.604	0.296

Component Affected	Commercial kob landings' fully activated	Commercial alternative landings' fully activated	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated	Income (fishing)' fully activated	Kob abundance' fully activated	Sector-specific policy implementation' fully activated
Income (fishing)	0.522	0.459	-0.410	0	0.523	0.512
Inshore trawl: effect on reef (habitat degradation)	0	0	0.604	0	0	-0.321
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0	0	0	0	0	-0.475
Kob abundance	-0.882	0	-0.575	0	0	0.116
Minimum catch (size) limits for kob	0	0	0	0	0	0.291
Price of kob and other target species (price setting by fishmongers)	-0.168	-0.291	0.169	0	-0.211	-0.260
Surveillance (patrol vessels/aerial)	0	0	0.604	0	0	0.352

iv) *Base Model 2: Comparison Of 'Ability to Secure A Sustainable Livelihood' Convergence Values*

Based on the convergence values (Figure 14), the fully activated components were ranked according to their influence on the 'Ability to secure a sustainable livelihood' in absolute terms, with higher-ranked components exerting greater influence.

- a) External economic pressures (-0.815, very challenging)
- b) Income (fishing) (0.762, meaningful improvement)
- c) Kob abundance (0.48, notable boost)
- d) Commercial kob catches (0.479, notable boost)
- e) Sector-specific policy implementation (0.472, notable boost)
- f) Prevailing sea surface temperature range (-0.447, challenging)
- g) Commercial alternative catches (0.429, slight boost)
- h) Inshore trawl: IUU fishery practices (-0.388, somewhat challenging)
- i) Wind events that drive upwelling (0.258, slight boost)
- j) Specific financial management skills (0.245, slight boost)
- k) Wind strength (-0.153, neither challenging nor favourable)
- l) Variability in rainfall patterns (-0.069, neither challenging nor favourable)

Despite the model adjustments, 'External economic pressures' continued to exhibit the most substantial negative effect on the 'Ability to secure a sustainable livelihood', while 'Income (fishing)' retained its position as the primary positive influence on 'Ability to secure a sustainable livelihood', consistent with *Base Model 1* and due to the direct connection (Figure 13). Mirroring their impact in *Base Model 1*, 'Sector-specific policy implementation' and 'Wind events that drive upwelling' contribute moderately positively. Conversely, 'Wind strength' and 'Variability in rainfall patterns' resulted in the weakest negative impacts. This contrasted with *Base Model 1*, where 'Inshore trawl: IUU fishery practices' ranked as the second weakest negative influence. Thus, the model

adjustments reflected a stronger impact of 'Inshore trawl: IUU fishery practices' on 'Ability to secure a sustainable livelihood' and a diminished influence of 'Wind strength'. Overall, *Base Model 2* outputs register lower values compared to *Base Model 1*, with exceptions noted in the activations of 'Income (fishing)', 'Kob abundance', and 'Commercial kob catches', which now exhibit stronger positive impacts and 'Inshore trawl: IUU' and 'External economic pressures', which manifest stronger negative effects. Furthermore, the overall impact of climate on the 'Ability to secure a sustainable livelihood' diminished, with economic components emerging as the more influential determinants.

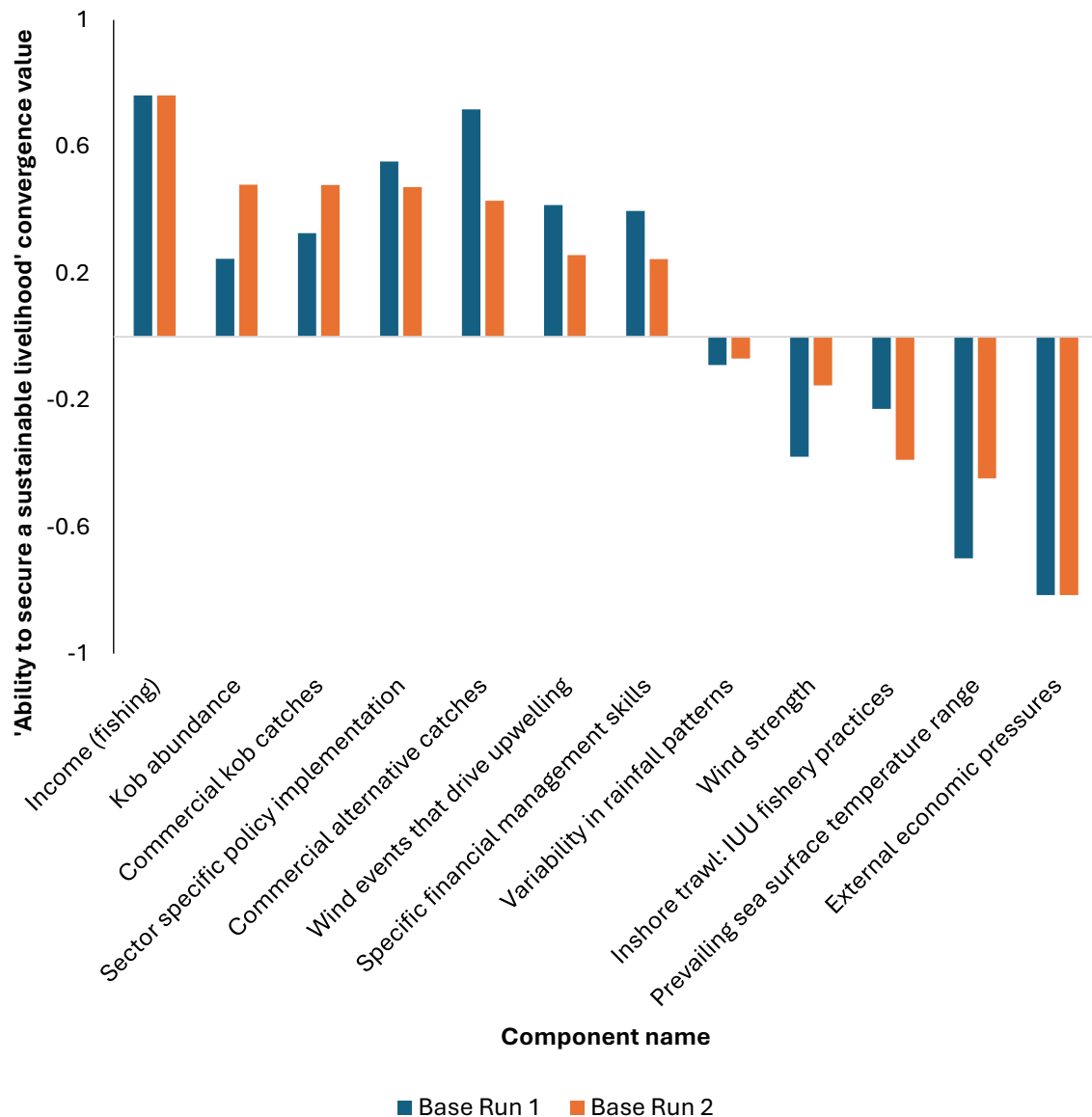


Figure 14 Comparison of key outputs from Base Model 1 vs Base Model 2. 'Ability to secure a sustainable livelihood' Convergence values after model calibration resulting from fully activating each component one at a time. Transmitters = 'External economic pressures', 'Wind strength', 'Prevailing sea surface temperature range', 'Wind events that drive upwelling', 'Specific financial management skills', 'Variability in rainfall patterns'. High *Centrality* = 'Commercial kob catches', 'Commercial alternative catches', 'Inshore trawl: IUU fishery practices', 'Income (fishing)', 'Kob abundance', 'Sector specific policy implementation'.

4.2.4 Regional Prototype Model Quantification Category Sensitivity Test

Once the Regional prototype model had been calibrated and its behaviour was deemed consistent with our system understanding, sensitivity tests followed the same procedure as in Base Models 1 and 2. It was then considered important to test the sensitivity of the quantifications to change and the dependency of outputs on these quantifications. This was done by conducting three tests. The initial categories were decided based on the total score when multiplying the consequence and likelihood scores allocated during the connection quantification exercise (convergence values can be found in Appendix B5).

In the first test, the medium quantification was divided into low medium and high medium, set at ± 0.6 and ± 0.8 , respectively, while low remained at ± 0.3 and high at ± 1 (*Table 20*). In the second test, the low quantification was changed from ± 0.3 to ± 0.25 , low medium to ± 0.5 , high medium to ± 0.75 , and high remained at ± 1 (*Table 20*). In the third test, the initial categories used to determine if a relationship was low, medium, or high were altered. Specifically, the low quantification was adjusted from ± 0.3 to ± 0.25 , low medium to ± 0.5 , high medium to ± 0.75 , and high remained at ± 1 (*Table 20*).

These quantification modifications were chosen to improve the model's accuracy and sensitivity, particularly concerning the *Hyperbolic Tangent Function*. The *Hyperbolic Tangent Function* mapped values between -1 and 1 and had a near-linear region around zero, which helped distinguish subtle input-value differences. The original quantifications fell within this near-linear region. Adding intermediate categories in Test 1 (0.6 for low medium and 0.8 for high medium) and adjusting values in Tests 2 and 3 (e.g., low changed to 0.25 , low medium to 0.5 , high medium to 0.75) increased the granularity of the analysis and allowed for a finer sensitivity analysis without distortion.

Based on how the *Hyperbolic Tangent Function* worked, the expected outcome was that small changes in these quantifications could lead to noticeable changes in the output due to the function's nonlinear response, especially as values approached ± 1 . Therefore, these sensitivity tests were important to ensure that the chosen categories (low, medium, high) were adequate and that the model could accurately differentiate between

various strengths of relationships. The goal was to determine if the initial three categories were sufficient or if additional categories were needed for better model accuracy and sensitivity.

Table 20: Quantification Categories and Scores Across Different Sensitivity Tests.

Test Number	Total Score	Category	Quantification
Original	1-10	Low	0.3
	11-20	Medium	0.7
	21-30	High	1
Test one	1-10	Low	0.3
	11-15	Low Medium	0.6
	16-20	High Medium	0.8
	21-30	High	1
Test two	1-10	Low	0.25
	11-15	Low Medium	0.5
	16-20	High Medium	0.75
	21-30	High	1
Test three	1-8	Low	0.25
	9-15	Low Medium	0.5
	16-23	High Medium	0.75
	24-30	High	1

i) Quantification Sensitivity Test 1: Medium Quantification Sensitivity Test

Consistent with Base Models 1 and 2, the transmitting components and those with the top six highest *Centrality* scores were activated individually. The sensitivity test outcomes were documented in Appendix B5, demonstrating changes with most within a

10% difference from *Base Model 2*. However, 'Ecosystem health' and 'Kob abundance' changed by 0.115 (-0.206 to -0.321) and 0.117 (-0.299 to -0.416), respectively, when 'Prevailing sea surface temperature range' was fully activated. Pushing them from one category into the next. This change occurred because the connections between 'Prevailing sea surface temperature range' and 'Kob abundance' and then from 'Kob abundance' to 'Ecosystem health' changed to 0.8. 'Income (fishing)' changed by 0.108 (neither challenging nor favourable) when 'Commercial alternative landings' was fully activated because the connection between the two changed to 0.6.

Convergence values were calculated to rank activated components based on their influence on the 'Ability to Secure a Sustainable Livelihood' component (see Figure 15). Despite adjustments in quantification, differences from *Base Model 2* convergence

values for 'Ability to Secure a Sustainable Livelihood' remained less than 10%, and their sequence in terms of impact remained unchanged.

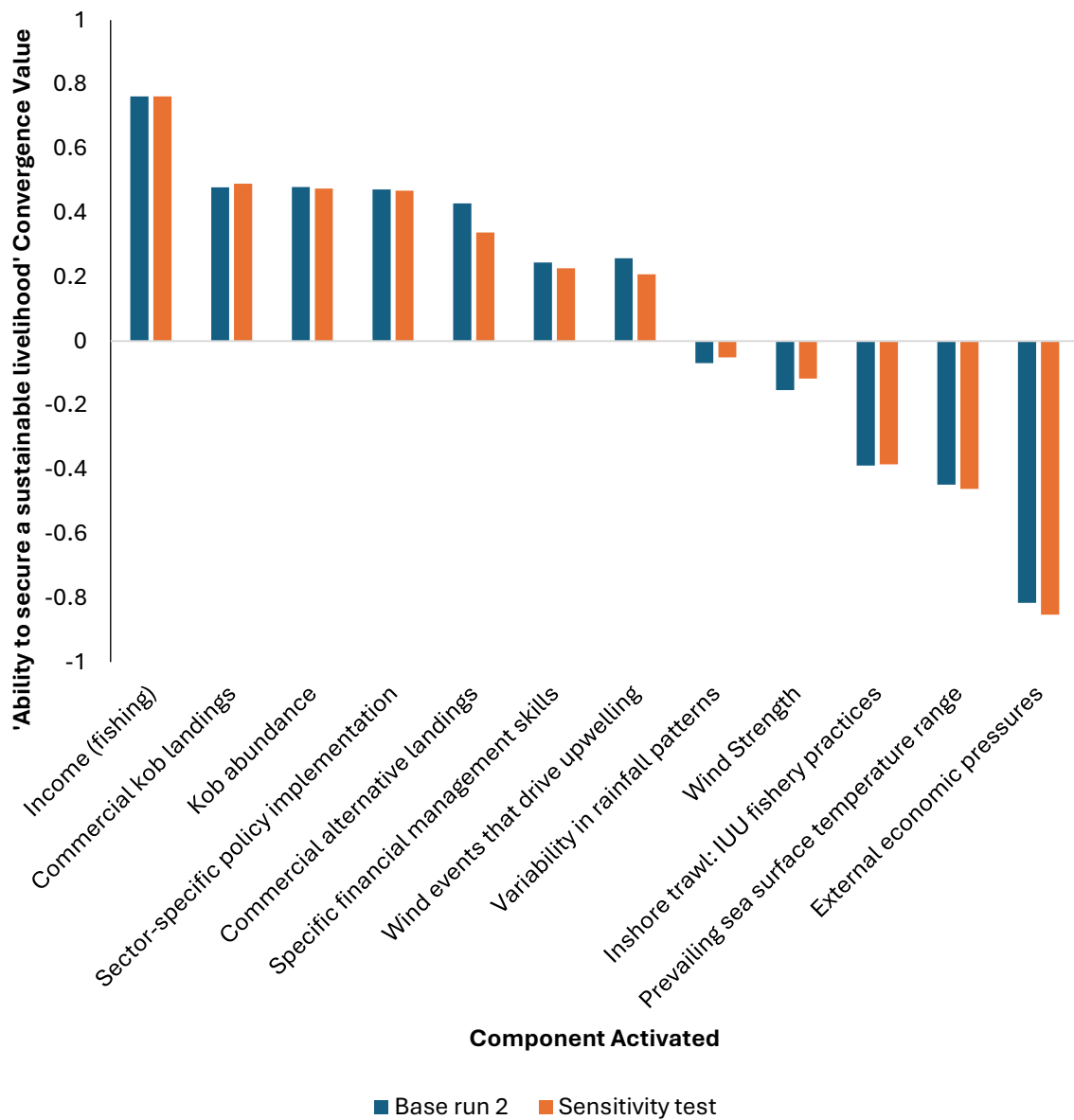


Figure 15: 'Ability to secure a sustainable livelihood' Convergence values after Base Model 2 and the sensitivity test, where using eight categories instead of six were tested, with low medium set to 0.6 and high medium set to 0.8.

ii) *Quantification Sensitivity Test 2: Adjusted Low And Medium Quantification Sensitivity Test*

Consistent with Base Models 1 and 2, the transmitting components and those with the top six highest *Centrality* scores were activated individually. The sensitivity test outcomes were documented in Appendix B5, demonstrating minor changes, with most within a 10% difference from *Base Model 2*. However, 'Price of kob and other target species (price setting by fish mongers)' changed by -0.142 when 'External economic pressures' was activated. 'Deterioration in sea state' changed by 0.101 when 'Wind Strength' was activated. 'Ability to secure a sustainable livelihood' and 'Income (fishing)' changed by 0.132 and 0.153, respectively, when 'Commercial alternative landings' was activated. 'Kob abundance' changed by 0.110 when 'Sector-specific policy implementation' was activated.

Convergence values were calculated to rank activated components based on their influence on the 'Ability to Secure a Sustainable Livelihood' component (see Figure 16). Despite adjustments in quantification, the majority of differences from *Base Model 2* convergence values for 'Ability to Secure a Sustainable Livelihood' remained less than 10%, except for 'Commercial alternative landings', which changed by 0.132 because 'Commercial alternative landings' has connections to 'Price of kob and other target species (price setting by fish mongers)' and 'Income (fishing)' which changed from -0.3 to -0.25 and from 0.7 to 0.5, respectively. Then, 'Price of kob and other target species (price setting by fish mongers)' connects to 'Income (fishing)', another changed quantification from 0.7 to 0.75. 'Income (fishing)', then connected to 'Ability to Secure a

Sustainable Livelihood'. Note that the ranking of kob abundance and commercial kob landings switch; however, both remain to exert a notable boost in terms of Appendix B5.

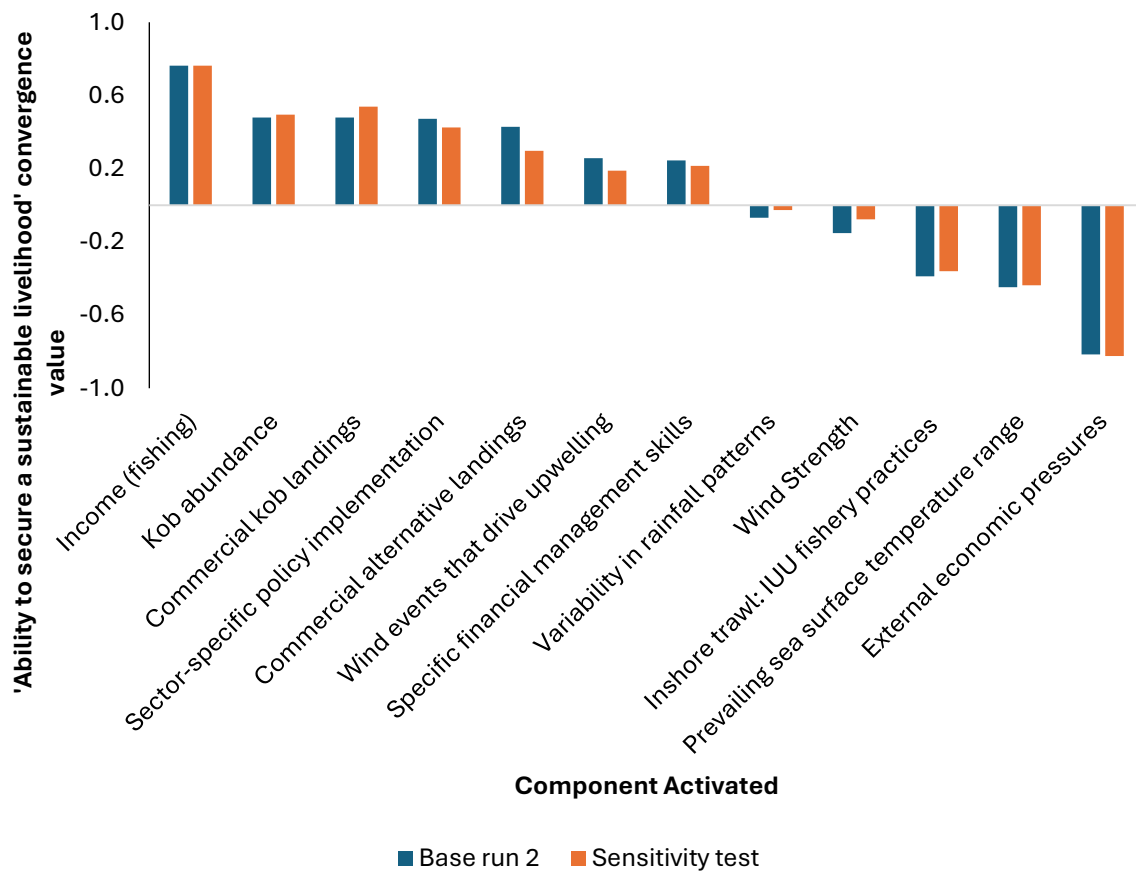


Figure 16: 'Ability to secure a sustainable livelihood' Convergence values after Base Model 2 and the sensitivity test with eight categories where the low quantification was changed from 0.3 to 0.25, low medium to 0.5, high medium to 0.75, and high remained at 1.

iii) *Quantification Sensitivity Test 3: Reclassified Relationship Quantification*

After altering the initial categories, 8 of the 57 total connections were changed to new categories. *Table 21* details these eight connections and the changes made.

Table 21: Connections that moved to a new category after reclassification.

Connection	Original category	New category
Sector-specific policy implementation -> Surveillance (patrol vessel/aerial)	Medium	High
Unsafe operating conditions -> Injury at sea	Low	Low medium
Commercial kob landings -> Commercial alternative landings	Low	Low medium
Sector-specific policy implementation-> Access to DFFE	Low	Low medium
Prevailing sea surface temperature range -> Commercial alternative landings	Low	Low medium
Prevailing sea surface temperature range -> Commercial kob landings	Low	Low medium
Variability in rainfall patterns -> Physical navigation dangers (river mouths)	Low	Low medium
Wind strength-> Wave Height	Low	Low medium

Consistent with Base Models 1 and 2, the transmitting components and those with the top six highest *Centrality* scores were activated individually. The sensitivity test outcomes are documented in Appendix B5, demonstrating minor changes, with most within a 10% difference from *Base Model 2*.

However, ‘Price of kob and other target species (price setting by fish mongers)’ changed by -0.142 when ‘External economic pressures’ was activated. ‘Wave height’ changed by -0.171 when ‘Wind Strength’ was activated. ‘Commercial alternative landings’ changed by 0.132 when ‘Wind events that drive upwelling’ was activated. ‘Physical navigation dangers’ changed by -0.171 when ‘Variability in rainfall patterns’ was activated. ‘Commercial alternative landings’ changed by 0.135 when ‘Commercial kob landings’ was activated. ‘Ability to secure a sustainable livelihood’ and ‘Income (fishing)’ changed by 0.132 and 0.153, respectively, when ‘Commercial alternative landings’ was activated. ‘Commercial alternative landings’ changed by -0.107 when ‘Inshore trawl: IUU fishery practices’ was activated. ‘Commercial alternative landings’ changed by 0.171 when ‘Kob abundance’ was

activated. 'Access to DFFE' and 'Surveillance (patrol vessels/aerial)' changed by -0.171 and -0.174, respectively, when 'Sector-specific policy implementation' was activated.

Convergence values were calculated to rank activated components based on their influence on the 'Ability to Secure a Sustainable Livelihood' component (see Figure 17). Despite adjustments in quantification, most differences from *Base Model 2* convergence values for 'Ability to Secure a Sustainable Livelihood' remained less than 10%, except for 'Commercial alternative landings', which changed by 0.132 for the same reasons mentioned above. Note that the ranking of kob abundance and commercial kob landings switch; however, both remain to exert a notable boost.

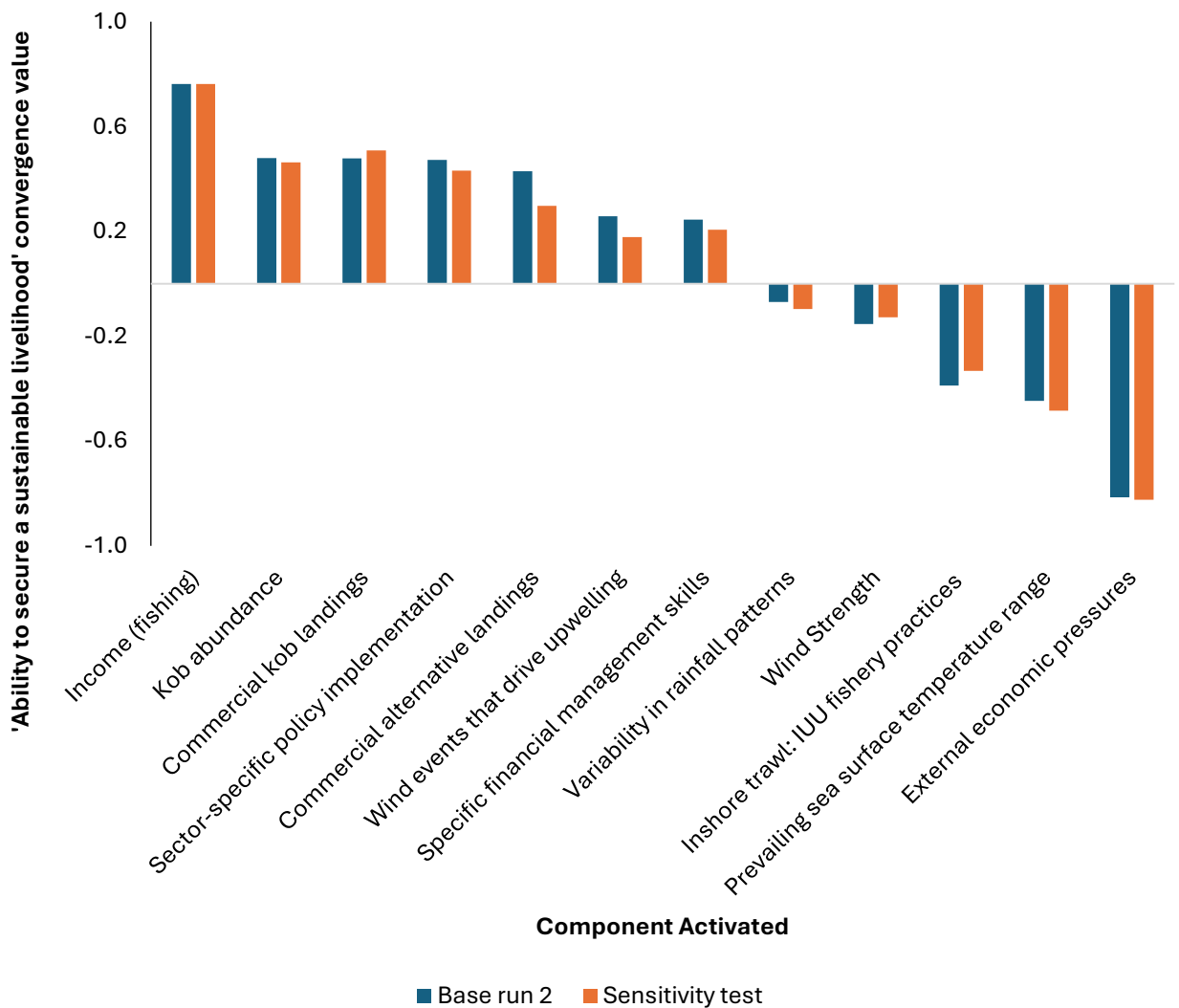


Figure 17: 'Ability to secure a sustainable livelihood' convergence values after Base Model 2 and the sensitivity test where the initial categories used to determine if a relationship was low, medium, or high were altered.

iv) *Quantification Sensitivity Test: Summary*

The Regional prototype model, after being calibrated to align with current understanding of the system, underwent sensitivity tests to evaluate the impact of varying quantifications on the model's outputs. Three tests were conducted to assess whether the initial three relationship categories were adequate or if a fourth category was

necessary. These tests adjusted the connection quantifications and examined the resulting model behaviour changes.

Test 1 divided the medium quantification into low medium and high medium at 0.6 and 0.8, respectively. Test 2 adjusted the quantifications further, with low changed to 0.25, low medium to 0.5, high medium to 0.75, and high remaining at 1. Test 3 altered the initial categories to see if some connections would shift into different quantification groups, using the same adjustments as in Test 2.

The results from these tests showed minor variations in *Indegree*, *Outdegree*, and *Centrality* scores. Most differences were within a 10% margin from the *Base Model 2* values. However, specific components such as 'Ecosystem health', 'Kob abundance', and 'Income (fishing)' exhibited higher variations due to the changes in connection quantifications. Convergence values for the 'Ability to Secure a Sustainable Livelihood' component remained largely consistent. The sensitivity tests confirmed that the six original relationship categories for reinforcing and dampening connections were adequate for quantifying the FCM, as adding a fourth category did not substantially alter the model's principal output.

5. Exercising The Regional Prototype Model

This section explores the process and outcomes of conducting scenario tests using the regional prototype model. It begins by detailing the methodology for adapting the four scenarios from Gammage et al. (2021), designed to compute varying environmental and social-economic conditions affecting the southern Cape fishery system. These scenarios, “Nothing much has changed,” “We will get there, eventually,” “The going is good (cold productive),” and “The future is bright (warm productive)”, each represent distinct shifts in key components of the system. The outcomes of these tests, focusing on how each scenario influences the livelihoods of fishers and the broader fishery system, will be analysed and compared. Results will include how these key components interact, converge, or diverge under different conditions, providing insights into the system's resilience and sustainability under different future possibilities. Finally, this section discusses the implications of these findings, emphasising how changes in modelled access to financial and regulatory resources can impact fishers' ability to secure sustainable livelihoods. A comparison between model scenarios reveals insights into the model system's capacity to cope with various economic and environmental stressors.

5.1 Regional Prototype Model: Developing Scenario Tests

With the regional prototype model built and calibrated and sensitivity tests completed, the next phase involved conducting scenario tests to assess the model's performance. Drawing on the original scenarios developed by Gammage et al. (2021), the four scenarios utilised were: “Nothing much has changed,” “We will get there, eventually,” “The going is good,” and “The future is bright.”

Six components were selected to represent key system variables to compute these scenarios effectively. Gammage et al. (2021) outline the changes inherent in each scenario. The selected components were: ‘Access to capital,’ ‘Sector-specific policy implementation’ (indicating fishers' access to rights), ‘Alternative employment

opportunities,’ ‘Commercial alternative landings (low value),’ ‘External economic pressures,’ and ‘Commercial kob landings.’ Table 22 details the modifications made to these six components for each of the four scenarios tested. Components not listed in Table 22 remained unchanged, initialised at 0, during the scenario testing, with the connections defined as per Appendix B2.

Scenario 1 - “Nothing much has changed”:

This scenario encompasses limited access to rights and low access to capital. It portrays a scenario with few chances in a resource-constrained setting where several components seriously impede macroeconomic and microeconomic progress. Participants face substantial difficulties due to a moderate constraint in ‘Access to capital’ (-0.7), resulting in fishers struggling to secure necessary equipment and training funds, impeding their ability to improve their livelihoods. Additionally, severely constrained access to fishing rights through inadequate ‘Sector-specific policy implementation’ (-1) exacerbates their struggles, as minimal regulatory support is available. The scenario also involves variability in marine resources, including ‘Commercial alternative landings’ (-0.7) and ‘Kob abundance’ (-0.7). Similarly, few ‘Alternative employment opportunities’ (-0.7) reflect limited job options outside of fishing. ‘External economic pressures’ are moderately high (+0.7), further straining an already challenging economic environment. This scenario roughly mirrors the situation between about 2011 and 2018, where limited resources and opportunities created a cycle of economic stagnation and hardship.

Scenario 2 - “We will get there , eventually”:

This scenario encompasses good access to rights but low access to capital. It gives an optimistic but cautious perspective. This scenario includes the establishment of primary and secondary cooperatives due to the implementation of the Small-Scale Fisheries

Policy, with new members progressively joining. However, because of the state of the economy when the policy was implemented, fishers are not given adequate cash infusion required to operationalise these cooperatives properly. The lack of access to fishing craft and funds to acquire and maintain gear remains the biggest obstacle to successfully exploiting community rights. Fishers are thus compelled to continue limited small-scale activities and crew on commercial linefish boats due to insufficient capital. Limited 'Access to capital' (-0.7) indicates ongoing financial constraints. However, good access to rights through 'Sector-specific policy implementation' (+0.7) offers a potential for improved regulatory support, aiding fishers in securing their livelihoods. The scenario also depicts limited availability of marine resources such as 'Commercial alternative landings' (-0.7) and 'Kob abundance' (-0.7), highlighting ongoing resource scarcity. 'Alternative employment opportunities' (-0.3) indicate marginal improvements in non-fishery jobs. 'External economic pressures' suggest a marginally better economic environment (0.3). This scenario implies some progress towards better conditions, where incremental improvements in policy and employment opportunities could eventually lead to more sustainable livelihoods for the community.

Scenario 3 - "The going is good" (cold productive):

This scenario encompasses limited access to rights but high access to capital. It presents a picture of development. A moderate increase in 'Access to capital' (0.7) provides fishers with better financial resources for investments. However, limited access to rights through 'Sector-specific policy implementation' (-0.7) indicates ongoing regulatory challenges. Increasing upwelling-favourable winds have resulted in cooling of the Agulhas Bank, increasing traditional cooler-water-associated species such as anchovy and sardine, shallow-water hake and yellowtail. Due to the limited fishing rights, the catches are insufficient to sustain a linefishery-based income. There are, however, good additional employment opportunities in the industrial fishing sector, such as on trawlers or in processing plants. 'Kob abundance' (-0.7) is limited due to the cooler

waters, but alternative species can be landed in the linefishery (0.3), such as hake, offering additional income sources. A substantial increase in 'Alternative employment opportunities' (1) reflects diverse job options outside of handline fishing. Despite access challenges, this scenario envisions a community benefiting from increased capital and diverse employment opportunities.

Scenario 4, "The future is bright" (warm productive):

In this context, the term "warm productive" ecosystem refers to a hypothetical scenario influenced by global warming, where the subtropical fish community from the east coast has shifted their distribution onto the central Agulhas Bank, in line with the biogeography in Blamey et al. (2015). The warming of the Agulhas Bank has caused warm temperate linefish species to migrate westward, enabling linefishers to adapt their target species without major changes in strategy. Notably, the fish biomasses of valuable linefish species, such as geelbek, have been fully restored. This scenario encompasses good access to rights and good access to capital, presenting a setting of development and economic security. Proactive government measures have created an environment conducive to continued participation in fishing. The successful implementation of the small-scale fisheries policy has enabled fishers to sustain and enhance their livelihoods, with fishery-derived income as their primary source. Fishers have accumulated sufficient wealth over the past 30 years to engage proactively in various economic activities. The scenario features a high increase in 'Access to capital' (1), allowing substantial livelihood investments. There is also increased access to rights through 'Sector-specific policy implementation' (1), providing regulatory support. The scenario shows an increase in high-value warm-temperate species such as geelbek, reflected in increased 'Kob (geelbek) abundance' (0.7) and an increase in 'Commercial alternative landings' (0.7) of warm-water species. Additionally, there is a substantial increase in 'Alternative employment opportunities' (1), indicating numerous job options outside the

fishery. ‘External economic pressures’ are low (-1), highlighting an optimal economic environment.

Table 22: Changes made to the activation values of six components to represent the four scenarios tested (derived from Gammage et al., 2021).

Activated Component	Scenario 1 - “Nothing much has changed”	Scenario 2 - “We will get there, eventually”	Scenario 3 - “The going is good” (cold productive)	Scenario 4 - “The future is bright” (warm productive)
Access to capital	-0.7	-0.7	0.7	1.0
Sector-specific policy implementation	-1.0	0.7	-0.7	1.0
Alternative employment opportunities	-0.7	-0.3	1.0	1.0
Commercial alternative landings *low value*	-0.7	-0.7	0.3 (hake)	0.7
External economic pressures	0.7	0.3	-0.3	-1.0
Kob abundance *high value*	-0.7	-0.7	-0.7	0.7 (geelbek)

5.2 Regional Prototype Model: Scenario Test Results

The results of the scenario tests in Table 23 and Figure 22 illustrate the convergence values of the components that changed in each scenario. Some components were not affected by the activated components in the scenarios and had convergence values of 0, including ‘Available sea days,’ ‘Current strength,’ ‘Deterioration in sea state,’ ‘Duration of fishing season,’ ‘Injury at sea,’ ‘Physical navigation dangers (river mouths),’ ‘Prevailing sea surface temperature range,’ ‘Specific financial management skills,’ ‘Unsafe operating conditions,’ ‘Variability in rainfall patterns,’ ‘Wave height,’ ‘Wind events that drive upwelling,’ and ‘Wind strength.’ These components predominantly belong to the

'Bio-physical' and 'Sea state' groups. These groups were not included among the components used to represent the four different scenarios (conceived using political and economic drivers) expressed through the availability of fish resources. The following describes the results of each scenario test.

5.2.1 Scenario 1 - "Nothing Much Has Changed" Convergence Values

Implementing Scenario 1 (Figure 18) resulted in changes across 15 model components, impacting fishers' livelihoods and sustainability. 'Access to capital' was set to be moderately low at -0.7, restricting fishers' ability to secure funds for equipment and training. This reduction impacted 'Access to craft,' which decreased to -0.798 (very challenging).

The absence of 'Sector-specific policy implementation' (set at -1) reflected minimal regulatory support, severely impacting 'Access to rights,' which converged to -0.604 (challenging). This implied limited 'Access to craft' to -0.798 (very challenging), 'Commercial kob landings' to -0.860 (substantial threat), and 'Income (fishing)' at -0.946 (substantial threat), impairing the 'Ability to secure a sustainable livelihood' at -0.885 (substantial threat). The absence of 'Sector-specific policy implementation' also negatively affected 'Access to DFFE,' which converged to -0.291 (somewhat challenging), and in turn impacted 'Surveillance (patrol vessels/aerial),' at -0.351 (somewhat challenging), leading to a challenging increase in 'Inshore trawl: IUU fishery practices' at 0.475.

Moderately low 'Kob abundance' (-0.7) implied convergence to a substantial threat to 'Commercial kob landings' at -0.86, in turn impacting 'Income (fishing)' at -0.946 (substantial threat) and the 'Ability to secure a sustainable livelihood' at -0.885 (substantial threat). This reduction also negatively influenced 'Ecosystem health' at -0.614 (challenging). Low 'Commercial alternative landings' (-0.7) reduced additional income sources, impacting 'Income (fishing)' to -0.850 (substantial threat) and the 'Ability to secure a sustainable livelihood' at -0.885 (substantial threat).

(neither challenging nor favourable). The effects on 'Commercial kob landings' at -0.707 (very challenging) and 'Income (fishing)' at -0.85 (substantial threat) persisted, affecting the 'Ability to secure a sustainable livelihood' at -0.784 (very challenging). However, improving 'Sector-specific policy implementation' (0.7), enhanced 'Access to rights' at 0.454 (notable boost) and slightly improved from scenario 1 for 'Commercial kob landings' at -0.707 (very challenging) and 'Income (fishing)' at -0.85 (substantial threat), leading to slight improvements in the 'Ability to secure a sustainable livelihood' at -0.784 (very challenging).

Improving 'Sector-specific policy implementation' also positively affected 'Access to DFFE' at 0.207 (neither challenging nor favourable) and 'Surveillance (patrol vessels/aerial)' at 0.224 (neither challenging nor favourable). This led to a reduction in 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' at -0.375 (slight boost) and positively influencing 'Commercial kob landings' from scenario 1 at -0.707 (very challenging) and 'Income (fishing)' at -0.85 (substantial threat), enhancing the 'Ability to secure a sustainable livelihood' from scenario 1 to -0.784 (very challenging).

'Alternative employment opportunities' improved (-0.3), positively impacting 'Income (other sources)' at -0.207 (neither challenging nor favourable) and improving the 'Ability to secure a sustainable livelihood' at -0.784. Reducing 'External economic pressures' (+0.3) impacted 'Input costs (running costs and equipment for fishing)' at 0.291 (somewhat challenging). These changes slightly enhanced 'Income (fishing)' at -0.850 (substantial threat) and the 'Ability to secure a sustainable livelihood' at -0.784. The improvement also affected the 'Price of kob and other target species (price setting by fish mongers)' at 0.209 (neither challenging nor favourable), enhancing the 'Ability to secure a sustainable livelihood' at -0.784.

'Kob abundance' was kept low (-0.7), impacting 'Commercial kob landings' at -0.707 (very challenging) and 'Income (fishing)' at -0.850, continuing to affect the 'Ability to secure a sustainable livelihood negatively' at -0.784. 'Commercial alternative landings'

was also kept low (-0.7), impacting 'Income (fishing)' at -0.207 and affecting the 'Ability to secure a sustainable livelihood' at -0.784.

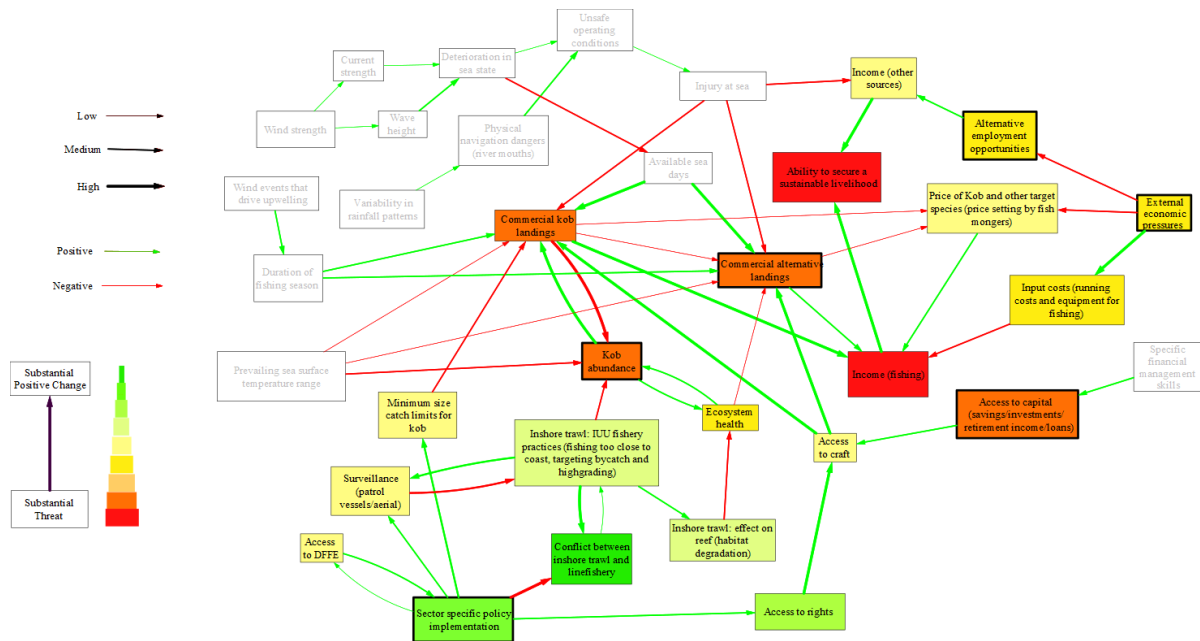


Figure 19: Regional prototype FCM showing the convergence values of Scenario 2 according to colour coding from red=substantial threat to dark green=substantial positive change.

5.2.3 Scenario 3 - "The Going Is Good" (Cold Productive) Convergence Values

In Scenario 3 (Figure 20), the positive change in 'Access to capital (savings/investments/retirement income/loans)' (+0.7) improved 'Access to craft' at 0.036 (neither challenging nor favourable). This positively influenced 'Commercial kob landings' from scenario 2 at -0.477 (challenging) and 'Income (fishing)' at 0.116 (neither challenging nor favourable), leading to substantial improvements in the 'Ability to secure a sustainable livelihood' at 0.617 (notable boost).

‘Sector-specific policy implementation’ was decreased (-0.7), negatively affecting ‘Access to rights’ at -0.454 (challenging). Despite the positive impact on ‘Commercial kob landings’ at -0.477 (challenging) and ‘Income (fishing)’ at 0.116 (neither challenging nor favourable) from scenario 2, the overall improvements in the ‘Ability to secure a sustainable livelihood’ at 0.617 (notable boost) were moderated by regulatory challenges. Declining ‘Sector-specific policy implementation’ also negatively impacted ‘Access to DFFE’ at -0.207 (neither challenging nor favourable) and ‘Surveillance (patrol vessels/aerial)’ at -0.223 (neither challenging nor favourable). This led to an increase in ‘Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)’ at +0.375 (somewhat challenging).

Despite these challenges, the positive impacts on ‘Commercial kob landings’ from scenario 3 at -0.477 (challenging) and ‘Income (fishing)’ at 0.116 (neither challenging nor favourable) contributed to substantial improvements in the ‘Ability to secure a sustainable livelihood’ at +0.617 (notable boost). ‘Alternative employment opportunities’ was improved (1.0), positively impacting ‘Income (other sources)’ at 0.604 (notable boost) and enhancing the ‘Ability to secure a sustainable livelihood’ at 0.617 (notable boost).

Reducing ‘External economic pressures’ (-0.3) positively impacted ‘Input costs (running costs and equipment for fishing)’ at -0.291 (slight boost). These changes improved ‘Income (fishing)’ at 0.116 (neither challenging nor favourable) and the ‘Ability to secure a sustainable livelihood’ at 0.617. The improvement also affected the ‘Price of kob and other target species (price setting by fish mongers)’ at 0.257 (slight boost), further enhancing the ‘Ability to secure a sustainable livelihood’ at 0.617.

‘Kob abundance’ was kept low (-0.7), impacting ‘Commercial kob landings’ at -0.477 (challenging) and ‘Income (fishing)’ at 0.116 (neither challenging nor favourable). Despite these challenges, the improvements in other components led to substantial enhancements in the ‘Ability to secure a sustainable livelihood’ at 0.617 (notable boost). ‘Commercial alternative landings’ was improved (+0.3), positively impacting ‘Income

(other sources)' at 0.604 (notable boost) and enhancing the 'Ability to secure a sustainable livelihood' at 0.617.

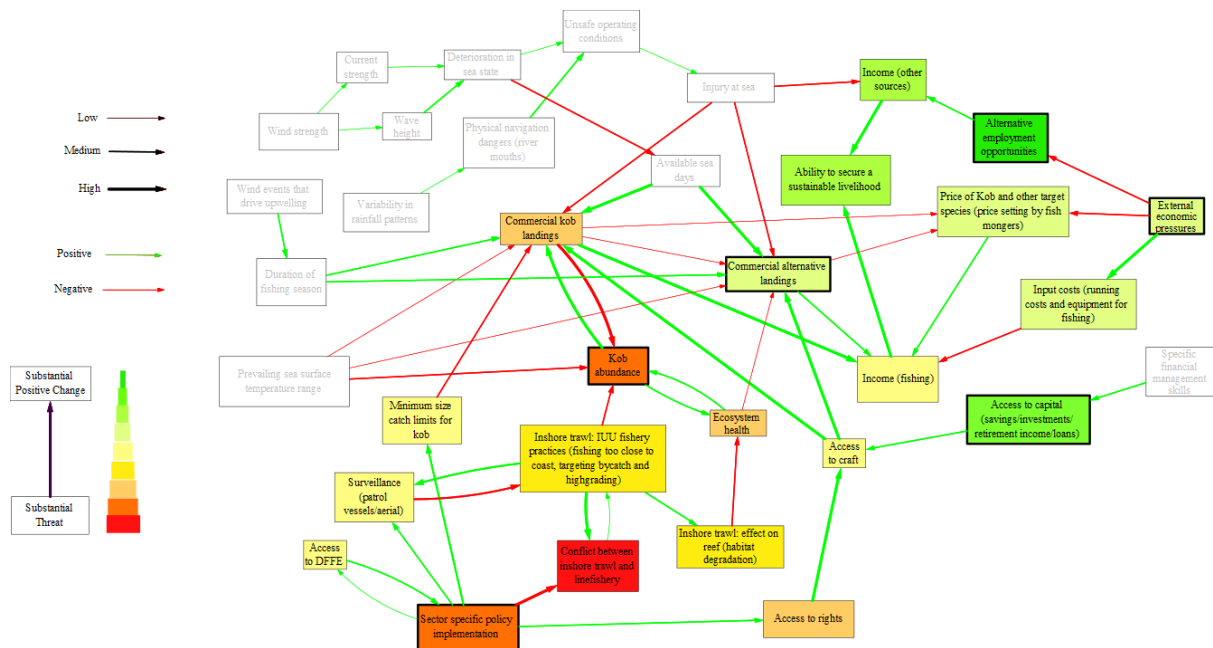


Figure 20: Regional prototype FCM showing the convergence values of Scenario 3 according to colour coding from red=substantial threat to dark green=substantial positive change.

5.2.4 Scenario 4 - “The Future Is Bright” (Warm Productive) Convergence Values

In Scenario 4 (Figure 21), the increase in ‘Access to capital (savings/investments/retirement income/loans)’ (+1.0) improved ‘Access to craft’ at 0.863 (substantial positive change). This positively influenced ‘Commercial kobs landings’ at 0.876 (substantial positive change) and ‘Income (fishing)’ at 0.968 (substantial positive change), leading to substantial improvements in the ‘Ability to secure a sustainable livelihood’ at +0.917 (substantial positive change).

‘Sector-specific policy implementation’ was increased (+1.0), enhancing ‘Access to rights’ at 0.604 (notable boost). This had a substantial positive impact on ‘Commercial kobs landings’ at 0.876 (substantial positive change) and ‘Income (fishing)’ at 0.968

(substantial positive change), leading to notable improvements in the 'Ability to secure a sustainable livelihood' at 0.917. The substantial improvement in 'Sector-specific policy implementation' also positively impacted 'Access to DFFE' at 0.291 (slight boost) and 'Surveillance (patrol vessels/aerial)' at 0.351 (slight boost). This reduced 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' at -0.475 (notable boost). These improvements further enhanced 'Commercial kob landings' at 0.876 (substantial positive change) and 'Income (fishing)' at 0.968 (substantial positive change), contributing to substantial improvements in the 'Ability to secure a sustainable livelihood' at 0.917.

'Alternative employment opportunities' increased (+1.0), enhancing 'Income (other sources)' at 0.604 (notable boost) and improving 'Ability to secure a sustainable livelihood' at 0.917. Reducing 'External economic pressures' (-1.0) positively impacted 'Input costs (running costs and equipment for fishing)' at -0.762 (meaningful improvement). These changes improved 'Income (fishing)' at 0.968 and the 'Ability to secure a sustainable livelihood'.

'External economic pressures' was reduced (-1.0), positively impacting 'Input costs (running costs and equipment for fishing)' at -0.762 (meaningful improvement). These changes improved 'Income (fishing)' at 0.968 and the 'Ability to secure a sustainable livelihood' at 0.917. The improvement also positively affected the 'Price of kob and other target species (price setting by fish mongers)' at 0.223 (neither challenging nor favourable), further enhancing the 'Ability to secure a sustainable livelihood'.

'Kob abundance' was increased (+0.7), enhancing 'Commercial kob landings' at 0.876 (substantial positive change) and 'Income (fishing)' at 0.968. These improvements enhanced the 'Ability to secure a sustainable livelihood' at 0.917. 'Commercial alternative landings' was improved (+0.7), positively impacting 'Income (fishing)' at 0.604 (notable boost) and enhancing the 'Ability to secure a sustainable livelihood'.

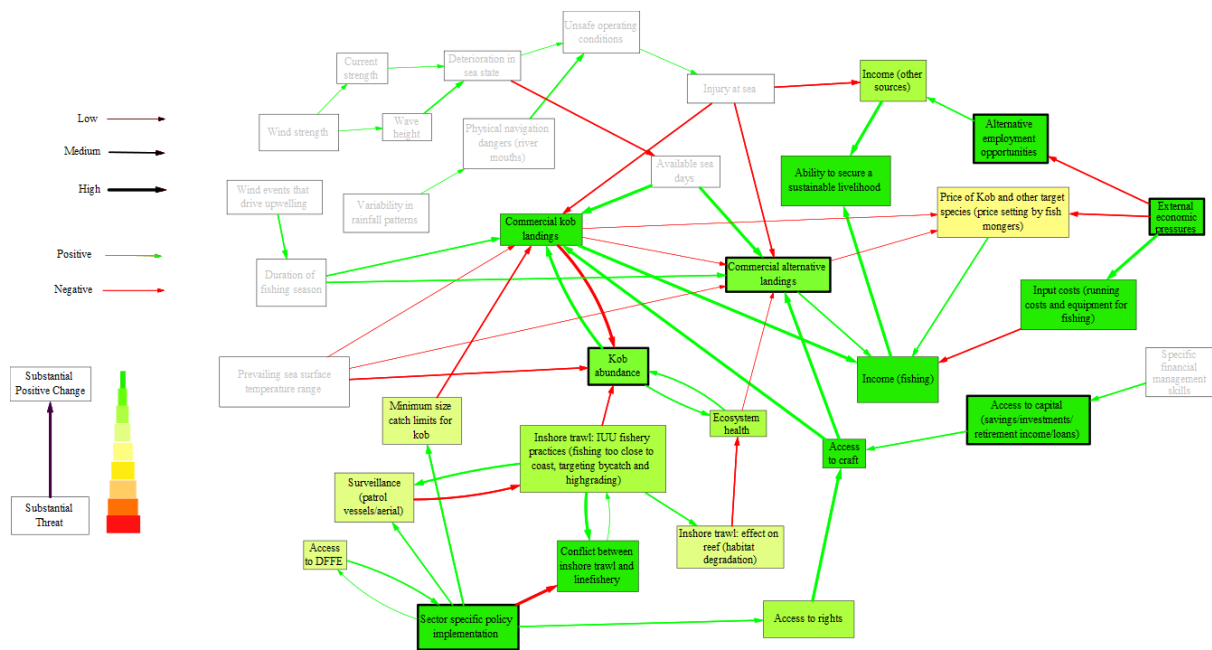


Figure 21: Regional prototype FCM showing the convergence values of Scenario 4 according to colour coding from red=substantial threat to dark green=substantial positive change.

5.2.5 Impact Of Scenarios 1 To 4 On 'Ability To Secure A Sustainable Livelihood'

The convergence values for the 'Ability to secure a sustainable livelihood' revealed notable differences across the four scenarios, reflecting varying economic stability and resilience levels among fishers. In the calibrated based model (Base Model 2), with 'External Economic Pressures' fully activated, the result was comparatively low, indicating a vulnerability in fishers' ability to maintain sustainable livelihoods under high external pressure. For example, with a convergence value of 0.762 (very challenging) for 'External Economic Pressures' and 0.480 (notable boost) for 'Income (fishing),' when 'Ability to secure a sustainable livelihood' was activated, the model underscores the impact of economic factors on fishers' stability, mainly when external forces are at play.

In Scenario 1 ("Nothing much has changed"), the 'Ability to secure a sustainable livelihood' was compromised, with a negative value of -0.885, indicating a substantial threat to maintaining a stable income and living conditions. This scenario's negative

convergence value highlighted the compounded adverse effects of limited access to capital (-0.7), poor sector-specific policy implementation (-1.0), inadequate alternative employment opportunities (-0.7), and negative impacts from commercial alternative landings (-0.7), kob abundance (-0.7), and external economic pressures (0.7).

Similarly, Scenario 2 ("We will get there, eventually") showed a negative value of -0.784, suggesting some improvement but still very challenging. The enhancement in sector-specific policy implementation (0.7) and slight relief (but still unfavourable) external economic pressures (0.3) provided some positive influence. However, moderate difficulties in access to capital (-0.7), commercial landings (-0.7), and kob abundance (-0.7) continued to hinder substantial progress, indicating that fishers still faced considerable barriers to securing sustainable livelihoods.

In contrast, Scenario 3 ("The going is good") presented a positive shift, with a value of 0.617, highlighting a notable boost for sustaining livelihoods. This improvement was driven by increased access to capital (0.7) and better employment opportunities outside the fishery sector (1.0). Additionally, positive changes in commercial alternative landings (0.3 for hake) contributed to this favourable outcome. While negative impacts from policy implementation (-0.7) and kob abundance (-0.7) persisted, they were outweighed by the positive influences, resulting in an improved livelihood outcome.

Scenario 4 ("The future is bright") represented the most favourable scenario, with a high value of 0.917 for the target component, demonstrating a substantial positive change for fishers to secure sustainable livelihoods.

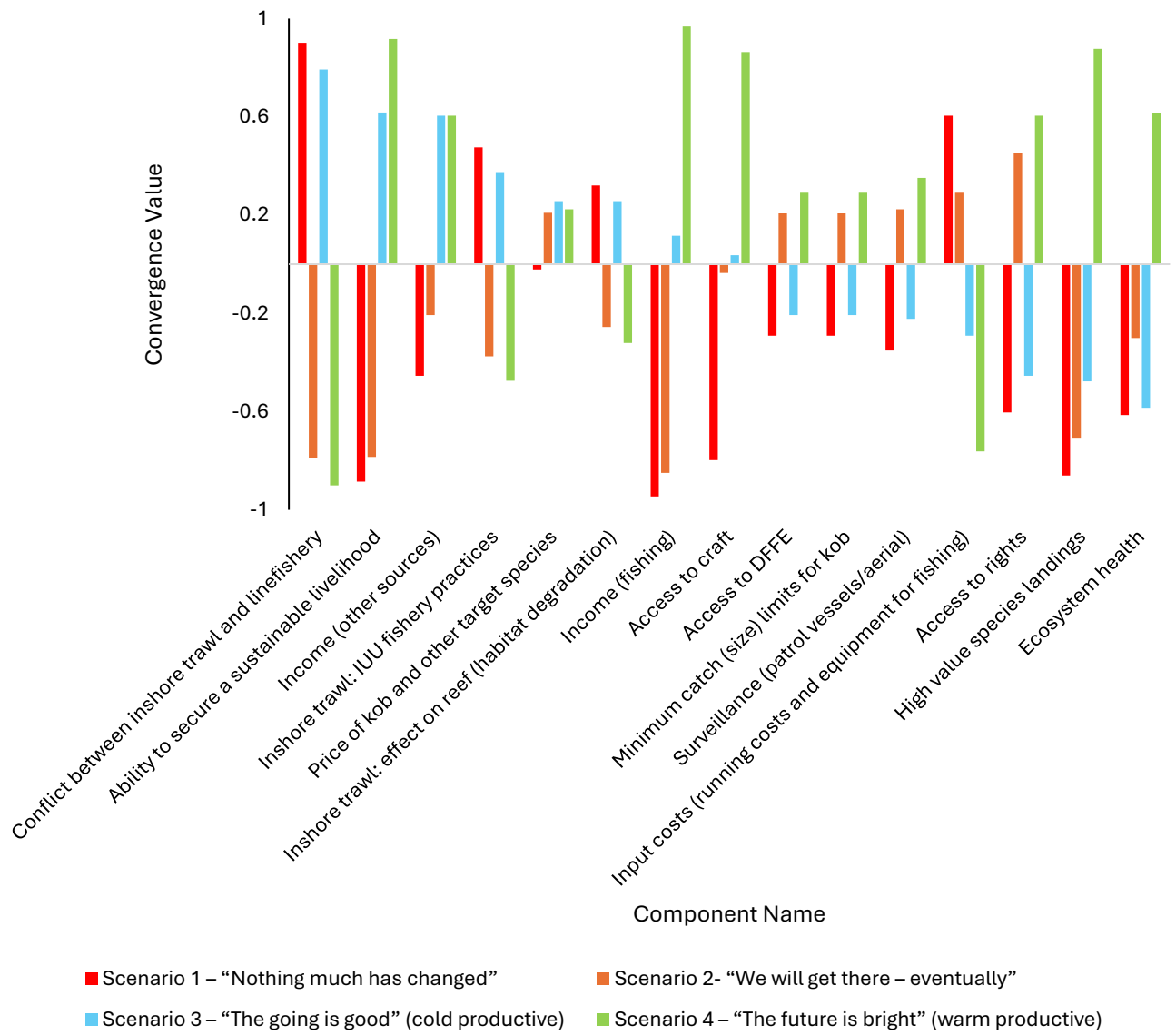


Figure 22: Convergence values for each scenario.

Table 23: Convergence values for each scenario. Green highlight indicates the activated/deactivated components and the values at which they were clamped.

Component Name	Scenario 1 - “Nothing much has changed”	Scenario 2 - “We will get there, eventually”	Scenario 3 - “The going was good” (cold productive)	Scenario 4 - “The future was bright” (warm productive)
Ability to secure a sustainable livelihood	-0.885	-0.784	0.617	0.917
Access to capital (savings/investments/retirement income/loans)	-0.700	-0.700	0.700	1.000
Access to craft	-0.798	-0.036	0.036	0.863
Access to DFFE	-0.291	0.207	-0.207	0.291
Access to rights	-0.604	0.454	-0.454	0.604
Alternative employment opportunities	-0.700	-0.300	1.000	1.000
Commercial alternative landings	-0.700	-0.700	0.300	0.700
Commercial kob landings	-0.860	-0.707	-0.477	0.876
Conflict between inshore trawl and linefishery	0.901	-0.791	0.792	-0.901
Ecosystem health	-0.614	-0.301	-0.585	0.614
External economic pressures	0.700	0.300	-0.300	-1.000
Income (fishing)	-0.946	-0.850	0.116	0.968

Component Name	Scenario 1 - “Nothing much has changed”	Scenario 2 - “We will get there, eventually”	Scenario 3 - “The going was good” (cold productive)	Scenario 4 - “The future was bright” (warm productive)
Income (other sources)	-0.454	-0.207	0.604	0.604
Input costs (running costs and equipment for fishing)	0.604	0.291	-0.291	-0.762
Inshore trawl: effect on reef (habitat degradation)	0.321	-0.256	0.257	-0.321
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0.475	-0.375	0.375	-0.475
Kob abundance	-0.700	-0.700	-0.700	0.700
Minimum catch (size) limits for kob	-0.291	0.207	-0.207	0.291
Price of kob and other target species (price setting by fish mongers)	-0.022	0.209	0.257	0.223
Sector-specific policy implementation	-1.000	0.700	-0.700	1.000
Surveillance (patrol vessels/aerial)	-0.351	0.224	-0.223	0.351

Relative importance of 'Access to Capital' and 'Policy Implementation'

The four scenarios analysed were based on contrasting 'Access to Capital' and 'Sector-Specific Policy Implementation'. Unsurprisingly, the best results were achieved when both were high. However, to determine which of these components is more important in supporting the 'Ability to Secure a Sustainable Livelihood' in the model, their impacts must be examined independently, without the influence of other activated components.

To isolate the effects of other activated components, scenarios were created where only 'Sector-Specific Policy Implementation' was activated and, separately, where only 'Access to Capital' was activated. The results, summarised in Table 24, reveal several notable insights. For instance, 'Ability to Secure a Sustainable Livelihood' reached a convergence value of 0.472 (notable boost) when 'Sector-Specific Policy Implementation' was activated, compared to a lower value of 0.352 (slight boost) when 'Access to Capital' was activated. This indicates that in the model, policy implementation is more influential in securing a stable livelihood for fishers than access to financial resources alone.

While the overall trends were positive when these two components were individually activated, certain contrasting effects were observed. For example, 'Ecosystem Health' showed a positive convergence value at 0.296 (slight boost) when 'Sector-Specific Policy Implementation' was fully activated, but a reduced convergence value at -0.261 (somewhat challenging) when only 'Access to Capital' was activated. This emphasises the need for policy to regulate capital use in a way that aligns with conservation goals.

A notable negative effect was observed in 'Conflict Between Inshore Trawl and Linefishery', which decreased at -0.901 (substantial positive change) under 'Sector-Specific Policy Implementation'. In contrast, this conflict component was neutral (0) when only 'Access to Capital' was activated, indicating that capital availability alone does not influence this conflict in the model.

Table 24: Convergence values when 'Sector-Specific Policy Implementation' and 'Access to Capital' were activated independently. Components not listed in the table maintained a convergence value of 0.

Component Name	'Sector-specific policy implementation' fully activated	'Access to capital' fully activated
Ability to secure a sustainable livelihood	0.472	0.352
Access to capital (savings/investments/retirement income/loans)	0	1
Access to craft	0.54	0.604
Access to DFFE	0.291	0
Access to rights	0.604	0
Commercial alternative landings	0.464	0.43
Commercial kob landings	0.423	0.219
Conflict between inshore trawl and linefishery	-0.901	0
Ecosystem health	0.296	-0.261
Income (fishing)	0.512	0.368
Inshore trawl: effect on reef (habitat degradation)	-0.321	0
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and highgrading)	-0.475	0
Kob abundance	0.116	-0.382
Minimum catch (size) limits for kob	0.291	0
Price of kob and other target species (price setting by fishermen)	-0.26	-0.193
Sector-specific policy implementation	1	0
Surveillance (patrol vessels/aerial)	0.352	0

The results of the scenario tests provide valuable insights into how varying species abundance and economic and policy conditions can affect the small-scale fisheries system in the southern Cape. By simulating different future scenarios and observing the

outcomes on key system variables, one can gain a better understanding of the resilience of fishers' livelihoods under changing conditions.

6. Discussion

This chapter provides an in-depth reflection on best practices and methodological challenges in applying fuzzy cognitive mapping (FCM) to small-scale linefisheries in the southern Cape, South Africa. It centres around the study's core research questions, focusing on integrating various bodies of knowledge to achieve semi-quantification and comprehensively represent the fisheries system. Additionally, this section identifies areas where FCM may benefit from further methodological advancements and refinement to improve its application in complex, data-scarce contexts.

The discussion begins with Research Question 1a, which addresses the feasibility of constructing a semi-quantitative FCM to effectively represent and extend the conceptual model of the small-scale linefisheries system developed by Gammage and Jarre (2020). In addressing the research question, developing a proof-of-concept (POC) model was a fundamental step in identifying and testing the most suitable methods for applying FCM to the southern Cape fishery system. Good modelling practice states that a POC model can explore and refine key model parameters (Neto et al., 2018). These are the choice of software, squashing function, inference rule, and *Lambda Parameter* in FCMs, which are essential for ensuring the model's accuracy. For this study, the *Hyperbolic Tangent Function*, the *Kosko Inference Rule*, and a *Lambda Parameter* value of 1 were selected. These choices were made based on their ability to provide stable and accurate model outputs. These choices and their impact on model behaviour have already been discussed extensively in Chapter 3, and as such, Research Question 1a will not be revisited in detail in this section, only reflections on good modelling practice will be discussed.

The discussion then moves to Research Question 1b, which explores integrating various bodies of knowledge, including traditional and expert expertise, to achieve semi-quantification of the FCM and create a comprehensive representation of the fisheries system. Lessons learned from the semi-quantification process, including what worked and what did not, are critical to this discussion.

Following this, the discussion examines Research Question 1c, which delves into identifying the key drivers of vulnerability, economics, policy, and climate, highlighted by

Gammage and Jarre (2020). It will also examine how these drivers shape the vulnerability of the southern Cape fishing communities and provide a detailed comparison with qualitative findings. By focusing on the additional insights generated by FCM, this discussion highlights how the approach enables the prioritisation and quantification of system dynamics that may not be evident in qualitative approaches alone.

Finally, the discussion addresses Research Question 2, which is explored by analysing how iterative refinements of model components, such as the squashing function, inference rule, and semi-quantification categories, enhance the alignment between the FCM and the scenario stories. These methodological choices are evaluated for their influence on model outcomes, providing a basis for further scenario analysis and development. This part of the discussion offers valuable insights and guidance for future applications of FCM in fisheries systems such as this one, illustrating how these components enhance analysis and communication.

Through these reflections, this discussion provides a comprehensive analysis of the integration of knowledge, methodological practices, and the unique insights FCM offers. It underscores the broader implications of applying FCM to the southern Cape small-scale linefisheries system and lays the groundwork for methodological advancements and future research in fisheries systems.

6.1 Reflections On Good Modelling Practice

This section answers the research question, *How can different bodies of knowledge be integrated to synthetically represent this fishery system?* by reflecting on the lessons learned from the semi-quantification process, specifically what worked and what did not. This study underscores the importance of good modelling practices, highlighting the iterative approach to refining model components such as the squashing function, inference rule, and semi-quantification categories. Carefully testing the model's sensitivity has provided insights into how specific methodological decisions affect its performance. While attempting to compare the findings with similar models, a lack of marine FCM SES studies that could serve as direct comparisons was encountered. Consequently, non-environmental or terrestrial FCMs and systems models employing

interdisciplinary approaches were referenced. This reflection on the process also guides best practices when applying FCM to represent the complexities of the southern Cape linefishery system.

6.1.1 Adapting The *fcm.infer* Function In R For Enhanced Flexibility In Scenario Testing Within The POC And Regional Models

This study adapted the *fcm.infer* function (Dikopoulou and Papageorgiou, 2017) in *RStudio* (R Core Team, 2023) by modifying the source code to better align with the research objectives. The original *fcm.infer* function only clamped activated components if they equalled strictly +1, without accounting for other non-zero values. Most studies that utilised the FCM package in R, including those by Dikopoulou (2021), Dikopoulou et al. (2023, 2018), Agostinho et al. (2023), Meechang and Watanabe (2023), Deviney et al. (2024), and Parisi (2024), activated components exclusively at 1, as this was the default setting of the package. However, to effectively run the scenarios adapted from Gammage and Jarre (2021) on the regional prototype, activating model components to various values between -1 and 1 was necessary. Therefore, the source code for the *fcm.infer* function was modified during the testing of the *POC model* to ensure that all non-zero values were correctly clamped during each iteration. The revised function accurately clamped components at their respective activation levels across the entire range of activation values in the *POC model* and was used when running scenarios on the regional model.

While most FCM studies, including those by Dikopoulou (2021) and others, restricted component activation to a value of 1, a few studies, such as Henly-Shepard et al. (2015) and Kokkinos et al. (2018), employed a broader activation range between -1 and 1 using *Mental Modeler*. However, as discussed in Section 3.4, *Mental Modeler* was unsuitable for this study. The flexibility of a range of activation values between -1 and 1 also proved beneficial in Henly-Shepard et al. (2015), where the study found that during the participatory modelling workshops, the participants identified specific components within their consensus model that needed to be adjusted to achieve favourable outcomes under a tsunami scenario. Similarly, Kokkinos et al. (2018) tested different scenarios on the acceptance of Waste Biorefinery Facilities by setting scenario

activation values to 0.1 for a worst-case scenario and 1 for a best-case scenario. Sujamol et al. (2018) developed an FCM that integrates fuzzy logic and neural networks to represent and analyse complex medical decision-making processes, particularly for disease diagnosis and prediction. Instead of activating components with a value of 1, they used a range between 0 and 1, employing RStudio with a randomly generated strength matrix. However, they did not use the `fcm.infer` function utilised in this study.

The advantage of using a specified range between -1 and 1 in these studies is the ability to activate or deactivate components incrementally. This allows for finer adjustments in component values, providing a more accurate and nuanced depiction of the investigated scenarios. Such flexibility is essential for capturing subtle changes that might be missed with only activating to 1. Based on these findings, it is recommended that other researchers adopt this method where a more detailed representation of activation is needed. Utilising a range of activation values that extends into negative values could better capture complex interactions, especially when modelling systems with antagonistic relationships, offering greater flexibility and accuracy in scenario analysis.

6.1.2 Iterative Calibration Of The Regional Model

The calibration of the regional model involved multiple steps to ensure it accurately reflected the fishery as perceived by the handline fishers in the southern Cape, as represented in Gammage and Jarre (2020). *Base Model 1* represents the initial configuration of our system, constructed using foundational assumptions and parameters derived from the literature and expert input. It served as the starting point for testing and refining the model. After running *Base Model 1*, various discrepancies were identified where the model outputs did not align with the modellers' and experts' knowledge of the system, highlighting areas where further adjustments and recalibrations were necessary.

The initial calibration revealed several areas where the model's representation of relationships between components was either overly simplified or misaligned with expected outcomes. For example, adjustments to the 'Prevailing sea surface temperature range' connections were particularly substantial. Initially, the model

showed an inappropriate increase in 'Kob abundance' with elevated temperatures, which contradicted the ecological expectation that higher temperatures should deter kob from the fishing grounds as they move out of their optimal temperature range. The recalibration corrected this by ensuring that 'Kob abundance' decreased as expected, aligning with ecological responses documented in the literature, particularly the findings of Tjipute (2011), who conducted a feasibility study for mass production of the silver kob in Namibia, and found that silver kob tolerate a temperature range of 13 to 25 °C but grow best at 23 °C; therefore an increase in the temperature range would adversely affect the kob abundance.

The calibration process served as an opportunity to validate the model's behaviour by comparing its outputs with established literature. The strong negative impact of 'External economic pressures' on 'Ability to secure a sustainable livelihood' was consistent with the findings of Gammage et al. (2017a), whose study examines the challenges faced by small-scale traditional commercial linefishers in the southern Cape region of South Africa. Gammage et al. (2017a) found that these fishers were impacted by various stressors, including climate variability, regulatory frameworks, and economic pressures, which hindered their ability to maintain sustainable livelihoods. Specifically, the study highlighted how rising input costs and static fish prices placed substantial financial strain on fishers, limiting their economic resilience and exacerbating their vulnerability to external shocks (Gammage et al., 2017a). Refer to Figure 10 for the indirect linkage between 'External economic pressures' and 'Ability to secure a sustainable livelihood'.

However, certain discrepancies required recalibration, such as the initially overemphasised connection between 'Inshore trawl: IUU fishery practices' and 'Ecosystem health.' By removing the direct connection and representing the indirect effects of IUU practices, where 'IUU fishery practices' impact 'Inshore trawl: effect on reef,' which subsequently affects 'Ecosystem health', the model demonstrated enhanced performance and provided more refined insights. This adjustment better captured the cascading effects of IUU practices on the ecosystem, in line with other findings where although other sectors can also impact the health of an ecosystem, fishing was shown to be the primary sector, raising the overall risk in South Africa's maritime ecosystems (Blamey et al., 2014; Bornman et al., 2024; Skein et al., 2022)

The recalibration of the connection between 'IUU fishery practices' and 'Ecosystem health' in the model addressed an issue observed during Base Model run 1. Initially, the direct connection between 'IUU fishery practices' and 'Ecosystem health' resulted in an excessively high reduction of 91% in ecosystem health, which was not reflective of real-world understanding. After recalibration, the impact of IUU fishing practices was adjusted to a more realistic 68% reduction in 'Ecosystem health,' aligning the model's outputs with expected ecological responses. A similar pattern was observed in the study by Atkinson et al. (2011), which assessed the impacts of demersal trawling on benthic infaunal and epifaunal assemblages in the southern Benguela upwelling region. They found that epifaunal populations were more disturbed in heavily trawled areas than lightly trawled ones, while infaunal populations were less affected. Likewise, Currie et al. (2020) documented changes in demersal fish communities on the inshore Agulhas Bank, revealing that over a century of fishing, including trawling, had severely altered benthic habitats and reshaped fish community structure. Historical fish assemblages, once dominated by species such as kob, have drastically declined, constituting only a small portion of catches (DFFE, 2023). These findings underscore the importance of recalibrating system models, as the original approach may have overemphasised the impacts of fishing practices on marine ecosystems.

Initially, the model suggested that the impact of 'Sector-specific policy implementation' on 'Access to DFFE' was moderate (medium strength). This assumption was based on the notion that policy implementation would moderately improve stakeholders' access to the DFFE. However, further calibration revealed that this connection had been overestimated. It became clear that additional factors, such as the requirement for fishers to be represented by associations and the pervasive mistrust in the system (Duggan, 2018), limited the effectiveness of policy implementation in improving access to DFFE. As a result, the strength of this connection was reduced from medium to low to address the issue mentioned above. This adjustment did not imply fewer issues with access but instead reflected a better understanding of the situation. The revised model recognised the complexity of the relationship, where policy implementation alone had a more limited and indirect impact on access. The recalibration of the model (from moderate to low impact of "Sector-specific policy implementation" on "Access to DFFE")

reflects the complexity of governance systems and the multifaceted challenges inherent in them. Pittman and Armitage (2016) emphasise similar issues in governance across the land-sea interface, such as the need for governance systems to be flexible and adapt to social and ecological realities.

The iterative recalibration process, though time-intensive, exemplified good modelling practice by continuously refining the model to improve its accuracy and reliability. Each recalibration step, whether correcting the 'Prevailing sea surface temperature range' influence on 'Kob abundance,' adjusting the impact of 'IUU fishery practices' on 'Ecosystem health,' or re-evaluating the strength of social-political connections, contributed to a representation of the southern Cape fishery system that better reflects the current understanding of this system. This careful calibration and validation ensured that the model could provide insights into securing a sustainable livelihood for fishers in scenario explorations. Gianelli et al. (2021) emphasised the critical role of integrating local ecological knowledge with scientific monitoring programmes to enhance adaptive capacities in fisheries operating within climate hotspots. This combined approach deepens system understanding and supports transformative governance processes, which are vital for effectively addressing climate-induced vulnerabilities. By adopting this comprehensive approach, the recalibration process reflects the dual strategy advocated by Gianelli et al. (2021).

6.1.3 Evaluating Semi-Quantification Categories

This study focused on whether increasing the number of categories from three to four or adjusting the quantification values would have a meaningful effect on the results. Specifically, three sensitivity tests were carried out: the first split the medium category into two, the second modified the low, low medium, high medium and high quantification values into 0.25, 0.5, 0.75, and 1, and the third reclassified relationships across all categories. These tests aimed to assess whether additional granularity regarding the number of categories and the specific relationship values would improve model performance. The results indicated that using three categories, with values of 0.3, 0.7, and 1, was sufficient, as introducing a fourth category or modifying the values did not improve the model's outcomes because most of the output values did not change by

more than 10%. Adjustments to the low and medium quantification values in the second test (e.g., lowering the low category value from 0.3 to 0.25 and the medium category value from 0.7 to 0.5) did not lead to notable changes in model results in this study. Similarly, increasing the granularity by adding more categories or subcategories, as done in the first and third tests, showed minimal impact on model outcomes.

This study utilised six categories, including positive and negative high, medium, and low values, aligning with approaches taken by other studies. Notably, the 'zero' quantification category was not used, as it indicates the absence of a relationship. Similarly, Navas de Maya and Kurt (2022) employed six categories. A review of existing literature revealed that many researchers employed more categories without clear justification or thorough testing of the impact on model sensitivity. For example, Meechang and Watanabe (2023) employed 10 categories but did not assess the effect of using fewer categories on model sensitivity. Parreño and Pablo-Martí (2024) and Mehryar et al. (2019) also utilised 10 categories without providing a rationale for such a level of granularity. By not conducting tests, these studies left the question of whether additional categories provided meaningful benefits unanswered. In contrast, this study directly addressed this gap by testing the impact of category numbers and values, finding that fewer categories could still capture the essential dynamics of the fishery system.

Other literature on scoring categories provided additional insights. Malek (2017), who examined fuzzy cognitive mapping (FCM) in the context of ecosystem-based management in Tunisia, emphasised the importance of simplicity in FCM, noting that its open and straightforward symbolic structure provides an ideal framework for involving non-expert stakeholders. Malek's study highlighted that while simplicity supported stakeholder participation, it could raise concerns regarding accuracy, particularly among technical experts. Similarly, Visscher and Yengo (2023), who investigated the accuracy of scoring research grants in the Netherlands using a multiple threshold model, found that increasing the number of scoring categories beyond five did not improve the accuracy of the results and concluded that a finite set of five distinct categories was sufficient. Similarly, Setiadi et al. (2020) conducted research with high school students in Indonesia and found that a five-category scale was more accurate than a three-category scale for predicting mathematics self-efficacy and learning outcomes.

Likewise, Aybek and Toraman (2022), whose research involved university students from eleven different universities across Türkiye, concluded that a five-point scale provided better reliability and test information than three- or seven-point scales. Similarly, the six-point Likert scale to classify responses into low, medium, and high categories for both negative and positive dimensions was found to be best.

This study explored the assumption that using more categories would enhance model detail and accuracy but found that, in practice, a simpler scheme with six categories was sufficient. Adding more categories or value adjustments had minimal impact on model outcomes, underscoring the importance of testing, which was a notable gap in prior studies. For future research involving stakeholders, using just three levels (low, medium, and high) across positive and negative dimensions was identified as an approach that could improve communication and engagement. This aligns with challenges noted in other contexts, such as Gammage and Jarre's (2020) experience conducting Bayesian modelling with fishers in the southern Cape, where clear communication approaches were essential. In preparation for further research with these communities, we focused on making our models more accessible. Future research could benefit from a similar approach, where the number of categories and value assignments are determined through context-specific testing rather than conventional or arbitrary methods. A practical recommendation is to use as few categories as possible for stakeholder communication, as highlighted by van den Belt (2004). Simplifying the parameterisation into six categories proved adequate to represent the dynamics of the system and can foster clear communication and support meaningful discussions without the distraction of excessive detail in situations such as this one, where uncertainties are high.

6.1.4 Conclusion

The study introduced several refinements to existing FCM methods to address the complexities of the small-scale linefisheries systems in the Southern Cape. This study modified the `fcm.infer` function (Dikopoulou and Papageorgiou, 2017) in RStudio (R Core Team, 2023) to enable the activation of components across a range of values between -1 and 1, enhancing its applicability for integrating diverse knowledge domains. This refinement enabled the effective testing of scenarios adapted from Gammage and Jarre

(2021) on the regional model, ensuring that all non-zero activation values were accurately clamped and providing a more detailed and synthetic representation of the system. The iterative approach to refining parameterisation, including the squashing function, inference rule, and semi-quantification categories, was instrumental in maintaining the model's intellectual coherence. Sensitivity testing confirmed that using six semi-quantification categories (high, medium, and low in both positive and negative directions) was sufficient to capture system dynamics without substantial gains from additional categories or value modifications.

The iterative calibration of the regional model improved alignment with real-world ecological and socio-economic understanding, ensuring outputs were consistent with expert knowledge and literature. For example, recalibrating the relationship between sea surface temperatures and kob abundance corrected discrepancies and improved the model's reliability. The recalibration process highlighted the importance of continual refinement in ensuring the model accurately reflects critical factors influencing fishers' livelihoods.

In conclusion, this study refined FCM methods by integrating diverse knowledge systems and enhancing model accuracy through iterative calibration and adaptations to the *fcm.infer* function and categorisation. Incorporating ecological, socio-economic, and experiential knowledge provided a holistic representation of the fishery system, contributing to best practices in FCM and improving methodologies for more reliable outcomes. Future research should build on these lessons, presenting the model to fishers for feedback to improve its communicability. This participatory step aligns with the rapid prototyping approach in Starfield and Jarre (2011) and highlights the potential for feedback to enhance the model's utility for system-based decision-making processes.

6.2 Insights From FCM Compared To Qualitative Approaches

The following section seeks to answer Research Question 1c: *Which additional insights can be generated from the Fuzzy Cognitive Map (FCM) compared to the qualitative approach? Specifically, which key drivers discussed in Gammage and Jarre (2020),*

economic, policy, and climate, contribute the most to the vulnerability of communities in the southern Cape? By examining the regional FCM, this section aims to identify key drivers of vulnerability within the southern Cape fishery system. This section first identifies and explains the top seven highest *Centrality* components within the fishery system model, selected based on their substantial *Indegree*, *Outdegree*, and *Centrality* scores. It then examines their roles, interactions, and feedback mechanisms, focusing on how these components influence and are influenced by the broader system. The analysis reveals the critical drivers shaping the fishery system and their contributions to ecological and societal outcomes by highlighting key ecological, economic, social, policy, and climate factors.

6.2.1 Examining Base Model 2 Component Metrics

This section provides an in-depth analysis of the components with the highest *Centrality* within the fishery system model. These components were selected for their high scores and relevance in identifying key drivers, i.e. economic, policy, and climate factors, contributing to the vulnerability of southern Cape communities, as noted by Gammage and Jarre (2020). The discussion excludes 'Commercial kob landings' and 'Commercial alternative landings,' as their prominence is inherently tied to modelling a fisheries system. The focus is instead on components such as 'Kob abundance,' 'Inshore trawl: Illegal, Unreported, and Unregulated (IUU) fishing practices,' 'Sector-specific policy implementation,' and other critical system elements. These components are discussed to understand their roles and interactions within the broader model. The discussion evaluates how incoming connections influence them and how they affect other components. This highlights their significance in shaping ecological and societal outcomes, revealing the critical drivers and feedback mechanisms that sustain or disrupt the fishery's dynamics. Similarly, Sayles et al. (2019) emphasised the utility of social-ecological network (SEN) analysis in sustainability sciences, demonstrating how fully articulated SENs can capture the intricate relationships and dynamics between social and ecological components.

i) Kob abundance

Kob abundance ranks third in *Indegree* and *Centrality*, following the more dominant components 'Commercial kob landings' and 'Commercial alternative landings.' It shapes the system with an *Indegree* of 3.1 and a *Centrality* score of 4.8. The outgoing connections from 'Kob abundance' contribute to an *Outdegree* score of 1.7, indicating a moderate influence over other model components. This *Outdegree* is higher than that of 'Income (fishing)' (1.0) but lower than 'Inshore trawl: IUU fishery practices' (3.1), positioning 'Kob abundance' as a critical, though not dominant, component within the model. Both 'Kob abundance' and 'Income (fishing)' have the same *Indegree* score of 3.1, indicating that external factors similarly influence them in the system. The strongest outgoing connection is to 'Commercial kob landings' with a strength of 1, forming a feedback loop where higher kob abundance facilitates increased landings, which, in turn, may lead to stock depletion (Figure 23). This feedback loop emphasises the interplay between population abundance and fishing intensity, which underlines the need for regular monitoring. Additionally, 'Kob abundance' positively influences 'Ecosystem health' (strength of 0.7), underscoring the role of kob populations in supporting broader model system stability (Figure 23).

Kob abundance ranks third in *Indegree* and *Centrality* within this study, following 'Commercial kob landings' and 'Commercial alternative landings.' With an *Indegree* of 3.1 and a *Centrality* score of 4.8, it plays a substantial role in shaping the system. By comparison, in Kontogianni et al.'s FCM study on multiple risks for the Black Sea environment, the 'Biodiversity' component had a lower *Indegree* (1.9) and *Centrality* score (2.3) (Kontogianni et al., 2012). These differences arise from variations in the structure and quantification of the models. Kontogianni's model included 26 components and 145 connections, making it more densely connected than this study, which featured 35 components and 57 connections. The higher density in Kontogianni's model spreads the influence across more connections, diluting the relative importance of individual components like 'Biodiversity.'

Additionally, the two studies used different quantification scales. Kontogianni's study measured connection strengths on a scale from -6 to 6, while this study used a range of -1 to 1. For consistency, metrics from Kontogianni's model were normalised by dividing

by 6. After standardisation, the connection strengths in Kontogianni's model ranged from 0.16 to 1 across 12 categories, whereas this study's connections ranged from 0.3 to 1 across six categories. This suggests that although Kontogianni's model had more connections, the weaker standardised values may have reduced the influence of components like 'Biodiversity.' In contrast, this study's fewer but stronger connections resulted in higher scores for key components such as 'Kob abundance,' highlighting the impact of connection strength in determining system dynamics and the prominence of critical elements.

With a *Centrality* score of 4.8, 'Kob abundance' is among the model's key components, ranking just below 'Commercial alternative landings' (5.3) but higher than 'Income (fishing)' (4.1), signifying its essential yet slightly lesser role in model system dynamics. This score suggests that kob population levels are crucial for both ecological integrity and the long-term sustainability of fisheries dependent on this species. The component's high-strength feedback loop with 'Commercial kob landings' and its sensitivity to environmental conditions, such as the 'Prevailing sea surface temperature range,' reflects its dual role as both an influential and reactive element within the model. This complexity indicates that while 'Kob abundance' supports system stability, it remains vulnerable to pressures such as fishing intensity and climate variability, necessitating management practices that balance economic goals with ecological sustainability. The arrangement of these interactions underscores 'Kob abundance' as a vital factor within feedback mechanisms that influence the broader fishery system dynamics (Figure 23).

The model shows that 'Kob abundance' is more influential and central than 'Income (fishing)' in the southern Cape fishery system. While 'Income (fishing)' primarily affects 'Ability to secure a sustainable livelihood' (strength of 1), its direct influence is limited (Figure 24). In contrast, 'Kob abundance' has a broader impact, shaping a wider range of interconnected factors and playing a more substantial role in the model system. This pattern contrasts with other models, such as those by Papageorgiou et al. (2020) and Alipour et al. (2019), which observed higher *Centrality* scores for income-related components. These comparisons underscore that, in this specific fishery model, 'Kob abundance' plays a more critical and far-reaching role than 'Income (fishing)',

emphasising the importance of the ecological health of key species over immediate economic factors in shaping the broader system dynamics.

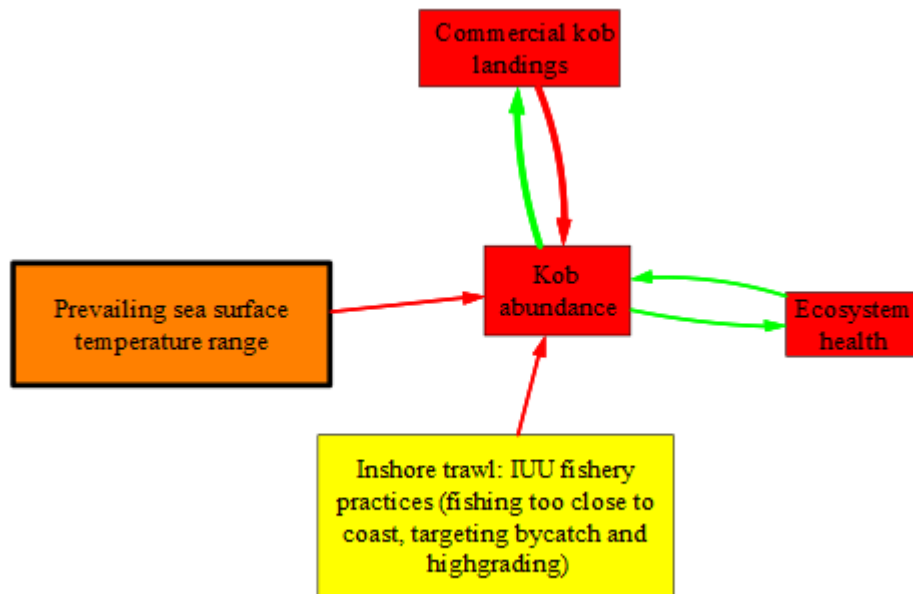


Figure 23: Portion of regional prototype FCM showing only connections going into and out of 'Kob abundance'. Green arrows are amplifying, and red arrows are dampening. Refer to Figure 10 for information on the arrow thickness.

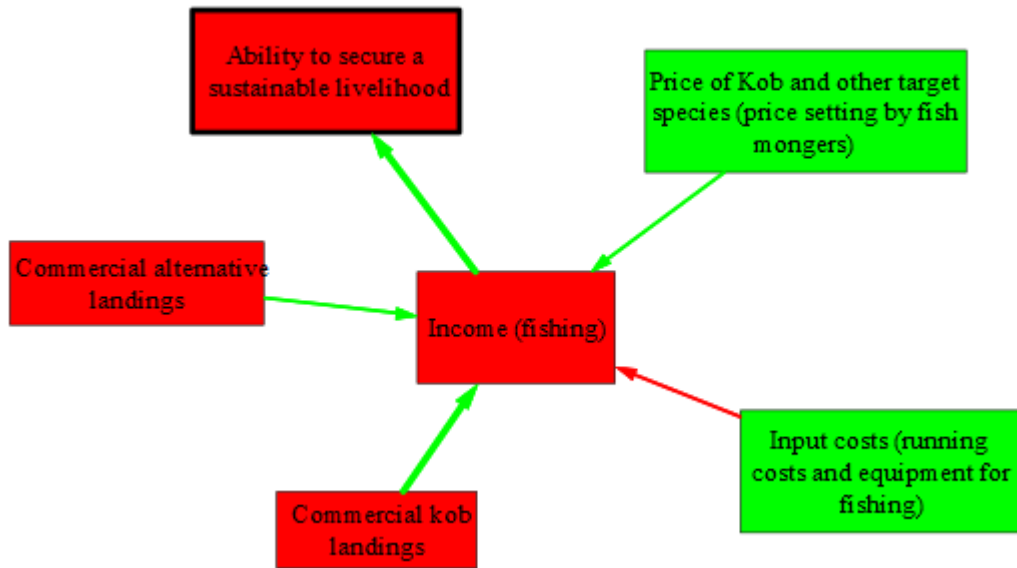


Figure 24: Portion of regional prototype FCM showing only connections going into and out of 'Income (fishing)'. Green arrows are amplifying, and red arrows are dampening. Refer to Figure 10 for information on the arrow thickness.

ii) Inshore Trawl: Illegal, Unreported, and Unregulated (IUU) Fishing Practices

The 'Inshore Trawl: IUU Fishing Practices' has the highest *Outdegree* score (3.1) and is one of the most influential components within the model. The extensive outgoing connections underscore its substantial impact on multiple components, including direct effects on 'Conflict between inshore trawl and linefishery' (strength of 1), 'Inshore trawl: effect on reef (habitat degradation)' (strength of 0.7), and 'Surveillance (patrol vessels/aerial)' (strength of 0.7). Additionally, it exerts a dampening influence on 'Kob abundance' with a strength of -0.7, signifying that IUU activities directly reduce fish stock health (Figure 25). These connections highlight the disruptive role of IUU fishing, contributing to environmental degradation, escalating conflict, and challenging regulatory capacity. Notably, the impact on surveillance efforts reflects a feedback loop, as increased IUU activity necessitates heightened monitoring efforts, stressing regulatory resources.

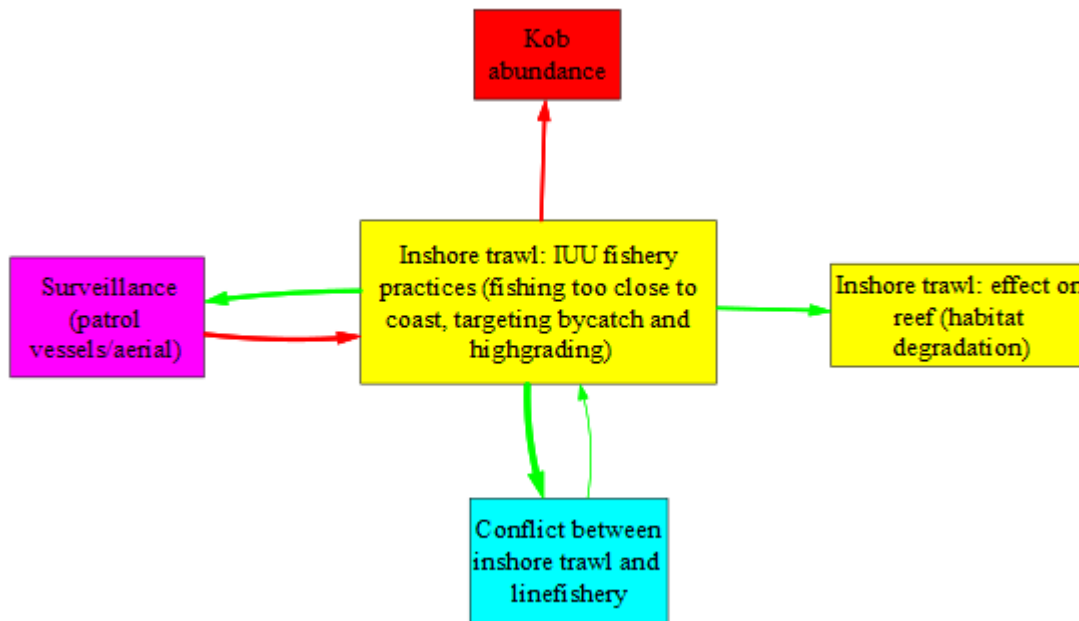


Figure 25: Portion of regional prototype FCM showing only connections going into and out of ‘Inshore trawl: IUU fishery practices’. Green arrows are amplifying, and red arrows are dampening. Refer to Figure 10 for information on the arrow thickness.

Regarding *Centrality*, ‘Inshore Trawl: IUU Fishing Practices’ scores 4.1, ranking as the fifth highest *Centrality* score in the model, just after ‘Income (fishing)’. This demonstrates its critical role as a pressure in the model, shaping the fishery system more than reacting to changes in the system. Alipour et al. (2019) model the development of solar photovoltaic (SPV) energy in Iran using a Fuzzy Cognitive Map (FCM) framework comprising 31 interconnected concepts and 135 causal connections. These components represent influential political, economic, social, technological, environmental, and legal (PESTEL) factors impacting the solar energy sector. In Alipour et al.’s (2019) model, ‘Private Sector Involvement’ holds a high *Centrality* score of 6.9 but primarily serves as a receiver, with an *Indegree* of 6.2 and a low *Outdegree* of 0.7, indicating external factors influence it more than it actively shapes the model system. Both ‘Inshore Trawl: IUU Fishing Practices’ and ‘Private Sector Involvement’ occupy pivotal positions in their respective models, but they do so in fundamentally different ways. The comparison between ‘Inshore Trawl: IUU Fishing Practices’ and ‘Private Sector

Involvement' is meaningful because both represent external sectors that exert or influence their respective models substantially.

iii) Sector-specific policy implementation

'Sector-specific policy implementation' had the second highest *Outdegree* score (3.0) after 'Inshore trawl: IUU fishery practices'. This score underscores its substantial influence in the model, marking it as an active driver of change. Through key outgoing connections, it impacts multiple components, emphasising its central role in shaping the system. For example, it maintains a feedback loop with 'Access to DFFE' (strength of 0.7), highlighting the mutual influence between policy execution and regulatory support (Figure 26). Additionally, its dampening effect on 'Conflict between inshore trawl and linefishery' reflects its capacity to mediate critical tensions within the system. This last connection is particularly substantial, emphasising that effective policy implementation can be essential to conflict resolution within the fishery sector. By regulating practices and enforcing sustainable fishing measures, equitable sector-specific policies help to mitigate conflicts and reduce the risk of sectoral discord. Furthermore, the connection

to surveillance efforts suggests that active policy implementation enhances regulatory oversight.

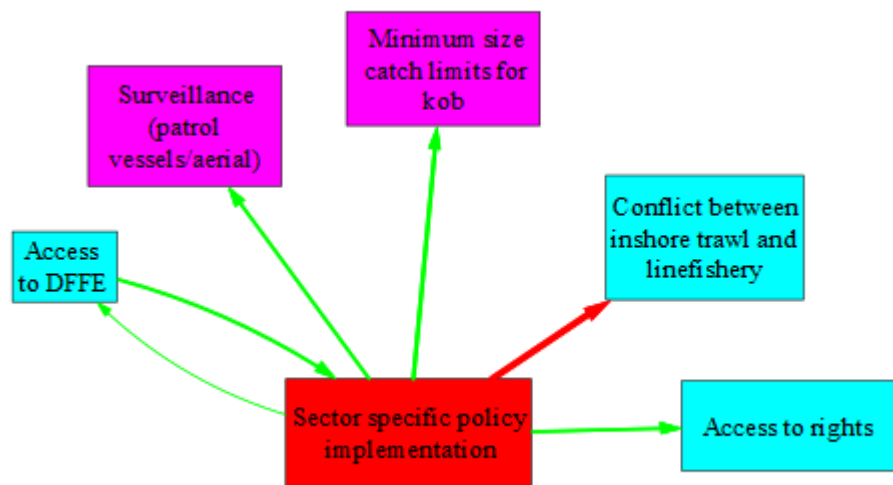


Figure 26: Portion of regional prototype FCM showing only connections going into and out of ‘Sector-specific policy implementation’. Green arrows are amplifying, and red arrows are dampening. Refer to Figure 10 for information on the arrow thickness.

Compared to similar components in other models, ‘Sector-specific policy implementation’ functions as a critical driver within the fishery model, evidenced by its high *Outdegree* of 3.0, indicating its active influence in shaping system dynamics. For instance, in Alipour et al.’s (2019) FCM, ‘Political Stability’ holds a lower *Centrality* of 2.0 and serves mainly as a receiver with an *Indegree* of 1.8 and an *Outdegree* of 0.2. This contrast illustrates that unlike the fishery model, where policy implementation directly influences practices, political stability in Alipour’s energy model serves more as a background condition that supports the system but does not actively drive change. In the fishery model, sector-specific policy implementation is a proactive force that shapes operational behaviour, reflecting the active role of governance in regulating resource-dependent sectors.

Additionally, the *Centrality* score of 3.7 for ‘Sector-specific policy implementation’ in this model closely aligns with that of ‘Political empowerment’ in Papageorgiou et al.’s (2020)

model, which has a *Centrality* of 3.8. This similarity highlights the comparable importance of governance-related factors in both models. While each component operates within a unique context—policy implementation in the fishery model versus political empowerment in broader livelihood contexts—their similar *Centrality* scores indicate a shared recognition of governance as crucial to system stability. Both variables reflect structure and accountability, emphasising the role of policy and empowerment in fostering resilience and community agency.

iv) Bio-physical/Climate components

This model's biophysical components (Figure 27) exhibited lower *Outdegree*, *Indegree*, and *Centrality* scores compared to the economic and political components, highlighting their more passive role within the model. Components in the model, such as 'Wave Height', 'Wind Events that Drive Upwelling', 'Current Strength', and 'Ecosystem health', are essential for maintaining ecosystem stability but exert limited influence on the model system's dynamics. This indicates that the biophysical system is well modelled because the fishers have limited understanding of this system. For example, 'Wave Height' has an *Outdegree* score of 0.7, which is moderate but lower than that of more influential components such as 'Commercial Kob Landings' (2.6). Its *Indegree* score of 0.3 suggests low sensitivity to external influences, indicating that while 'Wave Height' plays an essential role in ecosystem processes, it remains unaffected by changes driven by human activity or regulatory factors within the model system. Similarly, 'Prevailing Sea Surface Temperature Range,' a driver with an *Outdegree* of 1.3 shows how external environmental variables operate independently as per the model design. The model further indicates that 'Current Strength' and 'Wind Strength,' with *Centrality* scores of 0.6 each, and 'Variability in Rainfall Patterns,' with a *Centrality* of 0.3, have limited influence on the model system.

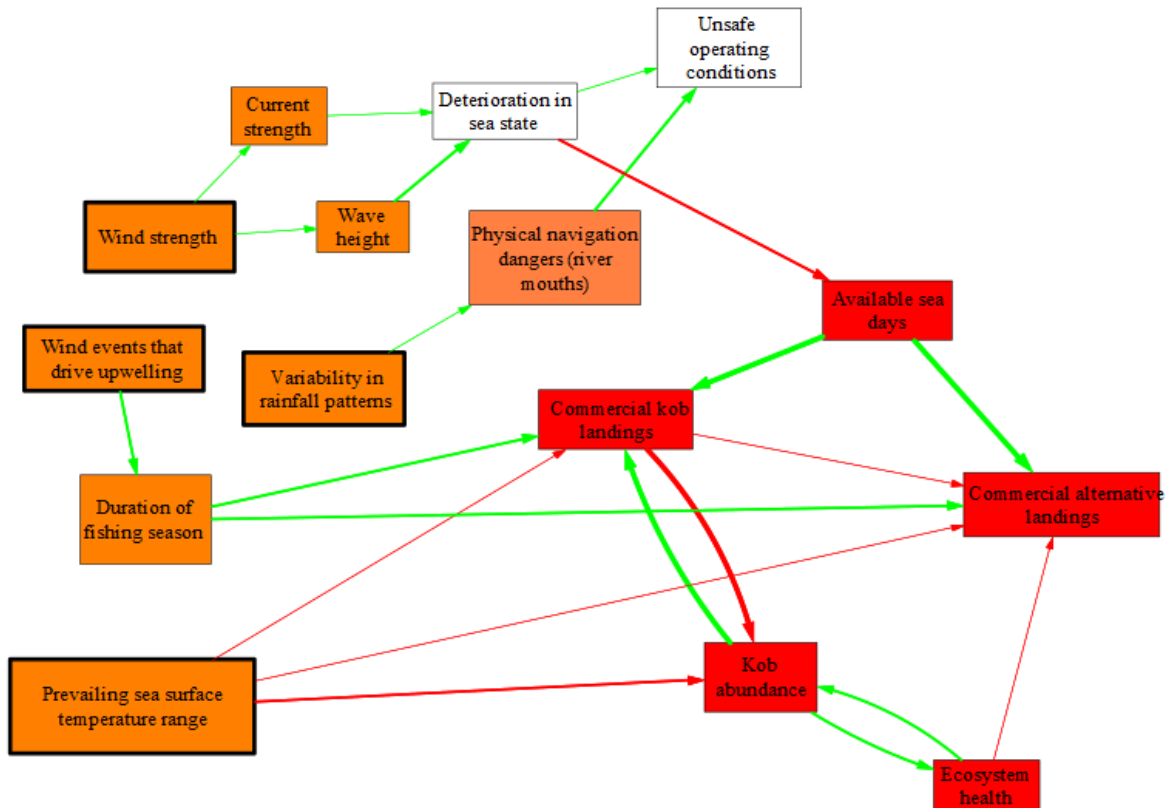


Figure 27: Portion of regional prototype FCM showing only connections going into and out of biophysical/climate components. Green arrows are amplifying, and red arrows are dampening. Refer to Figure 10 for information on the arrow thickness.

The 'Ecosystem Health' component in this model can be compared to 'Ecological State' in Kontogianni et al.'s (2012) model on multiple risks for the Black Sea environment. In Kontogianni's study, 'Ecological State' has an *Outdegree* of 0.3 and an *Indegree* of 1.3 (when standardised), indicating a weak influence within the system. In comparison, 'Ecosystem Health' in this study has a higher *Outdegree* of 1.0 and an *Indegree* of 1.4, suggesting a slightly higher role in driving components within this specific fishery system.

In comparing the role of natural assets across different studies, 'Natural Assets' in Papageorgiou et al.'s (2020) study holds a *Centrality* score of 0.8, indicating a low influence within that model. This is similar to the biophysical components in the current fishery model, such as 'Wave Height,' 'Wind Events that Drive Upwelling,' and 'Current Strength,' which also exhibit lower *Centrality* scores (ranging from 0.3 to 1.3). This comparison further supports the conclusion that natural or biophysical elements serve

more as boundary conditions rather than central forces within the design of these models. While critical for ecological processes, changes in these components do not propagate through the system as strongly as socio-economic drivers such as 'Commercial Kob Landings' or 'Income (Fishing).' This finding aligns with Alipour et al.'s (2019) model, which demonstrates that while environmental concerns are present, they are regarded secondary to energy and policy-driven components. In the fishery FCM, 'Ecosystem Health' holds a *Centrality* score of 2.4 (*Indegree* 1.4, *Outdegree* 1.0), indicating a moderate role in being influenced by and influencing other components.

6.2.2 Examining Base Model 2 Convergence Values Concerning Key Drivers Of Vulnerability In The Southern Cape Fishery System

In examining the base model's convergence values, this section explores the impact of key drivers on the vulnerability of the southern Cape fishery system. The analysis focuses on how various activations related to fish landings, economic pressures, policy, and climate factors shape the ability of fishers to maintain sustainable livelihoods. The results underscore the vital role of economic pressures while pointing to the influence of climate and policy interventions on the model.

i) Fish Landings Components Activation

The activation of 'Commercial kob landings' and 'Commercial alternative landings' resulted in substantial impacts on the system. Fully activating 'Commercial kob landings' impacted components as follows: the 'Ability to secure a sustainable livelihood' at 0.479 (notable boost) and 'Income (fishing)' at 0.522 (notable boost). This underscored the importance of kob landings to fishers' livelihoods. However, this came at a cost to 'Kob abundance,' which was highly negatively affected at -0.882 (substantial threat), reflecting the strong negative connection between these two components, as noted by Winker et al. (2012). This confirms the trade-off between economic gains and kob recovery. Overfishing this key species has resulted in negative consequences for the ecosystem (affected at -0.549 (challenging)) and fishers, as depleted stocks have reduced catches and income. These outcomes are consistent with findings in other ecosystems where anthropogenic pressures have disrupted ecological balances. For instance, Gray et al. (2015) showed a similar impact on ecosystem components when the 'Increased human population' was activated, causing decreases in 'Wildebeest and zebra' populations.

The model's results align with real-world observations, suggesting that modifying 'Commercial kob landings' to improve 'Kob abundance' would require a reduction in the fishing pressure of kob. This could be achieved through stricter regulations or a decrease in market demand. However, to truly mitigate the decline in kob abundance, it is also necessary to address 'Inshore trawl: IUU fishing practices,' which also negatively impacts kob stocks.

Gray et al. (2015) conducted a similar experiment by clamping population increases, which resulted in a decrease in 'Poor crop harvest' with a convergence of -0.004. Although Gray's component experienced a smaller negative convergence than our -0.882 for 'Kob abundance,' this difference may be attributed to their using the *Sigmoid Function* in Mental Modeler, which tends to dampen values (refer to Section 3.4). This finding highlights that other anthropogenic pressures can destabilise environmental components in FCM's, underlining the importance of mitigating these pressures in the real world to maintain ecological balance.

Activating 'Commercial alternative landings' showed impacts such as a positive effect on 'Income (fishing)' at 0.459 (notable boost) and the 'Ability to secure a sustainable livelihood' at 0.429 (slight boost), reflecting that alternative landings served as an essential buffer when kob stocks were low or insufficient. The difference between the two effects was only 0.030, indicating that the distinction between the 'notable' and 'slight' boosts was minor. Similarly, Halbrendt et al. (2014) created FCMs to identify key variables and relationships in agricultural systems. Halbrendt et al.'s (2014) 'minimum tillage' scenario involved simulating the introduction of minimum tillage by increasing its value in FCMs. Based on stakeholder beliefs, this approach assessed perceived changes in factors such as soil quality, soil moisture, and crop yield, indicating that adaptation strategies could enhance resilience. Notably, soil quality increased on average across the different maps of stakeholder groups. This comparison demonstrates how both 'Commercial alternative landings' and minimum tillage are strategies to buffer against resource insufficiencies while promoting resilience in their respective systems.

The moderate negative impact of 'Commercial alternative landings' on 'Commercial kob landings' at -0.434 (somewhat challenging) reflects dampening relationships between these components, where higher catches of alternative species landings reduced reliance on kob. This makes sense because alternative landings provide a crucial fallback in cases of kob stock depletion, allowing fishers to maintain some income and contribute to their livelihoods (Gammage et al., 2017b). Generally, diversification reduces dependence on a single species and helps fishers remain resilient in changing environmental conditions (Allison and Ellis, 2001).

ii) Economic Components Activation

When 'External economic pressures' were fully activated, the 'Ability to secure a sustainable livelihood' was substantially impacted at -0.815 (very challenging), and 'Income (fishing)' was affected at -0.743 (very challenging), illustrating the severe toll that external economic pressures had on fishers. Xu et al. (2023) highlight the critical role of livelihood capital assets, such as human and financial capital, in shaping resilience and alleviating poverty within fishing communities. These findings align with the observed importance of access to economic and social resources in reducing vulnerabilities in the southern Cape's small-scale fisheries, reinforcing the necessity to incorporate livelihood factors into social-ecological models. Additionally, 'Alternative employment opportunities' were negatively influenced, showing an effect of -0.604 (challenging). Notably, 'Input costs (running costs and equipment for fishing)' rose by 0.762 (very challenging), highlighting the increased financial burden on fishers during economic challenges. The 'Price of kob and other target species' also experienced a decline at -0.604 (challenging), further emphasising the compounded financial pressure on fishers under high economic pressures.

When 'Specific financial management skills' was activated, it positively affected 'Access to capital' at 0.604 (notable boost) and 'Access to craft' at 0.400 (slight boost), emphasising the importance of sound financial management in securing assets essential for fishing, as shown through the chain connection between the components, even though these are parameterised as 'low'. Continuing through commercial landings to income from fishing, the activation of 'Specific financial management skills' resulted in an improvement in 'Ability to secure a sustainable livelihood' at 0.245 (neither challenging nor favourable) despite the indirect connection. These skills help fishers navigate economic challenges. However, activating financial management skills at this level could not fully offset the broader impacts of external economic pressures. This observation is inferred based on the relative change in the 'Ability to secure a sustainable livelihood' when each component was activated separately.

iii) Policy components Activation

‘Sector-specific policy implementation’ and related governance components also played a crucial role in shaping fishers' outcomes. Activating ‘Sector-specific policy implementation’ led to improvements following the chain connection from ‘Access to rights’ at 0.604 and ‘Access to craft’ at 0.54, reflecting the role of policy in securing vital resources for fishers through model design. Through increased landings, these policy-driven enhancements could moderately positively affect ‘Income (fishing)’ at 0.512 and the ‘Ability to secure a sustainable livelihood’ at 0.472, showing how effective policy implementation could benefit fishers' livelihoods. This finding also supports Özesmi and Özesmi's (2004) findings on wetland conservation, where enforcement was crucial for ecological benefits, demonstrating that policy-driven strategies foster broader, sustainable resilience compared to financial access alone. The result is, however, lower than that of economic pressures and in a similar range as activation of kob landings.

Illegal, Unreported, and Unregulated (IUU) fishing practices were also activated and, as expected, led to severe negative effects on ‘Ecosystem health’ at -0.678 (very challenging) and increased ‘Conflict between inshore trawl and linefishery’ at 0.762 (very challenging). This reflected the destructive impact of IUU practices on marine ecosystems and the exacerbation of conflicts between competing fishing sectors. ‘Income (fishing)’ was moderately affected at -0.41 (somewhat challenging), illustrating the connection between linefishing and inshore trawl. The overall impact of IUU fishing practices on the ‘Ability to secure a sustainable livelihood’ was negative at -0.388 (somewhat challenging). Other components were also impacted, such as ‘Commercial kob landings’ at -0.519 (challenging) and ‘Price of kob and other target species (price setting by fish mongers)’ at 0.169 (neither challenging nor favourable). Impacts were also observed in ‘Inshore trawl: effect on reef (habitat degradation)’ at 0.604 (challenging) and ‘Surveillance (patrol vessels/aerial)’ at 0.604 (notable boost), highlighting complex interactions in the system. In alignment with our findings, Gray et al. (2015) observed that adding the establishment of a community wildlife management area mitigated illegal activities, achieving a decrease in poaching with a convergence of negligible -0.00066 in their model.

iv) Climate Components Activation

Activating climate-related factors such as 'Wind strength,' 'Sea surface temperature range,' and 'Wind events that drive upwelling' revealed localised influences on environmental and socio-economic components in the model. The activation of 'Wind strength' primarily impacted physical sea conditions, with notable changes in 'Current strength' and 'Wave height' (both at 0.291, somewhat challenging), while social-economic effects were minor. 'Ability to secure a sustainable livelihood' decreased slightly (-0.153, neither challenging nor favourable), however moderate declines occurred in 'Available sea days' (-0.196) and 'Commercial alternative landings' (-0.161). Ecological effects included modest increases in 'Kob abundance' (0.14) and 'Ecosystem health' (0.098). These findings align with the anticipated impact of wind strength on physical sea conditions rather than the wider fishery system. Future research could explore extreme scenarios, such as catastrophic changes in wind strength, to assess their potential to exacerbate vulnerabilities or create opportunities within the modelled fisheries.

The 'Prevailing sea surface temperature range' had a stronger impact in the model, particularly on socio-economic components. 'Commercial kob landings' (-0.536, challenging), 'Income (fishing)' (-0.48, challenging), and 'Ability to secure a sustainable livelihood' (-0.447, challenging) were substantially affected, reflecting how suboptimal temperatures reduce fish abundance and fishing success. The 'Commercial alternative landings' component was also affected, albeit less, with a value of -0.198 (neither challenging nor favourable), indicating a decline in the availability of other market fish with suboptimal temperatures. This reflects how changing temperatures are expected to reduce fish abundance and fishing success with the current resource base, negatively affecting fishers' income. Broader impacts, such as on 'Ecosystem health' (-0.206, neither challenging nor favourable), were minor due to indirect, low-strength connections. Rising sea temperatures reflect real-world challenges posed by climate change (Hobday et al., 2016), where temperature shifts can reduce the availability of target fish populations and challenge fishing success if seen in isolation (Duggan, 2012; Gammage, 2015).

Full activation of 'Wind events that drive upwelling' produced positive effects, with substantial increases in the 'Duration of fishing season' (0.604, notable boost) and smaller boosts in 'Commercial alternative landings' (0.311) and 'Income (fishing)' (0.263). However, these benefits came at the cost of reduced 'Ecosystem health' (-0.189, neither challenging nor favourable), driven by declining 'Kob abundance' (-0.274, somewhat challenging) due to heightened fishing pressure. The decrease in 'Ecosystem health' can be traced to the model dynamics where increased upwelling extended the fishing season, leading to higher fish catches. This heightened fishing pressure caused a decrease in 'Kob abundance,' which then negatively impacted 'Ecosystem health.' This outcome aligns with our understanding of this fishery and this ecosystem. The reduction in fish stock disrupts predator-prey relationships and affects overall biodiversity, leading to a decline in ecological stability (Coetzee et al., 2008). N. J. Bennett et al. (2018) highlights habitat restoration as a key stewardship action, encompassing activities such as restoring degraded habitats to improve ecological and social outcomes. Despite this, 'Ability to secure a sustainable livelihood' (0.258, slight boost) improved modestly, supported by extended fishing seasons and slight increases in 'Commercial kob landings' (0.148). These dynamics illustrate the tension between short-term economic gains and long-term resource sustainability that are reflected in the model.

The activation of 'Variability in rainfall patterns' had minimal overall impact. The most notable effect was on 'Physical navigation dangers' (0.291, somewhat challenging), reflecting potential hazards for river conditions. Impacts on socio-economic components such as 'Income (fishing)' (-0.027), 'Ability to secure a sustainable livelihood' (-0.069), and 'Commercial kob landings' (-0.014) were negligible, highlighting limited pathways connecting rainfall variability to fisheries and ecosystem functioning.

Overall, the findings demonstrate differential impacts of climate-related factors. While variables such as sea surface temperature and wind-driven upwelling significantly affect social-economic and environmental components, others exhibit localised or minor influences, such as wind strength and rainfall variability. Balancing short-term benefits with long-term sustainability remains essential in fisheries management amidst ongoing climate challenges.

6.2.3 Conclusion

This section sought to answer the research question: *Which additional insights can be generated from the FCM compared to the qualitative approach? Specifically, which key drivers discussed in Gammage and Jarre (2020) (economic, policy, climate) contribute the most to the vulnerability of the communities in the southern Cape?*

The FCM analysis offers a semi-quantitative framework that enhances understanding of these drivers by identifying their interactions, feedback loops, and relative influence on the system. Unlike qualitative approaches, the FCM allows for assessing direct and indirect relationships, enabling a nuanced understanding of how drivers amplify or mitigate vulnerabilities across ecological, economic, and governance dimensions.

Economic components are revealed as central to shaping the vulnerability of communities in the southern Cape, with 'external economic pressures' exerting particularly substantial impacts. When economic pressures are activated in the FCM, they substantially challenge fishers' livelihoods. Components such as rising input costs and falling market prices for target species reduce fishers' ability to maintain sustainable livelihoods. The model showed that economic pressures negatively influence not only income from fishing but also access to alternative employment opportunities and resources critical to the fishing communities. For example, input costs increase sharply under economic pressures, reflecting the growing financial burden on fishers, while declining prices for kob and other species reduce overall profitability. This interplay of pressures, highlighted quantitatively in the FCM, underscores the cascading effects of economic shocks, where reduced income and rising costs reinforce vulnerabilities. Moreover, the positive influence of financial management skills on components such as access to capital and craft suggests that targeted economic interventions could mitigate some of these challenges. The model emphasises that while economic pressures are immediate and severe, improving financial literacy and reducing input costs could provide crucial buffers against these vulnerabilities.

Policy components, particularly sector-specific policy implementation, are pivotal for reducing vulnerability. Activating policy-related components in the FCM demonstrates their ability to positively affect access to fishing rights, craft, and sustainable livelihood outcomes. For instance, quantifying policy impacts shows that robust sector-specific

policies can increase fishers' income and improve their ability to sustain livelihoods, albeit with a slightly lower effect compared to economic pressures. Policies also play a central role in addressing sectoral conflicts, such as those between inshore trawl and linefishery sectors. The FCM highlights how policy-driven enhancements, such as increased surveillance and enforcement of size limits, promote compliance and reduce the ecological pressures associated with overfishing. However, the model also reveals that inadequately enforced policies can exacerbate vulnerabilities ('Sector-specific policy implementation'), particularly if they fail to account for the interconnected nature of socio-economic and ecological components. The ability of well-implemented policies to strengthen surveillance, mitigate IUU fishing, and improve resource allocation highlights their critical importance.

While less influential, climate components still pose substantial localised and indirect risks to the system. The activation of climate-related drivers in the FCM, such as wind events driving upwelling and sea surface temperature range, reveals both short-term benefits and long-term challenges. Upwelling events, for example, boost fishing income and extend the fishing season due to nutrient-rich waters, providing a short-term economic advantage. However, extended favourable fishing conditions (due to upwelling) can strain ecosystem health by increasing fishing pressure on vulnerable stocks such as kob. Rising sea surface temperatures, as a ramification of the warming Agulhas current, are particularly concerning, as they likely reduce kob abundance and landings, thereby negatively affecting fishers' income and livelihoods. The FCM demonstrates these impacts, showing that sea temperature changes affect the system, exacerbating vulnerabilities in socio-economic components. While policy and economic factors often have more immediate and controllable impacts on socio-economic outcomes, climate components' indirect and compounding effects can amplify these challenges, especially in the long term. This underscores the importance of integrating climate considerations into policy design to mitigate systemic risks, for example through periodic revisions. The findings emphasise the need for adaptive management strategies to address these climate-related challenges.

The FCM provides a distinct advantage by quantifying relationships that qualitative methods cannot fully reveal. Economic pressures, such as those driven by kob

abundance and input costs, are identified as the most immediate and impactful drivers of vulnerability. However, their interplay with ecological health reveals the system's complexity, where economic benefits are closely tied to ecological stability. Policy interventions stand out as critical leverage points for mitigating vulnerabilities, with their ability to influence key outcomes such as resource access, regulatory compliance, and conflict resolution. While less influential, climate factors pose substantial localised risks that require long-term adaptive management. Overall, the findings emphasise the need for an integrated strategy that prioritises economic resilience of the linefishery, supports effective policy implementation and incorporates adaptive management to balance economic gains with ecological sustainability, securing fishers' livelihoods in the long term.

6.3 Analysis Of Scenario Outcomes And Their Impact On The Southern Cape Fishery System

This section explores how FCM can be applied to the scenario stories Gammage et al. (2021) developed to offer further insights into the southern Cape linefishery system. The flexibility of the FCM modelling approach allows for integrating various components, economic, policy, and environmental factors, into a cohesive model that mirrors the real-world interactions described in the scenarios. This section delves into each scenario, drawing on the FCM outputs to deepen our understanding of the interplay between various external pressures on fishers' livelihoods. The integration of Social-Ecological Network (SEN) approaches, as outlined by Sayles et al. (2019), provides a valuable lens for examining how network structures influence social-ecological outcomes. This aligns with the scenario-based modelling outcomes presented here, where social and ecological interactions play pivotal roles in determining system resilience and adaptive capacity.

6.3.1 Scenario Story Insights

i. Scenario 1 - "Nothing Much Has Changed"

The "Nothing Much Has Changed" scenario represented a state of overall stagnation and worsening conditions within the fishery system. To model this scenario, several components were clamped at moderate to highly unfavourable values according to the scenarios described by Gammage and Jarre (2021) (see Section 2.1.3 for further details). Key changes included activating the lack of access to capital (-0.7) and the absence of sector-specific policy implementation (-1), which illustrated a system increasingly constrained by economic and regulatory pressures. The scenario emphasised high external economic pressures (0.7), limited alternative employment opportunities (-0.7), and a decline in commercial alternative landings (-0.7), primarily consisting of low-value species. Additionally, the reduced abundance of kob (-0.7), a critical species within the fishery, further compounded these economic challenges.

After activation, the convergence values revealed that a decline in one area, such as policy implementation (-1), triggered a cascade of negative effects on livelihoods and

ecosystem health in the model. Unlike the CLD, which shows relationships, the FCM quantified these direct and indirect impacts, revealing the effects across the system that contribute to economic and environmental challenges across the system. The absence of sector-specific policy implementation (-1) directly influenced access to rights at -0.604 (challenging) and heightened conflict between inshore trawl and linefishery at 0.901 (substantial threat). This conflict, already shown to be exacerbated by increased IUU fishing at 0.475 (challenging), had a cascading effect, reducing the ability of fishers to secure sustainable livelihoods at -0.885 (substantial threat).

The increase in inshore trawl IUU (Illegal, Unreported, and Unregulated) fishery practices at 0.475 (challenging) highlighted the response of inshore trawl fishers to conflict between inshore trawl and linefishery at 0.901 (substantial threat) and decreased surveillance at -0.351 (somewhat challenging). This highlighted how increased illegal activities intensified resource competition and strained regulatory enforcement capabilities. This heightened conflict reduced the ability of fishers to secure a sustainable livelihood at substantial threat, exacerbating their financial instability.

The worsening habitat degradation due to increased inshore trawling at 0.321 (somewhat challenging) and the overall decline in ecosystem health at -0.614 (challenging) underscored the environmental toll of this scenario. This decline in ecosystem health was a driver of reduced income for fishers, as the diminishing health of the habitat directly affected fish stocks and their sustainability. As documented by Atkinson et al. (2011) and Currie et al. (2020), these activities' impacts on demersal and reef habitats were evident in the FCM's results, where environmental degradation propagated through connected variables.

As a result of these negative changes, the system experienced deteriorating conditions. The decline in income from fishing at -0.946 (substantial threat) and other income sources at -0.454 (challenging) further limited fishers' ability to sustain their livelihoods. These declines were driven by external economic pressures (0.7), which impacted input costs at 0.604 (challenging). The variability in rainfall patterns introduced potential safety hazards for river conditions but had negligible effects on key system components. Its impact on 'Income (fishing)' (-0.027), 'Ability to secure a sustainable livelihood' (-0.069), 'Commercial alternative landings' (-0.032), and 'Commercial kob landings' (-0.014) was

minimal, reflecting the lack of substantial pathways in the FCM. Similarly, 'Ecosystem health' and 'Kob abundance' experienced negligible changes, emphasising limited connections between rainfall variability and commercial fisheries or food security.

Indirect effects play a critical role in understanding the system's vulnerabilities. For instance, external economic pressures (0.7) indirectly affected income through increased input costs at 0.604 (challenging). The influence of sector-specific policy implementation (-1) on components such as surveillance at -0.351 (somewhat challenging) and conflict at 0.901 (substantial threat) revealed the multifaceted pathways through which regulatory changes impact system stability.

By recognising and addressing these direct and indirect connections, with their relative importance established through the (semi-) quantification in this FCM, policymakers and stakeholders can better design targeted interventions that address immediate issues and consider the cascading effects that shape the long-term sustainability of the fishery system.

ii) Scenario 2 - "We Will Get There, Eventually"

The "We Will Get There, Eventually" scenario presented a mixed picture, marked by slight improvements alongside persistent challenges. Key modifications included maintaining constrained access to capital (-0.7) while activating initial progress in sector-specific policy implementation (0.7), signalling potential improvements in governance. The scenario highlighted minor improvements in alternative employment opportunities (-0.3), suggesting that fishers might begin to access additional sources of income despite continuing economic difficulties. The sustained depression of commercial alternative landings (-0.7), especially low-value species, indicated that economic recovery within the fishery remained fragile. A slight easing of external economic pressures (0.3) relieved fishers, although kob abundance (-0.7) remained low, maintaining economic uncertainty.

The slight improvements in alternative employment opportunities and policy implementation had not yet translated into tangible benefits for most fishers, especially those with limited access to capital (-0.7). The FCM helped identify where small policy

changes supported income diversification and reduced conflicts over resource use. The decrease in conflict between the inshore trawl and the linefishery at -0.791 (very challenging), down from 0.901 in Scenario 1, suggested that policy improvements started to address resource allocation issues. Smythe (2024) similarly found that increased policy implementation in southern New England's offshore wind and fisheries sectors could reduce conflicts by establishing clear communication, coordination, and decision-making frameworks. Several approaches were found to help mitigate tensions, such as creating neutral bridging organisations that allowed for better communication and trust-building among stakeholders. An enhanced role for government agencies was also identified to ensure fair representation and conflict resolution (Smythe, 2024).

The slight increase in the price of kob and other target species at 0.209 (neither challenging nor favourable), up from -0.022 in Scenario 1, provided some economic relief due to decreased economic pressures, though it was not enough to drive substantial improvements in fishers' overall income. Income (fishing) at -0.850 (substantial threat) remained low, showing that limited access to capital continued to be a substantial barrier to fishers' ability to secure a sustainable livelihood at -0.784 (very challenging). Similarly, Xu et al. (2023) found that low access to capital reduced fishers' ability to secure sustainable livelihoods in Pakistan by limiting their income potential and making them vulnerable to economic and social variables. Their study suggested that improving access to financial, human, social, and natural capital through infrastructure and facilities could alleviate poverty and improve income (Xu et al., 2023).

Habitat degradation due to inshore trawling improved slightly from 0.321 to -0.256 (slight boost) which, combined with slight gains in ecosystem health at -0.301 (slight boost), up from -0.614, suggested that the environmental impacts of fishing were being mitigated.

Increased access to rights at 0.454 (notable boost), up from -0.604 in Scenario 1, due to enhanced policy implementation aligned with the findings of Hiriart-Bertrand et al. (2020). Their results indicated that implementing the 'Marine and Coastal Areas for Indigenous Peoples' policy in Chile increased access to fishing rights for Indigenous communities by assigning them management rights over marine areas. However, this policy also led to conflicts with non-indigenous fishers who feared limitations on their existing rights.

Increased but weak input costs at 0.291 (somewhat challenging), down from 0.604 in Scenario 1, pointed to a fishery system beginning to find its footing, although recovery was still a long way off due to the continued low levels of commercial kob landings at -0.707 (very challenging). Although other species were targeted when kob was unavailable, these alternatives were either low value (e.g., silvers, sharks) or low in abundance (e.g., redfish). The model indicated that fishers' income was also impacted when these alternative species were scarce. This highlighted the ongoing challenges in restoring the fishery to a more productive state. Similarly, Delgado-Ramírez et al. (2022) illustrated fishing as a vital economic activity, particularly for communities reliant on artisanal fishing. They distinguished between fishing as a way of life, livelihood, and job, underscoring that for many, fishing was not just about income but deeply intertwined with identity and community dynamics (Delgado-Ramírez et al., 2022).

Implementing Scenario 2 into a semi-quantitative FCM provided clear insights into where policy interventions could have the most impact. By revealing how external pressures and small gains in ecosystem health were interconnected, the FCM suggested leverage points for further reducing vulnerabilities and enhancing fishers' livelihoods. Key leverage points included sector-specific policy implementation, which improved access to fishing rights and enhanced surveillance efforts, thereby reducing IUU fishing and supporting sustainable resource use. Additionally, enhancing access to capital emerged as a critical intervention, as it could reduce constraints on acquiring essential fishing equipment, directly benefiting fishers' productivity and income. Improvements in alternative employment opportunities and efforts to reduce external economic pressures (e.g., high input costs and market volatility) were also shown to buffer fishers against economic shocks, diversifying income sources and increasing resilience. The contrasts between Scenarios 1 and 2 further highlighted the potential benefits of these targeted measures and the importance of strengthening access to financial and regulatory resources to foster a more resilient and sustainable fishery system.

iii) Scenario 3 - "The Going is Good" (Cold Productive)"

The "The Going Is Good (Cold Productive)" scenario illustrated improvements across several key components, suggesting a transition towards a more favourable economic

and environmental context. Here, policy implementation at -0.7 poses moderate barriers, while increased access to capital (0.7) enhances resilience. Multiple components were adjusted to reflect more positive states as outlined in the scenarios by Gammage and Jarre (2021) (see Section 2.1.3 for further details). A key change included increasing access to capital (0.7), indicating that fishers were better equipped to invest in their operations. Although sector-specific policy implementation (-0.7) showed a moderate decline, hinting at potential governance challenges that still needed attention, overall progress was evident. A substantial increase in alternative employment opportunities (1) emerged as a pivotal factor, enabling fishers to diversify their income and reduce dependency on the fishery alone. The scenario also featured a slight improvement in commercial alternative landings (0.3), particularly low-value species such as hake, and a reduction in external economic pressures (-0.3), contributing to economic recovery. However, the continued low abundance of kob (-0.7) remained a notable concern, indicating that not all fishery components were improving simultaneously.

The increase in illegal, unreported, and unregulated (IUU) practices at 0.375 (somewhat challenging), up from -0.375 in Scenario 2, indicated decreased regulation and compliance, suggesting a shift towards less sustainable practices in the fishery. This escalation in IUU practices and decreased policy implementation led to increased conflict between inshore trawl and linefisheries at 0.792 (very challenging), up from -0.791, reflecting worsening resource allocation and intensifying conflicts among fishing sectors. Habitat degradation due to inshore trawling increased at 0.257 (somewhat challenging), up from -0.256, underscoring persistent environmental challenges caused by increased IUU activities. Similarly, Attwood et al. (2011) and Currie (2017) found that trawling near coastal areas degraded crucial reef habitats and contributed to IUU fishing, exacerbating economic hardships for linefishers reliant on kob (Duggan, 2018) and causing environmental damage (Atkinson et al., 2011).

Access to craft at 0.036 (neither challenging nor favourable), up from -0.036 in Scenario 2, and access to rights at -0.454 (challenging), down from 0.454, showed notable changes, with access to craft improving due to increased access to capital (0.7), while reduced policy implementation contributed to decreased access to rights. Gammage et

al. (2017b) highlighted that fishers in the southern Cape with low financial resources and limited access to stable alternative income struggled to adapt to changes, even when willing to do so.

The decrease in input costs at -0.291 (slight boost), down from 0.291 in Scenario 2, eased the financial burden on fishers. The rise in income from fishing at 0.116 (neither challenging nor favourable, up from -0.85, and income from other sources at 0.604 (notable boost), up from -0.207, due to increased access to capital and alternative employment opportunities (1) supported their economic stability, fostering a more resilient community. Kapembwa et al. (2021) and Sowman and Raemaekers (2018) similarly found that alternative livelihood strategies contributed to income stability among fishers in South Africa, suggesting that small-scale fishers should diversify their income sources beyond fishing, as fishing income alone is often insufficient due to low catches and external shocks. Gammage et al. (2017b) also noted that fishers with alternative income sources such as pensions, rental income, and secondary jobs maintained financial stability when fishing income was insufficient. Fishers with prior experience in skilled trades, such as boat repair, farming, or running charters, could generate a more stable income than less-skilled work, helping them endure financial challenges without needing long-term adjustments. Sowman and Rebelo (2019) conducted a study with small-scale fishers in South Africa, identifying several adaptation strategies to address threats, including those associated with climate change. Among these strategies, they emphasised the necessity of financial training to enhance their capacity to respond effectively to these challenges (Sowman, 2020).

The increase in the price of kob and other target species at 0.257 (slight boost), up from 0.209 in Scenario 2, driven by reduced external economic pressures (-0.3), further bolstered economic stability. Kob, as the staple of the handline fishery in the southern Cape (Duggan et al., 2014; Duggan, 2018), remained crucial, and decreased catches implied lower income, with long-term negative impacts on livelihoods, especially for handline crews facing poverty.

The FCM demonstrated that while positive trends were emerging, the full recovery of fishers' livelihoods depended on addressing the persistent issue of kob abundance (-0.7). Even in this "cold productive" scenario, kob stocks had not recovered, resulting in

low landings, mainly of lower-value species. Policy and management strategies focusing on kob abundance were deemed essential for sustaining the gains in this scenario. The analysis revealed that improvements in access to capital (0.7) and employment opportunities (1) helped buffer some challenges, but long-term resilience required continuous attention to kob abundance and environmental management. The scenario underscored that while economic growth and increased income sources were promising, maintaining effective policies and managing ecological impacts were pivotal for a balanced and sustainable fishery system.

iv) Scenario 4 - "The Future is Bright" (Warm Productive)"

The "The Future Is Bright (Warm Productive)" scenario represented the most favourable outcome for the fishery system, highlighting positive changes across all key components. Key changes included the full restoration of access to capital (1) and the optimal implementation of sector-specific policy implementation (1), establishing a solid foundation for sustainable growth. The scenario highlighted many alternative employment opportunities (1), enhancing economic resilience by reducing fishers' reliance on the fishery and supporting income diversification. A substantial increase in commercial alternative landings (0.7), including valuable species such as geelbek, and the lowest levels of external economic pressures (-1) contributed to economic stability and growth. The recovery of kob abundance (0.7) was particularly noteworthy, signalling the resurgence of a critical species in the fishery and supporting ecological and economic health.

These positive changes resulted in a highly favourable system-wide outcome. The substantial improvement in kob abundance (0.7) led to an increase in commercial kob landings at 0.876 (substantial positive change). Driven by the distribution shift of subtropical fish communities from the east coast onto the central Agulhas Bank, this alleviated much of the pressure seen in other scenarios, allowing fishers to secure a sustainable livelihood at 0.917 (substantial positive change), up from 0.617 in Scenario 3. Coetzee et al. (2008) discuss a substantial shift in the distribution of South African sardine (*Sardinops sagax*) from the West Coast to the South Coast. While kob distribution shifts provided positive outcomes in this study, the eastward movement of

sardine created a spatial mismatch between fishing efforts and fish abundance, as the bulk of the sardine population relocated farther from established processing facilities on the West Coast. This mismatch led to increased fishing efforts on the South Coast to align with the sardine's new distribution (Coetzee et al., 2008).

The substantial improvement in the ability to secure a sustainable livelihood at 0.917 and optimal income levels from both fishing at 0.968 (substantial positive change) and other sources at 0.604 (notable boost), coupled with the lowest input costs at -0.762 (meaningful improvement), supported the economic viability of the fishery. Saksono et al. (2023) found that increased external pressures, such as rising fuel prices, raised input costs for small-scale fishers in Indonesia. Therefore, it was inferred that a decrease in 'External economic pressure' would result in lower input costs, as evidenced by this scenario's outputs. The stable price of kob and other target species at 0.223 (neither challenging nor favourable) due to decreased economic pressures (-1) further reinforced economic stability.

The decrease in IUU (Illegal, Unreported, and Unregulated) practices at -0.475 (notable boost), down from 0.375 in Scenario 3, reinforced the positive governance and regulatory environment, contributing to the overall sustainability of the fishery. Meanwhile, minimising habitat degradation at -0.321 (slight boost), down from 0.257 in Scenario 3, due to reduced inshore trawling led to substantial improvements in ecosystem health at 0.614 (notable boost), up from -0.585. Enhanced surveillance at 0.351 (slight boost) curbed inshore trawling IUU practices, reinforcing the fishery's positive governance and regulatory measures. Hiriart-Bertrand et al. (2020) similarly found that enhanced policy execution under Chile's Marine and Coastal Areas for Indigenous Peoples (MCAIP) reduced conflict by promoting dialogue and cooperation between Indigenous and non-Indigenous fishers. Clear management plans, inclusive participation platforms, and a better understanding of rights and responsibilities fostered collaboration and prevented misunderstandings (Hiriart-Bertrand et al., 2020).

The effective policy implementation also decreased conflict between inshore trawl and linefisheries at -0.901 (substantial positive change), down from 0.792 in Scenario 3, demonstrating an environment where different fishing sectors could coexist with minimal competition. The increased access to craft at 0.863 (substantial positive

change), up from 0.036 in Scenario 3, and access to rights at 0.604 (notable boost), up from -0.454 in Scenario 3, reflected a system that enabled better participation and equity among fishers. Consistent with Parreño and Pablo-Martí (2024) findings on improved municipal development under competitive sector growth, access to rights at 0.604 (notable boost) here promotes equity and environmental sustainability, reinforcing that strong governance positively impacts system health.

This scenario suggests that integrating comprehensive policy measures, financial access, and alternative employment opportunities creates a resilient and sustainable fishery system. The positive governance environment, reflected in sector-specific policy implementation and surveillance, emphasised that robust regulatory frameworks are key to fostering a sustainable and cooperative system. The findings of this study align with Bennett, N J et al. (2018)'s emphasis on identifying leverage points to enable effective local stewardship. For instance, the activation of Sector-Specific Policy Implementation in Scenario 4 mirrors their observation that targeted governance interventions can significantly enhance community adaptive capacity.

v) Scenario 5 – “Activating ‘Access to capital’ and ‘Sector-specific policy implementation separately”

In Scenario 5, which compared the impacts of sector-specific policy implementation and access to capital, notable contrasts were observed, highlighting the differing influence of these components on the fishery system. The results suggested that while both factors are crucial for sustainable livelihoods, effective sector-specific policy implementation had a broader positive effect on the system than access to capital alone.

The ability to secure a sustainable livelihood showed substantial gains with both activations, reaching 0.472 (notable boost) for policy implementation activation and 0.352 (slight boost) for access to capital activation. This indicated that policy measures directly influenced various elements within the fishery system, creating a more supportive environment for fishers. In addition, policy implementation had a more extensive effect on interconnected components, including access to rights at 0.604 (notable boost) and commercial kob landings at 0.423 (slight boost), essential for long-

term sustainability. Access to capital (1), on the other hand, primarily impacted the direct financial capability of fishers, improving access to craft at 0.604 (notable boost) and indirectly supporting income (fishing) at 0.368 (slight boost).

Ecosystem health experienced a positive change with sector-specific policy implementation at 0.296 (slight boost) but showed a negative impact with access to capital alone at -0.261 (somewhat challenging). This suggests that policy measures that integrate environmental management practices are essential for maintaining ecosystem stability, as unrestricted capital access without regulatory measures could lead to overexploitation and degradation. Policy implementation positively influenced kob abundance at 0.116 (neither challenging nor favourable) but saw a decline with access to capital alone at -0.382 (somewhat challenging). This underscores the importance of regulatory measures that protect critical species and ensure sustainable management. There was an increase in income (fishing) at 0.512 (notable boost) with policy implementation activation and 0.368 (slight boost) with access to capital activation. As well as improvements in commercial alternative landings at 0.464 (notable boost) with policy implementation activation and 0.43 (slight boost) with access to capital (keeping in mind that the difference was only 0.034, refer to Section 3.3 for category definitions). This highlighted how both strategies contributed to economic viability. However, the results indicated that policy-driven approaches were more effective in maintaining sustainable practices and broader system health.

The conflict between inshore trawl and linefisheries was substantially reduced with policy implementation at -0.901 (substantial positive change), reflecting that clear and enforceable policy measures can minimise competition and resource-related disputes. In contrast, access to capital did not impact this component, demonstrating that financial access alone is insufficient to address deep-rooted competitive dynamics within the fishery.

The decrease in IUU practices at -0.475 (notable boost) and improved surveillance at 0.352 (slight boost) under policy implementation highlighted the governance benefits, contributing to better compliance and sustainable practices.

In conclusion, the results indicated that while both sector-specific policy implementation and access to capital were important for supporting the fishery, policy implementation had a more widespread impact on creating a sustainable system. Integrating policies that promote equitable access to resources, environmental protection, and economic stability is vital for fostering resilience in fishery-dependent communities (Adger et al., 2005; Aswani et al., 2019; Hobday et al., 2016). The model outputs suggest that prioritising policy measures that address economic and ecological challenges holistically results in a more balanced and sustainable fishery system. This reinforces the importance of a policy-first approach when prioritising resource allocation.

6.3.2 Reflections And Conclusion

This section sought to answer the research question: *How can the semi-quantitative FCM be utilised to match the scenario stories in Gammage et al. (2021) and to analyse them further?*

Reflecting on integrating scenario stories into the model world emphasises this approach's strengths and complexities. Adjustments to activation clamping were essential for generating clearer insights into the dynamic interactions within the fishery system, enriching narratives with quantifiable details. Scenario 1, "Nothing Much Has Changed," exemplifies how moderate to highly unfavourable conditions, such as limited access to capital (-0.7) and inadequate policy implementation (-1), can trigger cascading negative effects. This scenario illustrates how insufficient policy action and economic strain exacerbate financial instability and conflict, reinforcing systemic fragility. The contrast between the qualitative depiction in causal loop diagrams (CLDs) and the quantifiable impacts in the FCMs developed in this study underscores the added value of FCM for exploring systemic outcomes.

Scenarios 2 through 5 presented a range of outcomes influenced by activating key components, including policy effectiveness and financial access. These insights validated that while financial resources bolstered system resilience, comprehensive policy measures were critical for overall health and sustainability. The model demonstrated the effects of enhanced governance, such as reduced illegal, unreported, and unregulated (IUU) fishing and improved access to rights, pinpointing essential leverage points for targeted interventions.

The model results also diverged from the original narratives designed by Gammage and Jarre (2021), uncovering unexpected challenges. For instance, In Scenario 2, "We Will Get There, Eventually," gradual improvement was anticipated, but the model suggested a less optimistic trajectory. The negative scores for sustainable livelihood (-0.784) and income rise (-0.85) indicated slow progress, implying that incremental policy adjustments fell short of overcoming entrenched systemic obstacles. Although the narrative proposed supplementary income from alternative activities, the model reflected ongoing economic hardships, signalling the need for more comprehensive

policy interventions. This is because the FCM only deals with the fishery system and does not explicitly model alternative activities outside fishing, such as carpentry or painting.

For Scenario 3, “The Going is Good,” the narrative depicted stable growth; however, the model highlighted persistent issues, such as habitat degradation (0.257) and rising IUU practices (0.375), indicating unresolved regulatory and environmental challenges. This suggested that economic growth alone could not mitigate all risks without adaptive regulatory efforts.

In conclusion, the scenario analysis using FCM highlighted the intricate interplay between economic, policy, and environmental factors in shaping the resilience of the southern Cape fishery system. By semi-quantitatively modelling the scenarios developed by Gammage et al. (2021), it was evident that policy implementation and access to capital were pivotal in influencing fishers’ livelihoods and system sustainability. The outputs underscored that while financial access provided immediate economic relief and bolstered individual resilience, sector-specific policy implementation contributed more broadly to sustainable practices and enhanced governance structures. This distinction revealed that policy-driven measures were essential for ecological health, conflict reduction, and fostering long-term resilience. Pittman and Armitage (2016) underscore the importance of creating governance systems that align with the functional dynamics of ecosystems, which is particularly relevant for addressing the vulnerability of fishing communities in the southern Cape.

Additionally, the scenario analysis highlighted that positive economic trends alone are insufficient without strong policy frameworks to support the fishers’ ability to put food on the table. Thus, targeted and comprehensive policy strategies and improved access to financial resources are necessary for building a sustainable and resilient fishery system.

6.4 Limitations And Future Research

Fuzzy Cognitive Mapping (FCM) was a useful tool for representing the fishery system, offering a snapshot of system interactions and emphasising the complex interdependencies within the system. However, this study identified several limitations involving data quality scores, the inability to capture temporal dynamics, and the semi-quantitative nature of the model, each of which is discussed in detail below.

One substantial limitation of FCM is its inability to capture temporal dynamics. While FCM effectively highlighted the relationships and interactions within the fishery system, it provides only a static representation. This limitation is particularly relevant in the context of dynamic stressors, such as climate change, where understanding the timing and evolution of system changes is critical. Addressing this limitation requires the integration of temporal dynamics into the model, such as through hybrid approaches combining FCM with dynamic ecosystem models such as Atlantis³ or Ecopath with Ecosim⁴. These extensions would provide a more robust framework for understanding how systems respond to changes over time.

Another limitation stems from the data quality scores assigned to the relationships within the FCM, which reflect the confidence level in the supporting evidence (Appendix B2). Scores ranged from 1 (very low confidence) to 4 (specific data support). In this study, most relationships (56%) were associated with high data quality scores of 4, reflecting reliable and well-documented evidence. However, 44% of the relationships were assigned lower scores of 3 and 2, indicating weaker evidence or reliance on indirect inferences rather than direct observations. Although the overall high average data quality score supports the reliability of the modelled relationships, the lower scores highlight areas requiring additional empirical research. It is recommended that a sensitivity analysis considering these data quality scores be conducted in future studies, as this was beyond the scope of the present work.

The FCM was designed based on a map co-developed with fishers, ensuring that the model aligned closely with their perspectives of the system. While this approach strengthens the model's relevance for small-scale fishers, it may not fully capture the

³ <https://research.csiro.au/atlantis/>

⁴ <https://ecopath.org/>

views of other stakeholders. However, this alignment was intentional and should not be considered a limitation, as the model was specifically designed to represent the system as understood by those most directly involved in it. The absence of substantial discrepancies between the model and existing knowledge reinforces the reliability of fishers' expertise and enhances the model's credibility for informing fisheries management and policymaking.

The semi-quantitative nature of FCM presents another limitation. By integrating diverse sources of knowledge and testing methodological choices, the FCM extended the conceptual understanding of the southern Cape fishery system. However, the semi-quantitative nature of the model means its outputs must be interpreted categorically rather than as precise numerical predictions. While this does not diminish the model's utility for exploring scenarios and informing management decisions, it is important when applying the results to practical decision-making contexts.

Future research could address these limitations by engaging further with communities that co-developed the original Causal Loop Diagram (CLD) presented in Gammage and Jarre (2020). For example, the scenarios co-developed with fishers from Melkhoutfontein could serve as a foundation for further exploration. Scenarios could be tested in which low kob abundance is combined with substantial financial resources or full access to rights. Conversely, scenarios where rights and financial resources are abundant but kob abundance is limited could be examined to assess whether such conditions might improve livelihood security despite resource scarcity. Insights from Gammage (2015), Gammage et al. (2017), and Gammage and Jarre (2020) suggest that fishers often avoid addressing resource scarcity, potentially because of concerns about revealing the inadequacy of other improvements under conditions of limited resources. Exploring such scenarios could provide valuable insights to address these challenges.

The applicability and relevance of FCM in supporting the sustainability of coastal communities from the southern Cape can be enhanced through these research directions. Refining the model to represent changes in ecosystems and communities will ensure its continued utility as a tool for fisheries management and policy-making.

6.5 Conclusions

This study applied Fuzzy Cognitive Modelling (FCM) to the small-scale linefishery system in the southern Cape, enhancing the conceptual model developed by Gammage and Jarre (2020). A semi-quantitative FCM approach explored effective methodologies for constructing and applying FCM to this complex social-ecological system whilst integrating diverse knowledge sources to expand the model. Additionally, the study aimed to identify key vulnerability drivers within the context of economic, policy, and climate-related factors affecting southern Cape fishing communities.

The FCM model effectively captured direct fishery-related elements and provided a robust framework for exploring complex social-ecological interactions. The dynamic interplay among local economies, educational opportunities, and community infrastructure shaped the social foundation that sustains fishers and their families.

Research Question 1a: The study demonstrates that robust methods for applying FCM, such as iterative calibration and sensitivity testing of key components (e.g., squashing functions and inference rules), are critical for achieving model accuracy and robustness. The proof-of-concept (POC) model provided a strong foundation for parameterising and calibrating the model. Through this process, adjustments were made to improve model reliability, aligning it closely with real-world observations. Key methodological decisions included selecting the *Hyperbolic Tangent Function*, *Kosko Inference Rule*, and a *Lambda Parameter* of 1, all of which produced stable and accurate outcomes as confirmed through sensitivity and assumption testing. The study demonstrated that using fewer, well-calibrated quantification categories (three in this case) effectively captured the essential dynamics of the fishery system, achieving a balance between simplicity and accuracy. Expanding the activation range to -1 to 1 enhanced the flexibility and realism of the scenarios, underscoring the importance of tailored methodological approaches.

Research Question 1b: Integrating diverse bodies of knowledge required careful attention to modelling practices and recalibration to reflect ecological dynamics and socio-economic realities. The findings highlighted discrepancies between model outputs and expert knowledge, underscoring the importance of iterative validation processes. Model accuracy was improved by combining empirical data, stakeholder

perspectives, and established literature, ensuring the FCM was scientifically rigorous and contextually relevant. For instance, recalibrating the relationship between sea surface temperature and kob abundance improved alignment with ecological data. Similarly, incorporating stakeholder insights on policy and socio-economic barriers ensured that the model reflected the lived realities of fishing communities.

Research Question 1c: The FCM analysis provided quantifiable insights that complemented the qualitative findings of Gammage and Jarre (2020), offering a deeper understanding of vulnerabilities within the southern Cape fishery system. The FCM quantified the impact of economic, policy and climate influences using metrics such as *Centrality* and *Indegree* scores. It identified "Commercial kob landings" as a critical economic factor with extensive influence. By juxtaposing the immediate impacts of economic and policy drivers with the indirect effects of climate variables, the FCM highlighted the importance of adaptive management that addresses interconnected vulnerabilities. Economic drivers, such as rising input costs and income variability, emerged as the most substantial contributors to vulnerability, emphasising the need for targeted interventions to enhance financial stability. Policy drivers ranked second, demonstrating both the benefits of effective implementation and the risks of poorly enforced measures. Although climate drivers ranked third, their cascading impacts through economic and policy pathways highlighted the necessity of integrated adaptation strategies.

Research Question 2: By semi-quantitatively modelling the scenario stories from Gammage et al. (2021), the FCM revealed nuanced dynamics within the fishery system. In alignment with scenario narratives, the semi-quantitative FCM proved a valuable tool for delving into the underlying dynamics of the fishery system. Through analysing direct and indirect linkages, the model fostered a deeper understanding of which elements could be targeted for meaningful, strategic change. It validated the systemic importance of financial access and policy effectiveness whilst exposing unforeseen challenges, such as the persistence of regulatory and environmental risks. The analysis demonstrated that financial resources alone cannot mitigate systemic vulnerabilities; comprehensive policy frameworks are essential for ecological and social resilience. Scenarios such as "Nothing Much Has Changed" and "The Going is Good (Cold

productive)” highlighted the interplay between economic trends, policy implementation, and environmental factors, illustrating the FCM's ability to enrich narrative scenarios with quantitative insights.

This study underscores the value of FCM as a methodological tool to explore the vulnerabilities of complex social-ecological systems. By integrating both qualitative and quantitative insights, FCM reveals critical linkages and stressors that underpin the susceptibility of South Africa’s small-scale linefishery to social, economic, and environmental challenges. It also refines FCM approaches to better capture and contextualise the diverse knowledge systems that influence vulnerability, emphasising the importance of nuanced perspectives in identifying and addressing root causes. By highlighting the unique vulnerabilities of small-scale fishing communities, the study demonstrates how system approaches such as FCM enhance our understanding of the dynamic interplay between external pressures and internal system responses. While the findings can inform adaptive management strategies, the primary contribution lies in offering critical insights into the vulnerabilities of the fishers, shaping the resilience and sustainability of these communities in the face of mounting challenges.

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8. Appendix

Appendix A

1 Prototype Quantifications

Table 25: Overview of all 8 relationships within the prototype FCM.

	+/-	Reason	Relationship	Data Quality (1-4)
'Risk of injury' -> 'Fish catches'	-	An increase in the 'Risk of Injury' leads to a decrease in 'Fish catches' (negative relationship). Supporting Evidence: Crew and skippers in Melkhoutfontein typically lack health insurance, as only a limited clinic is available in the area. Additionally, these fishers often lack the financial means to cover medical expenses privately (Gammage et al. 2019). Consequently, in the event of an injury, their access to medical care is severely restricted, impacting their ability to continue fishing. According to Gammage et al. (2019), 46% of respondents expressed concerns about being unable to provide for their families if they were unable to fish. It is important to note that the fishing season and the corresponding income from the targeted species play a major role in determining the extent of these challenges.	0.7	3
'Risk of injury' -> 'Income'	-	An increase in 'Risk of Injury' leads to a decrease in 'Income' (negative relationship). Supporting Evidence: Fishing is the primary income source for the individuals involved in this study. In the event of an injury, these fishers face substantial obstacles in seeking alternative employment, primarily due to their limited expertise in other fields. Specifically, 49% of participants possess gardening skills, while 17% are skilled in welding (Gammage et al. 2017a). Unfortunately, their injuries may impede their ability to perform these tasks effectively. Moreover, Gammage et al. (2019) revealed that 46% of respondents expressed concerns about their inability to provide for their families if they were unable to fish. It is also essential to consider the seasonality of fishing, as the fishers' income tends to peak during the fishing season for the targeted species.	0.7	3
'Risk of injury' -> 'Ability to secure a sustainable livelihood'	-	An increase in 'Risk of Injury' leads to a decrease in 'Ability to secure a sustainable livelihood' (negative relationship). Supporting Evidence: Fishing serves as the primary source of income for the participants in this study. In the unfortunate event of an injury, these fishers face major challenges in seeking alternative employment, as their secondary skills are gardening (49%) and welding (17%), both of which could be hindered if they were injured (Gammage et al. 2017). Furthermore, according to Gammage et al. (2019), 46% of respondents believed that providing for their families would be		3

		impossible if they could not fish. It is essential to consider the seasonality of fishing, as the fishers' income tends to be higher during the targeted species' fishing season.		
'Unsafe operating conditions' -> 'Risk of injury'	+	An increase in 'Unsafe operating conditions' leads to an increase in 'Risk of injury' (positive relationship). Supporting Evidence: To mitigate the risk of injuries, skippers in the fishing industry prioritise safety by refraining from venturing out when conditions become hazardous. However, if fishers do find themselves in unsafe operating conditions, various injuries can occur, such as hypothermia, frostbite, non-freezing cold injuries, trench foot, immersion foot, and heat stress (International Labour Organization 2007). Additionally, there are other risks to consider, such as the potential for fishing vessels to be wrecked or capsized, the occurrence of fires and explosions on board, and the dangers of being washed overboard or experiencing slips, trips, and falls due to the vessel's motion or slippery surfaces (International Labour Organization 2007).	0.3	4
'Deterioration in sea state' -> 'Unsafe operating conditions'	+	An increase in 'Deterioration in sea state' leads to an increase in 'Unsafe operating conditions' (positive relationship). Supporting evidence: 'Deterioration in sea state' refers to the worsening conditions caused by increased wind, leading to rougher and more unpredictable seas. According to Tara Lyttle (2018), there is a moderate positive relationship between wind-induced deterioration and sea state, as it can result in a 10-20cm increase in wave height. While this contributes to a deterioration in the sea state, it does not necessarily render fishing unsafe. However, findings from GULLS surveys indicate that 77% of the respondents expressed concerns about fishing in dangerous conditions due to changes in weather patterns (Gammage et al. 2019).	0.7	3
'Deterioration in sea state' -> 'Ability to secure a sustainable livelihood'	-	An increase in 'Deterioration in sea state' leads to a decrease in 'Ability to secure a sustainable livelihood' (negative relationship). Supporting Evidence: According to the GULLS study conducted by Gammage et al. (2019), 46% of respondents believed it is "not at all possible" to provide for their families if they cannot engage in fishing. This information highlights the substantial dependence on fishing as a means of livelihood. However, in contrast, 76% of the GULLS respondents reported that there has been 'no change' in their livelihoods attributed to alterations in the marine habitat (Gammage et al. 2019). These findings suggest that while the respondents recognise the critical role of fishing in supporting their families, they perceive minimal impact on their livelihoods stemming from changes in the marine environment.	0.3	2
'Fish catches' -> 'Income'	+	An increase in 'Fish catches' leads to an increase in 'Income' (positive relationship). Supporting Evidence: According to Gammage et al. (2017), it was noted that nearly half of the fishers in Melkhoutfontein have additional sources of income to rely on, indicating a medium-level relationship. Furthermore, approximately half of the participants reported previous involvement in various full-time economic activities before transitioning to commercial fishing, which equipped them with alternative skill sets (Gammage et al. 2017). These skill sets encompassed boat and outboard motor repair, panel beating and spray painting services, accommodation rental, subsistence farming, beekeeping, and operating boat charters (Gammage et al. 2017). While these fishers possess alternative skills and income sources, it is essential to recognise that fishing remains their primary source of income. In line with the GULLS	0.7	3

		<p>study, Gammage et al. (2019) found that 46% of respondents expressed that it is 'not at all possible' to provide for their families if they cannot fish. Additionally, 41% of respondents indicated they would seek financial assistance from their families when they cannot fish (Gammage et al. 2019). These findings highlight the critical role of fishing in sustaining the livelihoods of the participants and underscore the challenges they face when unable to engage in their primary occupation.</p>		
'Income' -> 'Ability to secure a sustainable livelihood'	+	<p>An increase in 'Income' leads to an increase in 'Ability to secure a sustainable livelihood' (positive relationship).</p> <p>Supporting Evidence: Given that fishing serves as these participants' primary source of income, the relationship between income and the ability to provide for their families can be considered highly positive. Gammage et al. (2019) revealed that 51% of respondents had not made any provisions for financial security, 85% had no savings, and 64% were aware of where to access cash in emergencies. These statistics highlight the lack of financial stability and preparedness among the participants. The data strongly indicate that low income, not solely limited to fishing earnings, drastically hampers their ability to meet basic needs such as putting food on the table.</p>	1	3

2 Testing 'Fcm.Infer' Function

Table 26: Convergence values in the *POC model* when using the 'fcm.infer' function and activating 'Deterioration in sea state' to -1,-0.7,-0.3,0,0.3,0.7, and 1. Note that the results appear nonsensical. See text for details.

Component Name	'Deterioration in sea state' activation value and corresponding convergence values in model components						
	-1	-0.7	-0.3	0	0.3	0.7	1
Ability to secure a sustainable livelihood	0.125	0.125	0.126	0	-0.126	-0.125	-0.698
Deterioration in sea state	-0.143	-0.143	-0.143	0	0.143	0.143	1.000
Fish catches	0.009	0.009	0.009	0	-0.009	-0.009	-0.061
Income	0.016	0.016	0.016	0	-0.016	-0.016	-0.103
Risk of injury	-0.013	-0.013	-0.013	0	0.013	0.013	0.087
Unsafe operating conditions	-0.043	-0.043	-0.043	0	0.043	0.043	0.291

Appendix B

1 Regional Model Structural Changes

Due to the semi-quantitative nature of FCMs, it was necessary to re-evaluate the structure of the FCM before commencing with parameterising the model connections. The re-evaluation exercise was done by carefully considering every component and connection in the model and determining if clarification in the wording was needed, if the connection could be quantified based on the current data or knowledge of the system, or if a component/connection needed to be added to better show the dynamics of the system. Table 15 illustrates the structural modifications implemented in the model through the re-evaluation process.

Table 27: Regional structural modifications

Action	Detail	Reason
Insertions	South Westerly wind strength' -> 'Wave Height'	South-westerly wind contributes to increased wave height and deterioration in sea state, affecting fishing conditions.
	South Easterly wind events' -> 'Duration of fishing season'	An increase in the number of south-easterly wind events had contributed to extending the fishing season, providing more opportunities for fishing and catch accumulation.
	Duration of fishing season' -> 'Kob catches' and -> 'Alternative catches'	A longer fishing season directly correlates with increased fish (kob and silvers) catches, allowing for more fishing days and higher catch potential.
	Alternative catches' -> 'Ability to secure a sustainable livelihood (put food on the table)'	Unlike kob catches, Silvers could be taken home by fishers as fry, directly contributing to their ability to secure a sustainable livelihood by providing food for their families.
	Alternative catches' -> 'Using the Riemhou fishing method'	When Alternative catches were low, fishers tend to increase the use of the Riemhou fishing method to catch more fish, which impacts their overall catch and livelihood.
	Alternative catches' -> 'Income (fishing)'	Increased Alternative catches could substantially boost income derived from fishing activities, enhancing the financial aspect of fishers' livelihoods.
	Kob catches' -> 'Alternative catches'	On days when kob catches were low or non-existent, fishers target Silvers as an alternative catch.
	Available sea days' -> 'Alternative catches'	The more fishing days available, the higher the chance of catching Silvers, directly affecting catch accumulation and income.
	Variability in optimal sea surface temperature range (for Kob and Silvers to bite)' -> 'Alternative catches'	Silvers prefer a temperature range of 12.6-19.5°C, while kob's preferred range was 13-16°C. Variability in this temperature range impacts fish behaviour and catch rates, making it a crucial factor in Alternative catches.

	Variability in rainfall patterns' -> 'Alternative catches'	Seasonal shifts in rainfall patterns could disrupt critical life-history stages such as spawning and migration for Silvers, affecting their availability and catches.
	Using the Riemhou fishing method' -> 'Alternative catches'	Utilising the Riemhou fishing method could increase Alternative catches
	Access to craft' -> 'Alternative catches'	Access to boats and fishing gear directly affects the ability to catch Silvers, as fishers rely on proper equipment for their livelihood.
	Risk of injury (compromises ability to fish)' -> 'Alternative catches'	Injuries could hinder fishers' ability to fish effectively or prevent them from fishing altogether, decreasing Alternative catches.
	Alternative employment opportunities' -> 'Income (Other sources)'	Engaging in alternative employment, such as gardening and welding, could increase income from sources other than fishing, diversifying livelihoods.
	Income (other sources)' -> 'Ability to secure a sustainable livelihood (put food on the table)'	Income from sources other than fishing directly contributes to securing a sustainable livelihood by providing additional financial support.
	Risk of injury (compromises ability to fish)' -> 'Income (other sources)'	Injuries could limit the ability to engage in other trades, like gardening and welding.
Deletions	Fish (Kob) catches' -> 'Ability to secure a sustainable livelihood (put food on the table)'	Kob catches indirectly affect the ability to secure a sustainable livelihood through their impact on income.
	Change in prevailing winds (direction, strength, and seasonality)' -> 'Changes in current strength and wave height'	'Change in prevailing winds (direction, strength and seasonality)' was deleted.
	Change in prevailing winds (direction, strength, and seasonality)' -> 'Fish (Kob) catches'	'Change in prevailing winds (direction, strength and seasonality)' was deleted.
	Changes in atmospheric pressure' -> 'Changes in current strength and wave height'	'Changes in atmospheric pressure' was deleted
	Changes in atmospheric pressure' -> 'Fish (Kob) catches'	'Changes in atmospheric pressure' was deleted
	Changes in current strength and wave height' -> 'Unsafe operating conditions'	Current strength and wave height do not directly affect the safety of operating conditions. Wave height affects the deterioration of the sea state, which in turn affects the safety of operation conditions
	Access to commercial rights' -> 'Ability to secure a sustainable livelihood (put food on the table)'	Access to commercial rights impacts the access to craft, affecting livelihood indirectly.
	Access to commercial rights' -> 'Fish (Kob) catches'	Access to commercial rights impacts the access to craft, affecting fish catches indirectly.
	Uncertainty' -> 'Ability to secure a sustainable livelihood (put food on the table)'	'Uncertainty' directly impacts 'access to commercial rights' and indirectly affects the ability to secure a sustainable livelihood.
	Specific financial management skills' -> 'Income (fishing and other sources)'	Specific financial management skills primarily affect fishers access to capital, indirectly influencing income from various sources.
	Deterioration in sea state' -> 'Ability to secure a sustainable livelihood (put food on the table)'	The deterioration in sea state affects the number of available sea days, and the safety of operating conditions directly, and the ability to secure a sustainable livelihood indirectly.
	Risk of injury (compromises ability to fish)' -> 'Ability to secure a sustainable livelihood (put food on the table)'	Risk of injury primarily affects kob catches and income from other sources, indirectly impacting the ability to secure a sustainable livelihood.

	Changes in atmospheric pressure'	This component was removed due to too many confounding variables affecting atmospheric pressure, making quantifying its direct links difficult.
	Change in prevailing winds (direction, strength, and seasonality)'	This component was split into 'South-westerly strength' and 'South-easterly events' for clarity.
	Alternative employment opportunities -> Income (Fishing)'	Alternative employment opportunities affects income from other sources, not fishing.
	Inshore trawl: effect on reef (habitat degradation)' -> 'Kob catches'	Habitat degradation primarily affects the ecosystem's health, influencing Kob abundance rather than catches directly.
	Inshore trawl: illegal fishery practices (fishing too close to the coast, targeting, and dumping of bycatch)' -> 'Kob catches'	Illegal, Unreported, and Unregulated (IUU) fishing practices primarily impact ecosystem health and Kob abundance rather than catches directly.
Adjustments	Price setting by fishmongers' changed to 'Competition between fishmongers'	Clarification to emphasise that the change in the competitive landscape among fishmongers influenced the pricing dynamics.
	Price of kob and other target species' changed to 'Price of kob and other target species (paid to fishers)'	Clarification to specify that this refers to the money paid directly to the fishers.
	Access to rights' changed to 'Access to commercial rights'	Clarification that these rights pertain to commercial use.
	Changes in rainfall patterns' changed to 'Variability in rainfall patterns'	Clarification to indicate whether there was increasing or decreasing variability in rainfall patterns.
	Access to DAFF' changed to 'Access to DFFE'	To reflect the change from DAFF to DFFE.
	Different methods in linefishery' changed to 'Using the Riemhou fishing method'	Clarification to specify the method used and to describe it as an increasing or decreasing component.
	Inshore trawl: Illegal fishery practices (fishing too close to the coast, targeting and dumping of bycatch)' changed to 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting and dumping of bycatch)'	Clarification to indicate that these were Illegal, Unreported, and Unregulated (IUU) fishing practices.
	Stringent catch (size) limits for kob' changed to 'Minimum catch (size) limits for kob'	Clarification to specify that these limits were minimum size and to describe it as either increasing or decreasing.
	Changes in current strength and wave height' changed to 'Wave height'	Due to insufficient data on the impact of current strength on deterioration in sea state.
	Changes in optimal sea surface temperature range' changed to 'Variability in optimal sea surface temperature range (for Kob and Silvers to bite)'	Clarification to indicate whether the sea surface temperature range for Kob and Silvers to bite was increasing or decreasing.
	Split 'Fish (kob) catches' into 'Kob catches' and 'Alternative catches'	Kob was not the only species captured, despite being the most valuable and traditionally fished species. Kob was consistently prioritized by fishers, highlighting its significance as a high-value fish with the potential for substantial profitability. However, the profitability of kob fishing was prone to fluctuations depending on the species' seasonality, quantity, and availability. Silvers were captured but not as profitable or sustainable for subsistence; however, the fishers could take silvers fry home for food security.
	Split 'Income (fishing and other sources)' into 'Income (fishing)' and 'Income (other sources)'	Clarification to distinguish between two separate income streams.

	Input costs (running costs and equipment)' changed to 'Input costs (running costs and equipment for fishing)'	Clarification to specify that input costs pertain to fishing, not other trades.
	Risk of injury (compromises ability to fish)' changed to 'Risk of injury (compromises ability to fish and perform in other trades)'	Clarification to indicate that the risk of injury could impact both fishing and engagement in other trades.

2 Regional Quantifications Table

Table 28: Overview of all 57 relationships within the regional FCM, their respective likelihood scores (ranging from 1=Remote to 6=Likely) and consequence scores (ranging from 0=Negligible to 5=Catastrophic) multiplied for a total score. These have been classified into relationship categories, as 0 to 10=Low, 11 to 20=Medium, and 21 to 30=High. Data quality scores range from 1=Very low confidence to 4=specific data support. Changes made to the model after calibration.

Relationship Group	Relationship number	Relationship	+ / -	Reason	Likelihood Score	Consequence Score	Total Score	Relationship Category	Data Quality Score	Changes made after calibration testing
Sea state	1	Deterioration in sea state -> Available sea days	-	A deterioration of the sea state due to shifts in wind conditions and increasing wave heights has been documented during the kob fishing season from 1997 to 2012 (Ward et al. 2021, Lyttle et al. 2021). Such changes may impact boat stability and thus reduce the number of viable fishing days (Gammage et al. 2017b). This relationship was interpreted as a possible (L=4) likelihood since wave height has only increased by 10-20 cm in the southern Cape over this period. However, if the sea state is severely deteriorated (strong wind and strong well), sea days could be majorly reduced (C=4).	4	4	16	Medium	4	
	2	Deterioration in sea state -> Unsafe operating conditions	+	Refer to relationship 1 for a description of deterioration in the sea state. The documented changes are not expected to make fishing unsafe, resulting in an unlikely (L=3) likelihood. However, if the wave height were to increase further, it may have a substantial (C=3) consequence on the safety of operating conditions since strong wind /	3	3	9	Low	4	

				high swell conditions typically only last for a few days.						
	3	Injury at sea - > Commercial alternative landings	-	Refer to relationship 4 for information on injury at sea affecting catches. This is also a major (C=4) consequence because catches will be compromised for a few weeks but not the entire fishing season.	4	4	16	Medium	4	
	4	Injury at sea - > Commercial kob landings	-	The stability of boats can be compromised by high waves or strong winds, potentially leading to injuries while fishing. Such conditions can decrease the ability to engage in fishing activities effectively, possibly (L=4) reducing commercial kob catches. This is classified as a major (C=4) but not a catastrophic consequence because catches will be compromised for a few weeks but not the entire fishing season.	4	4	16	Medium	4	
	5	Injury at sea - > Income (other sources)	-	When fishers experience injuries at sea and cannot fish, they may be unable to work or participate in other income-generating activities, decreasing their income from sources other than fishing (Gammage et al. 2017b). However, since there is a high unemployment rate in South Africa (Mlatsheni and Leibbrandt 2014) and in the southern Cape, with only one or two alternative jobs (e.g. construction or gardening), it is unlikely (L=3) that they can do any other work, and their income will decrease dramatically. However, if they are injured to the point where they cannot work for over a month, this may have a catastrophic (C=5) effect on their income from sources other than fishing.	3	5	15	Medium	4	
	6	Unsafe operating conditions -> Injury at sea	+	Sea state deterioration, characterised by higher waves and stronger winds, can directly affect boats' stability and, therefore, the safety of operations. If the operating conditions are unsafe, it is rare (L=2) for fishers to go to sea and risk being injured.	2	5	10	Low	4	

				However, if skippers go out in highly unsafe operating conditions (including high wave height, faulty equipment, and crew who possibly cannot swim), there may be catastrophic (C=5) consequences.						
Key Components	7	Available sea days -> Commercial alternative landings	+	Refer to relationship 7 for information on available sea days affecting catches.	6	4	24	High	4	
	8	Available sea days -> Commercial kob landings	+	Fewer sea days have been documented (L=6) since 2007 (Ward et al. 2021). However, occasional good catches continue to be reported (Duggan 2018), resulting in a consequence score corresponding to a major (C=4) (but not catastrophic) reduction in catches.	6	4	24	High	3	
		Commercial alternative landings -> Ability to secure a sustainable livelihood	+	While commercial alternative catches may be captured, it is important to emphasise that the significance of this relationship lies not in generating income for fishers but in the opportunity to sometimes (L=2) bring the fish home as fry. This will contribute to food security minorly (C=1). Compared to kob, these alternative catches are less profitable or sustainable for subsistence.	2	1	2	Low	2	Remove because the connection is affecting 'Ability to secure a sustainable livelihood' too strongly.
	9	Commercial alternative landings -> Income (fishing)	+	Kob is the staple of the handlinefishery in the southern Cape (Duggan et al. 2014, Duggan 2018). Although other species are targeted if kob are not available, these are either low value (silvers, sharks) or low abundance (redfish) (Gammage et al. 2017b). If fishers can catch and sell more commercial alternative species, it is possible (L=4) to generate profit for them (Gammage et al. 2017a). If caught, they can contribute substantially (C=3) to the fishers' income (Gammage et al. 2017a).	4	3	12	Medium	4	
	10	Commercial alternative	-	Added during model calibration because activating 'Commercial alternative landings'				Low	2	Add because the

		landings -> Price of kob and other target species (price setting by fish mongers), Add a dampening connection of low strength		was not affecting the ' Price of kob and other target species' when it should. Low strength because						model needs to show the relationship between landings and price.
	11	Commercial kob landings -> Commercial alternative landings	-	Fishers in the southern Cape noted that kob is considered the most economically viable and sustainable target species (Gammage et al. 2017b). Therefore, if commercial kob catches increase, fishers could possibly (L=4) focus more on targeting kob. Leading to a substantial (C=3) decline in catches of other commercially viable specie.	4	3	12	Medium	3	Change to low strength because the effect of the relationship was too strong
	12	Commercial kob landings -> Income (fishing)	+	Kob is the staple of the handlinefishery in the southern Cape (Duggan et al. 2014a, Duggan 2018), and catches have been decreasing (L=6). Although other species are targeted if kob are not available, these are either low value (silvers, sharks) or low abundance (redfish) (Gammage et al. 2017b). Decreased catches, therefore, imply lower income, which, in the context of poverty of the handline crew, results in a long-term, detrimental impact on income (C = 5).	6	5	30	High	4	
	13	Commercial kob landings -> Kob abundance	-	Kob is the staple of the handlinefishery in the southern Cape (Duggan et al. 2014a, Duggan 2018), and fishing pressure remains high in the southern Cape (Winker et al. 2012). This is causing (L=6) (DFFE 2000) a decline in their abundance over time since environmental changes pose another, albeit less well-quantified pressure (see above).	6	4	24	High	4	

				Unsustainable catches are therefore evaluated to have a major (C=4) consequence on kob abundance.						
14	Commercial kob landings -> Price of kob and other target species (price setting by fish mongers)	-		Added during model calibration because activating 'Commercial kob landings' was not affect the ' Price of kob and other target species' when it should.				Low	2	Add because the model needs to show the relationship between landings and price.
15	Ecosystem health -> Commercial alternative landings	-		Added during calibration because 'Ecosystem health' affects 'Commercial kob landings' via the connection to 'Kob abundance' but did not affect 'Commercial alternative landings'. Low strength because it is a direct connection unlike the medium strength connection to 'Kob abundance'				Low	2	Add because the model needs to show the relationship between ecosystem health and alternative landings. The relationship between ecosystem health and kob landings is already shown in the model.
16	Ecosystem health -> Kob abundance	+		Ecosystem health has been documented to be deteriorating through, e.g., high fishing pressure from both the handline and inshore trawl fisheries (Winker et al. 2012), destruction of reefs by boat anchors and trawl bobbins (Duggan et al. 2014b), and increased variability in wind/upwelling	6	3	18	Medium	3	

				regime (Blamey et al. 2015) (L=6). Kob is less abundant around a damaged reef, but alternative habitats remain, resulting in a severe (C=3) consequence score.						
17	Income (fishing) -> Ability to secure a sustainable livelihood	+		Fishing is the primary source of income for the participants in this study (Gammage et al. 2017b, Gammage et al. 2019, Ward et al. 2022) (L=6). The significance of this income cannot be overstated, as it helps fishers meet their fundamental needs and adequately provide for their families (C=5). This results in the highest consequence and likelihood scores.	6	5	30	High	4	
18	Income (other sources) -> Ability to secure a sustainable livelihood	+		The Melkhoutfontein and Stillbaai fishers have engaged in various alternative trades or secondary livelihood activities. These include repairing boats and outboard motors, panel beating and spray-painting services, renting out accommodation, subsistence farming, beekeeping, operating boat charters, and fixing cars (Duggan et al. 2014a, Gammage et al. 2017b). These activities already provide (L=6) some income. While reportedly less lucrative than good fishing, this income makes an extraordinary (C=5) livelihood contribution.	6	5	30	High	4	
19	Kob abundance -> Commercial kob landings	+		Kob has become scarce in the southern Cape (Winker et al. 2012, Duggan 2018) (L=6). Increased fishing efforts cannot compensate fully for the reduced abundance, and kob catches have been decreasing, but occasional good catches still occur, making it a major (C=4) consequence.	6	4	24	High	4	
20	Kob abundance -> Ecosystem health	+		Although there has been some recovery in kob stocks on the southern coast between 1987 and 2011, the stock is still considered overexploited (L=6) (Winker et al. 2012). The absence of predators (such as kob) can cause ecosystem regime shifts where the	6	3	18	Medium	3	

				ecosystem becomes dominated by other species (Blamey et al. 2014). Although other sectors can also impact the health of an ecosystem, fishing was shown to be the primary sector, raising the overall risk in South Africa's maritime ecosystems (Blamey et al. 2014, Skein et al. 2022). However, the term 'fishing' incorporates waste, noise pollution and many other factors on all flora and fauna, not just reduced kob abundance (C=3).						
21	Sector-specific policy implementation -> Access to rights	+	While commercial handlinefishing rights have been allocated since 2005, the re-allocation process (FRAP 2013) was severely problematic, as was the implementation of the Small-Scale Fisheries Policy (Norton 2014, Sowman et al. 2014), directly affecting fishers' access to rights. Some interim relief permits have been granted to historically disadvantaged individuals. Therefore, there is a high (L=5), but still not certain, likelihood that implementing the Small-Scale Fisheries Policy will increase access to rights. This will have critical (C=4) consequences for access to rights.	5	4	20	Medium	4		
22	Sector-specific policy implementation -> Conflict between inshore trawl and linefishery	-	The policy implementation is contradictory in that a minimum individual size is implemented for the handlinefishery but not for the inshore trawl fishery. Moreover, surveillance of fishing activities at sea is poor (Norton 2014), so the IUU activities that are commonly reported cannot be ruled out (L=5). Consequently, there is continued conflict between the linefishery and the inshore trawl fishery (Visser 2015, Duggan 2018) (C=5).	5	5	25	High	4		
23	Sector-specific policy implementation	+					Low	2	Add because the Policy dictates	

		on -> Minimum catch (size) limits for kob								changes in minimum catch size limits.
	24	Sector-specific policy implementation -> Surveillance (patrol vessel/aerial)	+	While commercial handlinefishing rights have been allocated since 2005, the re-allocation process (FRAP 2013) was severely problematic, as was the implementation of the Small-Scale Fisheries Policy (Norton 2014). Regulation of sector-specific policy can only occur if implemented, resulting in the highest consequence score (C=5). However, just because policy is implemented does not guarantee it will be regulated (L=5).	5	5	25	High	3	Change to medium strength because the effect of the relationship was too strong
	25	Sector-specific policy implementation -> Access to DFFE	+	While commercial handlinefishing rights have been allocated since 2005, the re-allocation process (FRAP 2013) was severely problematic (Norton 2014). The Small-Scale Fisheries Policy has not been implemented in the region, although it was gazetted in 2013 (L=3). Even where policy is implemented, there are problems regarding stakeholder access to DFFE related to the need to be represented by an association, even in the commercial handlinefishery, increasing general mistrust in the handlinefishery system (C=4) (Duggan 2018).	3	4	12	Medium	3	Change to low strength because the effect of the relationship was too strong
		Sector-specific policy regulation -> Minimum catch (size) limits for kob	+	Kob catch minimum size limits result from fisheries management policies promoting sustainable fishing, protecting fish populations, and maintaining aquatic ecosystem health. The current legal minimum size limit for silver kob in the handlinefishery is 50cm (DFFE 2023). Minimum size limits are changed occasionally (L=5). Although fishers see the benefit of increasing the larger size limit (Duggan et al. 2014a), there is also unhappiness with its implementation in the	5	4	20	Medium	2	Remove because Policy Regulation was changed to 'Surveillance (patrol vessels/aerial) and this changed component

				linefishery alone (and not in the trawl fishery) (Gammage et al. 2017b). Consequently, this was evaluated to have a major (C=4) consequence.						does not affect minimum catch size limits.
Regulation/M anagement	26	Minimum catch (size) limits for kob -> Commercial kob landings	+	Refer to relationship 24 for information on minimum size limits for silver kob. Fishers have expressed dissatisfaction with the increased minimum size limit for kob, as it requires them to release more fish than they would have otherwise been able to keep and sell (Gammage and Jarre 2020); however, this size increase has not been extreme; consequently, this was evaluated to have a substantial (C=3) consequence.	5	3	15	Medium	3	
	27	Surveillance (patrol vessel/aerial) -> Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading)	-	Small-scale fishers perceive an imbalance in the regulation and policing of the fishing sectors. They argue that inshore trawl fishers undergo less scrutiny, and current bycatch allowances make it easier for them to occasionally (L=5) engage in practices such as targeting bycatch and high grading (Greenston 2014). Proper implementation of policy through permit conditions is evaluated to have a major (C=4) but not catastrophic impact on IUU fishery practices because even if the fishery was highly regulated, it is impossible to monitor all inshore trawl fishing activities, and some IUU practices are likely to slip through the cracks.	5	4	20	Medium	4	
Biophysical	28	Current strength -> Deterioration in sea state	+	Refer to relationship 35 for information on Agulhas current strength. Changes in current strength would only have a minor (C=1) effect on sea state deterioration since this is mainly driven by wind (Lyttle et al. 2021)	2	1	2	Low	2	
	29	Duration of fishing season -> Commercial	+	Refer to relationship 33 for information on the extension of the fishing season affecting fish catches. The consequence score is evaluated as substantial (C=3) because the	5	3	15	Medium	4	

		alternative landings		duration of the fishing season will only affect species that favour the changed environmental conditions.						
	30	Duration of fishing season -> Commercial kob landings	+	Refer to relationship 32 for information on the extension of the fishing season. With an extension of the fishing season, fishers would occasionally (L=5) have more opportunities to go out to sea and target kob. However, catching kob is not guaranteed even if the fishing season is extended, so this is considered a major (C=4) but not an extraordinary consequence.	5	4	20	Medium	4	
	31	Physical navigation dangers (river mouths) -> Unsafe operating conditions	+	Fishers in the southern Cape reported that higher waves and stronger winds made it more difficult to leave the nearshore through river mouths and safely navigate back to shore (Gammage et al. 2017b, Duggan 2018). Due to compromised boat stability, these navigation dangers occasionally (L=4) affect the safety of operating conditions. This can substantially (C=3) but not majorly affect the fishers since the fishers will not go out if navigation dangers are evident.	4	3	12	Medium	4	
	32	Prevailing sea surface temperature range -> Commercial alternative landings	-	Refer to relationship 27 for information on how changing sea surface temperatures affect catches.	6	4	24	High	3	Change to low strength because the effect of the relationship was too strong.
	33	Prevailing sea surface temperature range -> Commercial kob landings	-	The Agulhas Current has experienced major sea surface warming from 1982 to 2019 (Rouault et al. 2009, Rasmeni 2023) (L=6). However, there have also been changes in the overall amount of upwelling and the number of upwelling days in the southern Cape, bringing deep cold water to the surface (Lamont et al. 2018). Fishers reported that kob were deterred from the southern Cape during cooler sea	6	4	24	High	3	Change to low strength because the effect of the relationship was too strong.

				temperatures caused by upwelling (Duggan 2012). On the other hand, fishers found that when the water was too warm, the kob did not bite (Gammage et al. 2017b). This means that since the sea temperature range is changing, there are major (C=4) but not catastrophic effects on commercial kob catches since it depends on the magnitude of the change.						
	34	Prevailing sea surface temperature range -> Kob abundance	-					Medium	2	Add because the model needs to show the relationship between sea surface temperature and kob abundance.
	35	Variability in rainfall patterns -> Physical navigation dangers (river mouths)	+	Farmers in the southern Cape have observed changes in rainfall patterns, including increased unpredictability, more intense rainfall events, longer dry periods between rainfall, and a shift of seasonal winter rainfall into summer months (Ward et al. 2021). The more intense rainfall events possibly (L=4) result in higher river inflow and outflow to the sea. This will moderately (C=2) increase the difficulty for southern Cape fishers to leave the nearshore through river mouths with higher waves (Gammage et al. 2017b).	4	2	8	Low	2	
	36	Wave height -> Deterioration in sea state	+	Lyttle et al. (2021) predicted a 10-20 cm increase in wave height for the southern Cape. This increase in wave height, along with other destabilising factors such as wind and wave directionality and wave and current interactions, has occasionally (L=5) contributed to the deterioration of the sea state (Lyttle et al. 2021). However, since the	5	3	15	Medium	4	

				reported increase in wave height is only 10-20 cm, this increase will have a substantial (C=3) impact on the deterioration of the sea state but will not be major.						
	37	Wind events that drive upwelling-> Duration of fishing season	+	Beginning in the mid-2000s, weaker westerly winds were seen throughout the autumn and winter seasons (Ward et al. 2018); this is consistent with research showing that upwelling on the Agulhas Bank increased at this time (Blamey et al. 2015, Lamont et al. 2018). Fishers in Stillbaai have noticed a change in fishing seasons, where fishers can occasionally (L=5) catch fish, starting in the winter and continuing through the summer months. This is a major (C=4) increase from only fishing in the spring/summer seasons (Duggan 2012).	5	4	20	Medium	2	
	38	Wind strength -> Current strength	+	No strengthening of the Agulhas Current has occurred since the early 1990s (L=2) (Beal and Elipot 2016). Instead, evidence indicates that it has broadened due to increased eddy activity due to stronger winds (Beal and Elipot 2016). However, if the wind strength were to increase current strength, this would only be minorly (C=1).	2	1	2	Low	4	
	39	Wind strength-> Wave Height	+	Fishers' observations indicate increased extreme wind days and changes in wind patterns (Ward et al. 2021). Additionally, there is evidence that wind speeds have increased over time, resulting in an estimated 10-20 cm increase in wave height on the inshore region of the southern Cape (Lyttle et al. 2021, Ward et al. 2021) (L=6). However, this is only a moderate (C=2) increase in wave height.	6	2	12	Medium	3	Change to low strength because the effect of the relationship was too strong.
Inshore Trawl	40	Inshore trawl: effect on reef (habitat degradation)	-	Refer to relationship 37 for information on trawling affecting reef habitats. This degradation of the reef habitat occasionally (L=5) decreases ecosystem health. The biological and structural levels of the natural	5	4	20	Medium	4	

		-> Ecosystem health		system are majorly impacted and may take up to a year to recover (C=4).						
41		Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Conflict between inshore trawl and linefishery	+	Small-scale fishers in the southern Cape perceive an imbalance in regulating or policing between sectors (Norton 2014). They raise concerns about bycatch allowances, discarding at sea, and the policing of the inshore trawl fishery (Norton 2014). Furthermore, the linefishery has strict minimum landing size limits imposed on kob, but no such restriction exists for the inshore trawl fishery (Attwood et al. 2011, Gammage et al. 2017a). This has led (L=6) to conflict between the two fisheries, exacerbated by overlapping operation areas (Visser 2015). This conflict has been evident since the 1940s (C=5) (Visser 2015).	6	5	30	High	4	
		Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Ecosystem health	-	This relationship refers to the inshore trawl vessels targeting bycatch and high grading. The inshore trawl fishery has no limit on the bycatch that may be landed (Attwood et al. 2011), currently affecting (L=6) many non-target species populations in the shallow areas of the Agulhas Bank (Japp et al. 1994, Nel et al. 2007). Although other sectors can also impact the health of an ecosystem, fishing was shown to be the primary sector, raising the overall risk in South Africa's maritime ecosystems (Blamey et al. 2014, Skein et al. 2022). However, the term 'fishing' includes all fisheries sectors, not just inshore trawling (C=3).	6	3	18	Medium	2	Remove because there is already a connection from 'Inshore trawl: IUU fishery practices' to 'Inshore trawl: effect on reef (habitat degradation)' which is then connected to 'Ecosystem health'

	42	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Inshore trawl: effect on reef (habitat degradation)	+	Linefishers in the southern Cape have expressed their concern regarding the impact of trawling on the greater marine and fishery system (Gammage et al. 2017a). It is possible (L=3) that the inshore trawl fishery is fishing too close to the coast and damaging reef habitats, as accused by the linefishers. Nonetheless, if the inshore trawlers are fishing too close to the coast, this would have a major (C=4) effect on reef habitat by reducing the complexity of the reef habitat (Auster and Langton 1999).	4	4	16	Medium	2	
	43	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Kob abundance	-	The inshore trawl fishery does not have a limit on the amount of bycatch that may be landed (Attwood et al. 2011). Due to this, the inshore trawl has the second-highest bycatch of any South African fishery (L=5), and a large portion is marketable (Fennessy and Groenewald 1997, Attwood et al. 2011). This suggests that many non-target fish species (including kob) are caught as bycatch. Additionally, kob catch abundance decreased between historical (1898-1904; 1922-1948) and repeat (1985-2010) trawl surveys; however, impacts of multiple fishing sectors are expected to have contributed to the observed changes (Currie 2017) (C=3).	5	3	15	Medium	3	
	44	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and	+	Small-scale fishers in the southern Cape perceive an imbalance in regulating or policing between the sectors (Norton 2014). If there is an increase in Inshore trawl: IUU fishery practices, such as fishing too close to the coast, targeting bycatch, and high-grading (selectively discarding lower-value catch), it could possibly (L=4) result in a greater demand for sector-specific policy	4	4	16	Medium	4	

		high-grading) -> Surveillance (patrol vessel/aerial)		regulation to address these issues. However, full implementation of increased regulation could take up to 5 years (C=4).						
Economic	45	Access to capital (savings/inve stments/ retirement income/loan s) -> Access to craft	+	A lack of capital makes it more difficult for fishers to access craft (Gammage et al. 2019). Many fishers in the southern Cape earn less than R5000 per month and lack financial security plans (Gammage et al. 2019). Over 60% cannot access reserves if fishing fails (Gammage et al. 2019). Limited access to capital occasionally (L=5) hinders fishers' ability to acquire suitable vessels. Acquiring vessels is a major (C=4) criterion for securing commercial linefish rights (DAFF 2013).	5	4	20	Medium	4	
	46	Access to craft -> Commercial alternative landings	+	Refer to relationship 44 for information on how access to craft affects catches.	6	5	30	High	3	
	47	Access to craft -> Commercial kob landings	+	Due to the lack of fish, it seems that there are more fishers looking for a site on a boat than boats that are available to go out to sea (Gammage et al. 2017a). So, it is highly likely (L=6) that access to craft will decrease commercial kob catches. This decrease in catches will be catastrophic (C=5) since kob can only be caught commercially with boats; no access to a boat means no catch.	6	5	30	High	3	
	48	Alternative employment opportunitie s -> Income (other sources)	+	There are limited employment opportunities for fishers in the southern Cape, with only one or two alternative jobs (e.g. construction or gardening (L=5) (Gammage et al. 2017b). However, this provides most of (L=4) the income from sources other than fishing; hence, it is given the highest likelihood and consequence scores.	5	4	20	Medium	4	

	49	External economic pressures -> Alternative employment opportunities	-	Increased economic pressures can prevent fishers from developing lucrative skills and income outside fishing (Gammage et al. 2017a, 2017b), which occasionally (L=5), limits their ability to pursue well-paid employment outside of the fishing industry. The effect of this is major (C=4).	5	4	20	Medium	4	
	50	External economic pressures -> Input costs (running costs and equipment for fishing)	+	Economic pressures manifest in several ways, including the rise in fuel prices, heightened cost of living, pricing determined by intermediaries, disparities in prices of alternative species, and limited access to credit from banks (Gammage et al. 2017a). All of the above already results (L=6) in an increase in input costs for fishers. This is a major (C=4) but not catastrophic increase.	6	4	24	High	4	
	51	External economic pressures -> Price of kob and other target species (price setting by fish mongers)	-	If the national economy is experiencing a downturn, there may be a decrease in consumer demand for fish. The price of kob is determined by intermediaries, who buy the fish from the fishers and resell it, rather than by the fishers themselves (Gammage et al. 2017a), and therefore, an economic downturn might possibly (L=4), cause fishmongers to decrease their fish prices (Gammage et al. 2017a). This decrease would be substantial (C=3).	4	3	12	Medium	4	
	52	Input costs (running costs and equipment for fishing) -> Income (fishing)	-	Input costs in the fishing industry, such as fuel, insurance, gear, and bait costs, have all increased (Gammage et al. 2017a). However, the price of fish, specifically kob, per kilo has stayed constant over the years. This occasionally (L=5) leads to a situation where fishers bear the increasing input costs without the ability to increase the price they receive for their catch. This majorly (C=4) decreases their income from fishing (Gammage et al. 2017a).	5	4	20	Medium	4	
	53	Price of kob and other	+	The price of kob is determined by intermediaries, who buy the fish from the	6	3	18	Medium	4	

		target species (price setting by fish mongers)-> Income (fishing)		fishers and resell it, rather than by the fishers themselves (Gammage et al. 2017a). If fishmongers decrease the price of kob and other target species, it will (L=6) decrease the profitability of fishing activities for the fishers. However, the fishmongers do not have a monopoly on the fish price, and the fishers can push back, so this is a substantial (C=3) but not major consequence.						
	54	Specific financial management skills -> Access to capital (savings/investments/retirement income/loans)	+	In the southern Cape, a group of fishers displayed limitations in their financial management skills, encountering difficulties diversifying their livelihoods (Gammage et al. 2017b). Eighty-five percent of the participants in a study done on fishers in the southern Cape did not have access to savings (Gammage et al. 2019), which suggests that the constrained financial management skills observed in the majority of the fishers can possibly (L=4) contribute to the difficulties they experience in gaining access to sufficient capital for their endeavours. Access to capital is catastrophically (C=5) affected in this case	4	5	20	Medium	4	
Social	55	Access to DFFE -> Sector-specific policy implementation	+	There are problems regarding stakeholder access to DFFE related to the need to be represented by an association, even in the commercial handlinefishery, increasing general mistrust in the system (Duggan 2018). It is possible (L=4) that increased access to the DFFE will increase policy implementation. If it does, the increase in policy implantation will be major (C=4).	4	4	16	Medium	4	
	56	Access to rights -> Access to craft	+	Implementing the small-scale fisheries policy (Norton 2014, Sowman et al. 2014) directly affects fishers' access to rights. Some interim relief permits have been granted to historically disadvantaged individuals. Therefore, if the fisher has a	6	4	24	High	4	

				right, they will definitely (L=6) have access to the craft. Since they are rightsholders and not just crewmembers, they will have access to craft with major (C=4) consequence.						
	57	Conflict between inshore trawl and linefishery -> Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading)	+					Low	2	Add because an increase in conflict will increase the illegal fishing practices by the Inshore trawl fishery.
		Conflict between inshore trawl and linefishery -> Sector-specific policy regulation	+	Small-scale fishers in the southern Cape perceive an imbalance in regulating or policing between the sectors (Norton 2014). They raise concerns about bycatch allowances, discarding at sea, and the policing of the inshore trawl fishery (Norton 2014). This leads to a historical conflict between the two fisheries, exacerbated by overlapping operation areas (Visser 2015). This suggests that conflicts between the two sectors could rarely (L=2) increase the need for stricter policy and regulation. However, this policy change would have a major (C=4) impact.	2	4	8	Low	2	remove

3 Base Model 1 Component Metrics

Table 29: Base Model 1 Component metrics

Concept	Outdegree	Indegree	Centrality
Commercial kob catches	2.7	6.1	8.8
Commercial alternative catches	1	5.1	6.1
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and highgrading)	3.8	0.7	4.5
Income (fishing)	1	3.1	4.1
Kob abundance	1.7	2.4	4.1
Sector specific policy implementation	3.4	0.7	4.1
Access to craft	2	1.7	3.7
Sector specific policy regulation	1.4	2	3.4
Ecosystem health	0.7	2.1	2.8
Available sea days	2	0.7	2.7
External economic pressures	2.4	0	2.4
Income (other sources)	1	1.4	2.4
Injury at sea	2.1	0.3	2.4
Ability to secure a sustainable livelihood	0	2.3	2.3
Conflict between inshore trawl and linefishery	0.3	2	2.3
Duration of fishing season	1.4	0.7	2.1
Prevailing sea surface temperature range	2	0	2
Deterioration in sea state	1	1	2
Access to rights	1	0.7	1.7
Input costs (running costs and equipment for fishing)	0.7	1	1.7
Access to capital (savings/investments/retirement income/loans)	0.7	0.7	1.4
Access to DFFE	0.7	0.7	1.4
Alternative employment opportunities	0.7	0.7	1.4

Inshore trawl: effect on reef (habitat degradation)	0.7	0.7	1.4
Minimum catch (size) limits for kob	0.7	0.7	1.4
Price of kob and other target species (price setting by fish mongers)	0.7	0.7	1.4
Wave height	0.7	0.7	1.4
Unsafe operating conditions	0.3	1	1.3
Wind strength	1	0	1
Physical navigation dangers (river mouths)	0.7	0.3	1
Specific financial management skills	0.7	0	0.7
Wind events that drive upwelling	0.7	0	0.7
Current strength	0.3	0.3	0.6
Variability in rainfall patterns	0.3	0	0.3

4 Understanding The Model: Results Of Calibrating The Base Run On The Regional Fuzzy Cognitive Model

Transmitter components fully activated

'Wind strength' fully activated

Problem: 'Wave height' is too strong due to the direct medium-strength connection from the fully activated component.

Solution: Wind strength-> Wave Height. Change the connection to low strength to reduce the impact.

Table 30: Convergence values for the regional FCM when 'Wind Strength' is clamped at 1 and the connection from Wind strength-> Wave Height is changed to low-strength.

Component Name	Old Convergence Value	New Convergence Value	Difference
Wave height	0.604	0.291	0.3
Deterioration in sea state	0.47	0.283	0.2
Kob abundance	0.226	0.14	0.1
Ecosystem health	0.157	0.098	0.1
Unsafe operating conditions	0.14	0.085	0.1
Injury at sea	0.042	0.025	0.0
Current strength	0.291	0.291	0.0
Income (other sources)	-0.029	-0.018	0.0
Commercial kob catches	-0.12	-0.073	0.0

Commercial alternative catches	-0.257	-0.161	-0.1
Income (fishing)	-0.291	-0.183	-0.1
Available sea days	-0.318	-0.196	-0.1
Ability to secure a sustainable livelihood	-0.379	-0.245	-0.1

Fixed? Yes, the wave height is now of low strength, aligning with Lyttle et al.'s (2021) reported low increase in wave height in Still Bay.

'Prevailing sea surface temperature range' fully activated

Problem: 'Kob abundance' should not increase since an elevated temperature should deter kob from the fishing grounds. This has happened because 'Prevailing sea surface temperature range' is dampening 'Commercial kob catches' which in turn increases 'Kob abundance'.

Solution:

- Prevailing sea surface temperature range -> Commercial kob catches, Change to dampening low strength connection.
- Prevailing sea surface temperature range -> Commercial alternative catches, Change to dampening low strength connection.
- Prevailing sea surface temperature range -> Kob abundance, Add dampening medium strength connection. Medium strength because the original connection to 'Commercial kob catches' was medium strength.

Table 31: Convergence values for the regional FCM when 'Prevailing sea surface temperature range' is clamped at 1 and dampening low-strength connections are added from 'Prevailing sea surface temperature range' to 'Kob abundance' and 'Commercial alternative catches'

Component Name	Old Convergence Value	New Convergence Value	Difference
Commercial alternative catches	-0.619	-0.146	0.5
Ability to secure a sustainable livelihood	-0.699	-0.639	0.1
Income (fishing)	-0.679	-0.712	0.0
Commercial kob catches	-0.395	-0.789	-0.4
Ecosystem health	0.387	-0.253	-0.6
Kob abundance	0.582	-0.37	-1.0

Fixed? Yes, 'Kob abundance' is now decreasing.

‘Specific financial management skills’ fully activated

Problem: ‘Income (fishing)’ should be stronger than ‘Ability to secure a sustainable livelihood’. However, the 'Commercial alternative catches' connection contributes to 'Ability to secure a sustainable livelihood', elevating its Convergence value.

Solution: Commercial alternative catches -> Ability to secure a sustainable livelihood, Remove connection

Table 32: Convergence values for the regional FCM when 'Specific financial management skills' is clamped at 1 and the connection from Commercial alternative catches -> Ability to secure a sustainable livelihood is removed

Component Name	Old Convergence Value	New Convergence Value	Difference
Access to capital (savings/investments/retirement income/loans)	0.604	0.604	0.0
Access to craft	0.4	0.4	0.0
Commercial alternative catches	0.293	0.293	0.0
Commercial kob catches	0.139	0.139	0.0
Ecosystem health	-0.18	-0.18	0.0
Kob abundance	-0.259	-0.259	0.0
Income (fishing)	0.332	0.331	0.0
Ability to secure a sustainable livelihood	0.397	0.32	-0.1

Fixed? Yes, ‘Income (fishing)’ is now stronger than ‘Ability to secure a sustainable livelihood.’

Highest Centrality scores components fully activated

‘Commercial alternative catches’ fully activated

Problem: Values for ‘Income (fishing)’ and ‘Ability to secure a sustainable livelihood’ should be stronger when ‘Commercial kob catches’ is fully activated than when ‘Commercial alternative catches’ is fully activated considering that alternative species are typically less lucrative and not the primary target of the fishery.

Solution: Commercial alternative catches -> Ability to secure a sustainable livelihood, Remove connection

Table 33: Convergence values for the regional FCM when 'Commercial alternative catches' is clamped at 1 and the connection from Commercial alternative catches -> Ability to secure a sustainable livelihood is removed.

Component Name	Old Convergence Value	New Convergence Value	Difference
Income (fishing)	0.604	0.604	0.0
Ability to secure a sustainable livelihood	0.718	0.54	-0.2

Table 34: Convergence values for the regional FCM when 'Commercial kob catches' is clamped at 1 and the connection from Commercial alternative catches -> Ability to secure a sustainable livelihood is removed.

Component Name	Old Convergence Value	New Convergence Value	Difference
Ability to secure a sustainable livelihood	0.327	0.478	0.2
Income (fishing)	0.52	0.52	0.0

Ecosystem health	-0.549	-0.549	0.0
Commercial alternative catches	-0.604	-0.604	0.0
Kob abundance	-0.882	-0.882	0.0

Fixed? Yes, Values for 'Income (fishing)' and 'Ability to secure a sustainable livelihood' are stronger when 'Commercial kob catches' is fully activated than when 'Commercial alternative catches' is fully activated.

‘Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)’ fully activated

Problem: Ecosystem health’ should not decrease so strongly and should not be stronger than ‘Inshore trawl: effect on reef (habitat degradation)’. This is because of the direct connection from the fully activated component. test 2

Solution

- Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Ecosystem health, Remove connection because there is already a connection from ‘Inshore trawl: IUU fishery practices’ to ‘Inshore trawl: Habitat degradation’ and then to ‘Ecosystem health’
- Ecosystem health -> Alternative catches, Add dampening low strength connection to account for the influence of ‘Ecosystem health’ on ‘Commercial alternative catches,’ which is not adequately represented. This adjustment is warranted because the connection from ‘Ecosystem health’ to ‘Kob abundance’ is of medium strength, followed by a high-strength connection to ‘Commercial kob catches.’ Therefore, to align the direct link to ‘Commercial alternative catches,’ it should be of low strength.

Table 35: Convergence values for the regional FCM when 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' is clamped at 1 as well as the changes mentioned above.

Component Name	Old Convergence Value	New Convergence Value	Difference
Ecosystem health	-0.907	-0.629	0.3

Ability to secure a sustainable livelihood	-0.228	-0.079	0.1
Income (fishing)	-0.369	-0.25	0.1
Commercial alternative catches	0.459	0.569	0.1
Kob abundance	-0.555	-0.452	0.1
Commercial kob catches	-0.709	-0.653	0.1
Conflict between inshore trawl and linefishery	0.762	0.762	0.0
Inshore trawl: effect on reef (habitat degradation)	0.604	0.604	0.0
Minimum catch (size) limits for kob	0.471	0.471	0.0
Sector-specific policy regulation	0.73	0.73	0.0

Fixed? Yes, Ecosystem health' is decreasing moderately and is not stronger than 'Inshore trawl: effect on reef (habitat degradation).'

Problem: 'Minimum catch (size) limits for kob' should not be affected since increased regulation should result in sending out more patrol vessels, not increasing the minimum size limit. This is attributed to the direct medium-strength connection to 'Sector-specific policy regulation', which is then connected to the fully activated component.

Solutions

- Change 'Sector specific policy regulation' to 'Surveillance (patrol vessels/aerial)'
- Remove link from 'Patrol vessels' to "Minimum size
- Add link from 'Sector specific policy implementation' to 'Minimum size'

- Add link from 'Conflict' to 'IUU'

Table 36: Convergence values for the regional FCM when 'Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' is clamped at 1

Component Name	Old Convergence Value	New Convergence Value	Difference
Commercial kob catches	-0.709	-0.573	0.1
Inshore trawl: effect on reef (habitat degradation)	0.604	0.73	0.1
Income (fishing)	-0.369	-0.297	0.1
Ability to secure a sustainable livelihood	-0.228	-0.18	0.0
Conflict between inshore trawl and linefishery	0.762	0.762	0.0
Sector-specific policy regulation/Surveillance (patrol vessels/aerial)	0.73	0.73	0.0
Ecosystem health	-0.907	-0.931	0.0
Commercial alternative catches	0.459	0.381	-0.1
Kob abundance	-0.555	-0.652	-0.1
Minimum catch (size) limits for kob	0.471	0	-0.5

Fixed? Yes, 'Minimum catch (size) limits for kob' is now not affected.

'Kob abundance' fully activated

Problem: 'Income(fishing)' too weak due to the connection from 'Commercial alternative catches', which has been dampened by 'Commercial kob catches'.

Solution: Commercial kob catches -> Commercial alternative catches. Change the connection to low strength in order to reduce the impact.

Table 37: Convergence values for the regional FCM when 'Kob abundance' is clamped at 1 and the connection from Commercial kob catches -> Commercial alternative catches is changed to low strength.

Component Name	Old Convergence Value	New Convergence Value	Difference
Commercial alternative catches	-0.488	-0.225	0.3
Ability to secure a sustainable livelihood	0.246	0.44	0.2
Income (fishing)	0.397	0.54	0.1
Commercial kob catches	0.762	0.762	0.0
Ecosystem health	0.604	0.604	0.0

Fixed? Yes, Income (fishing)' is now stronger.

Problem: Changes in 'Kob abundance' should affect 'Price of kob and other target species (price setting by fish mongers)' since typically, an increase in kob abundance would lead to more supply in the market, potentially decreasing the price paid to fishers.

Solutions:

- Commercial kob catches -> Price of kob and other target species (price setting by fish mongers), Add dampening low strength connection
- Commercial alternative catches -> Price of kob and other target species (price setting by fish mongers), Add a dampening connection of low strength, Add dampening low strength connection.

Table 38: Convergence values for the regional FCM when 'Kob abundance' is clamped at 1 as well as the changes mentioned above.

Component Name	Old Convergence Value	New Convergence Value	Difference
Commercial kob catches	0.762	0.762	0.0
Ecosystem health	0.604	0.604	0.0
Commercial alternative catches	-0.488	-0.488	0.0
Ability to secure a sustainable livelihood	0.246	0.199	0.0
Income (fishing)	0.397	0.348	0.0
Price of kob and other target species (price setting by fishmongers)	0	-0.082	-0.1

Fixed? Yes, Changes in 'Kob abundance' now affect 'Price of kob and other target species (price setting by fish mongers)'

‘Sector-specific policy implementation’ fully activated

Problem: ‘Ability to secure a sustainable livelihood’ is too strong due to the direct connection to 'Commercial alternative catches'.

Solution: Commercial alternative catches -> Ability to secure a sustainable livelihood, Remove connection

Table 39: Convergence values for the regional FCM when 'Sector-specific policy implementation' is clamped at 1 and the connection from Commercial alternative catches -> Ability to secure a sustainable livelihood is removed.

Component Name	Old Convergence Value	New Convergence Value	Difference
Kob abundance	0.117	0.117	0.0
Commercial kob catches	0.408	0.408	0.0
Income (fishing)	0.525	0.525	0.0
Minimum catch (size) limits for kob	0.32	0.32	0.0
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	-0.32	-0.32	0.0
Access to rights	0.604	0.604	0.0
Access to DFFE	0.604	0.604	0.0
Access to craft	0.54	0.54	0.0
Sector-specific policy regulation	0.474	0.474	0.0
Conflict between inshore trawl and linefishery	-0.867	-0.867	0.0
Inshore trawl: effect on reef (habitat degradation)	-0.221	-0.221	0.0
Ecosystem health	0.431	0.431	0.0
Commercial alternative catches	0.249	0.249	0.0

Ability to secure a sustainable livelihood	0.537	0.482	-0.1
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Fixed? Yes, 'Ability to secure a sustainable livelihood' is now weaker.

Problem: 'Access to DFFE' affected too strongly due to a direct medium-strength connection to the fully activated component.

Solution: Sector-specific policy implementation-> Access to DFFE. Change the connection to low strength in order to reduce the impact.

Table 40: Convergence values for the regional FCM when 'Sector-specific policy implementation' is clamped at 1 and the connection from Sector-specific policy implementation-> Access to DFFE is changed to low strength

Component Name	Old Convergence Value	New Convergence Value	Difference
Kob abundance	-0.138	0.117	0.3
Ecosystem health	0.275	0.431	0.2
Commercial alternative catches	0.15	0.249	0.1
Inshore trawl: IUU fishery practices	-0.321	-0.32	0.0
Access to rights	0.604	0.604	0.0
Access to craft	0.54	0.54	0.0
Sector-specific policy regulation	0.474	0.474	0.0
Conflict between inshore trawl and linefishery	-0.867	-0.867	0.0
(Fishing too close to the coast, targeting			0.0
bycatch and high grading)			0.0

Inshore trawl: effect on reef (habitat degradation)	-0.22	-0.221	0.0
Minimum catch (size) limits for kob	0.321	0.32	0.0
Ability to secure a sustainable livelihood	0.553	0.537	0.0
Income (fishing)	0.579	0.525	-0.1
Commercial kob catches	0.556	0.408	-0.1
Access to DFFE	0.604	0.291	-0.3

Fixed? Yes, 'Access to DFFE' is now weaker.

Changes that need to be made to the model

Table 41: Changes that need to be made to the model based on calibration results.

	Connection	Change
Alter quantification	Wind strength-> Wave Height	Change the connection to low strength in order to reduce the impact.
	Commercial kob catches -> Commercial alternative catches	Change the connection to low strength in order to reduce the impact.
	Sector-specific policy implementation -> Sector-specific policy regulation	Change the connection to medium strength in order to reduce the impact.
	Sector-specific policy implementation-> Access to DFFE	Change the connection to low strength in order to reduce the impact.
	Prevailing sea surface temperature range -> Commercial alternative catches	Change the connection to low strength in order to reduce the impact.
	Prevailing sea surface temperature range -> Commercial kob catches	Change the connection to low strength in order to reduce the impact.
Remove connection	Commercial alternative catches -> Ability to secure a sustainable livelihood	Remove connection
	Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading) -> Ecosystem health	Remove connection
	Sector-specific policy regulation -> Minimum catch (size) limits for kob	Remove connection
	Conflict between inshore trawl and linefishery -> Sector-specific policy regulation	Remove connection
Add connection	Prevailing sea surface temperature range -> Kob abundance	Add dampening medium strength connection
	Ecosystem health -> Alternative catches	Add dampening low strength connection
	Commercial kob catches -> Price of kob and other target species (price setting by fish mongers)	Add dampening low strength connection
	Commercial alternative catches -> Price of kob and other target species (price setting by fish mongers), Add a dampening connection of low strength	Add dampening low strength connection

	Sector-specific policy implementation -> Minimum catch (size) limits for kob	Add amplifying medium strength connection
	Conflict between inshore trawl and linefishery -> Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high-grading)	Add amplifying low strength connection
Change component name	'Sector specific policy regulation'	Change to 'Surveillance (patrol vessels/aerial)'
	Commercial kob catches	Commercial kob landings
	Commercial alternative catches	Commercial alternative landings

5 Regional Prototype Model Quantification Category Sensitivity Test

In the first test, the medium quantification was divided into low medium and high medium, set at ± 0.6 and ± 0.8 , respectively, while low remained at ± 0.3 and high at ± 1

Table 42: Regional Prototype Model Quantification Category Sensitivity Test 1

Component Affected	Convergence Value																	
	External economic pressures' fully activated			Wind Strength' fully activated			Prevailing sea surface temperature range' fully activated			Wind events that drive upwelling' fully activated			Specific financial management skills' fully activated			Variability in rainfall patterns' fully activated		
	Base run 2	Sensitivity test	Change	Base run 22	Sensitivity test 2	Change 2	Base run 24	Sensitivity test 3	Change 3	Base run 26	Sensitivity test 4	Change 4	Base run 28	Sensitivity test 5	Change 5	Base run 210	Sensitivity test 6	Change 6
Ability to secure a sustainable livelihood	-0.815	-0.852	0.037	-0.153	-0.117	-0.036	-0.447	-0.460	0.013	0.258	0.208	0.050	0.245	0.227	0.018	-0.069	-0.051	-0.018
Access to capital (savings/investments/retirement income/loans)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.664	-0.060	0.000	0.000	0.000	
Access to craft	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.400	0.486	-0.086	0.000	0.000	0.000	
Alternative employment opportunities	-0.000	-0.664	0.060	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

	60 4																	
Available sea days	0.00 0	0.00 0	0.00 0	- 0.19 6	- 0.20 2	0.00 6	0.0 00	0.000	0.000	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Commercial alternative landings	0.00 0	0.00 0	0.00 0	- 0.16 1	- 0.16 3	0.00 2	- 0.1 98	- 0.209	0.011	0.31 1	0.25 8	0.05 3	0.29 5	0.34 8	- 0.05 3	- 0.03 2	- 0.03 1	- 0.00 1
Commercial kob landings	0.00 0	0.00 0	0.00 0	- 0.07 3	- 0.06 0	- 0.01 3	- 0.5 36	- 0.614	0.078	0.14 8	0.15 9	- 0.01 1	0.13 9	0.14 3	- 0.00 4	- 0.01 4	- 0.01 1	- 0.00 3
Conflict between inshore trawl and linefishery	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.0 00	0.000	0.000	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Current strength	0.00 0	0.00 0	0.00 0	0.29 1	0.29 1	0.00 0	0.0 00	0.000	0.000	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Deterioration in sea state	0.00 0	0.00 0	0.00 0	0.28 3	0.25 6	0.02 7	0.0 00	0.000	0.000	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Duration of fishing season	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.0 00	0.000	0.000	0.60 4	0.66 4	- 0.06 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Ecosystem health	0.00 0	0.00 0	0.00 0	0.09 8	0.12 8	- 0.03 0	- 0.2 06	- 0.321	0.115	0.18 9	0.28 8	0.09 9	0.18 0	0.26 7	0.08 7	0.02 0	0.02 5	- 0.00 5
Income (fishing)	- 0.74 3	- 0.77 7	0.03 4	- 0.13 5	- 0.10 4	- 0.03 1	- 0.4 80	- 0.497	0.017	0.26 3	0.21 1	0.05 2	0.24 9	0.23 0	0.01 9	- 0.02 7	- 0.01 9	- 0.00 8
Inshore trawl: effect on reef (habitat degradation)	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.0 00	0.000	0.000	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and highgrading)	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.0 00	0.000	0.000	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0

Income (other sources)	- 0.40 0	- 0.48 6	0.08 6	- 0.01 8	- 0.01 4	- 0.00 4	0.0 00	0.000	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	- 0.04 2	- 0.03 1	- 0.01 1
Injury at sea	0. 00 0	0.00 0	0.00 0	0. 02 5	0.02 3	0.00 2	0.0 00	0.000	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 06 0	0.05 2	0.00 8
Input costs (running costs and equipment for fishing)	0. 76 2	0.76 2	0.00 0	0. 00 0	0.00 0	0.00 0	0.0 00	0.000	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0
Kob abundance	0. 00 0	0.00 0	0.00 0	0. 14 0	0.16 1	- 0.02 1	- 0.2 99	- 0.416	0.117	- 0. 27 4	- 0. 37 1	0.09 7	- 0. 25 9	- 0. 34 2	0.08 3	0. 02 8	0.03 0	- 0.00 2
Physical navigation dangers (river mouths)	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0.0 00	0.000	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 29 1	0.29 1	0.00 0
Price of kob and other target species (price setting by fish mongers)	- 0. 60 4	- 0.53 7	- 0.06 7	0. 07 0	0.06 7	0.00 3	0.2 17	0.242	- 0.025	- 0. 13 7	- 0. 12 4	- 0.01 3	- 0. 12 9	- 0. 14 6	0.01 7	0. 01 4	0.01 2	0.00 2
Unsafe operating conditions	0. 00 0	0.00 0	0.00 0	0. 08 5	0.07 7	0.00 8	0.0 00	0.000	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 20 1	0.17 3	0.02 8
Wave height	0. 00 0	0.00 0	0.00 0	0. 29 1	0.29 1	0.00 0	0.0 00	0.000	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0
	Convergence Value																	
	Commercial kob landings' fully activated		Commercial alternative landings' fully activated		Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated			Income (fishing)' fully activated		Kob abundance' fully activated		Sector-specific policy implementation' fully activated						

Component Affected	Base run 2	Sensitivity test	Column 1	Base run 22	Sensitivity test 2	Sensitivity test 22	Base run 24	Sensitivity test 3	Sensitivity test 3 2	Base run 26	Sensitivity test 4	Sensitivity test 42	Base run 28	Sensitivity test 5	Sensitivity test 52	Base run 210	Sensitivity test 6	Sensitivity test 7
Ability to secure a sustainable livelihood	0.479	0.490	- 0.011	0.429	0.338	0.091	- 0.388	-	-	0.762	0.762	0.000	0.480	0.475	0.005	0.472	0.469	0.003
Access to craft	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.540	0.581	-0.041
Access to DFFE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.291	0.000
Access to rights	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.604	0.664	-0.060
Commercial alternative landings	-0.434	-0.451	0.017	0.000	0.000	0.000	-0.048	-	-0.070	0.000	0.000	0.000	-0.047	-0.029	-	0.464	0.502	-0.038
Commercial kob landings	0.000	0.000	0.000	0.000	0.000	0.000	-0.519	-	-0.531	0.000	0.000	0.000	0.762	0.762	0.000	0.423	0.491	-0.068
Conflict between inshore trawl and linefishery	0.000	0.000	0.000	0.000	0.000	0.000	0.762	0.762	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.901	-0.908	0.007
Ecosystem health	-0.549	-0.619	0.070	0.000	0.000	0.000	-0.678	-	-0.763	0.000	0.000	0.000	0.604	0.664	-	0.296	0.395	-0.099
Income (fishing)	0.522	0.536	- 0.014	0.459	0.351	0.108	-0.410	-	-0.405	0.000	0.000	0.000	0.523	0.516	0.007	0.512	0.509	0.003
Inshore trawl: effect on reef (habitat degradation)	0.000	0.000	0.000	0.000	0.000	0.000	0.604	0.664	-	0.000	0.000	0.000	0.000	0.000	0.000	-0.321	-0.390	0.069

Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.475	-0.514	0.039
Kob abundance	-0.882	-0.904	0.022	0.000	0.000	0.000	-0.575	-0.592	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.116	0.132	-0.016
Minimum catch (size) limits for kob	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.291	0.000
Price of kob and other target species (price setting by fish mongers)	-0.168	-0.163	- 0.005	-0.291	-0.291	0.000	0.169	0.178	- 0.009	0.000	0.000	0.000	-0.211	-0.216	0.005	-0.260	-0.289	0.029
Surveillance (patrol vessels/aerial)	0.000	0.000	0.000	0.000	0.000	0.000	0.604	0.664	- 0.060	0.000	0.000	0.000	0.000	0.000	0.000	0.352	0.370	-0.018

In the second test, the low quantification was changed from ± 0.3 to ± 0.25 , low medium to ± 0.5 , high medium to ± 0.75 , and high remained at ± 1

Table 43 : Regional Prototype Model Quantification Category Sensitivity Test 2

	Convergence Value							
	External economic	Wind Strength' fully activated	Prevailing sea surface	Wind events that drive upwelling' fully activated	Specific financial management	Variability in rainfall patterns' fully activated		

Component Affected	pressures' fully activated			temperature range' fully activated			skills' fully activated			pressures' fully activated			temperature range' fully activated			skills' fully activated		
	Base run 2	Sensitivity test	Change	Base run 22	Sensitivity test 2	Change 2	Base run 24	Sensitivity test3	Change 3	Base run 26	Sensitivity test 4	Change 4	Base run 28	Sensitivity test 5	Change 5	Base run 210	Sensitivity test6	Change 6
Ability to secure a sustainable livelihood	0.815	-0.824	0.009	-0.153	-0.077	-0.076	-0.447	-0.438	-0.009	0.258	0.189	0.069	0.245	0.215	0.030	-0.069	-0.027	-0.042
Access to capital (savings/investments/retirement income/loans)	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.604	0.635	-0.031	0.000		0.000
Access to craft	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.400	0.443	-0.043	0.000		0.000
Alternative employment opportunities	0.604	-0.635	0.031	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000			0.000
Available sea days	0.000		0.000	-0.196	-0.135	-0.061	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000
Commercial alternative landings	0.000		0.000	-0.161	-0.114	-0.047	-0.198	-0.178	-0.020	0.311	0.216	0.095	0.295	0.338	-0.043	-0.032	-0.018	-0.014
Commercial kob landings	0.000		0.000	-0.073	-0.044	-0.029	-0.536	-0.558	0.022	0.148	0.155	0.007	0.139	0.143	-0.004	-0.014	-0.007	-0.007
Conflict between inshore trawl and linefishery	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000
Current strength	0.000		0.000	0.291	0.245	0.046	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000

Deterioration in sea state	0.000		0.000	0.283	0.182	0.101	0.000		0.0	0.000		0.000	0.000		0.000	0.000		0.000
Duration of fishing season	0.000		0.000	0.000		0.000	0.000		0.0	0.604	0.635	-0.031	0.000		0.000	0.000		0.000
Ecosystem health	0.000		0.000	0.098	0.075	0.023	-0.206	-0.278	0.1	0.189	-0.235	0.046	0.180	-0.221	0.041	0.020	0.012	0.008
Income (fishing)	-0.743	-0.725	0.018	-0.135	-0.071	0.064	-0.480	-0.470	0.0	0.263	0.192	0.071	0.249	0.219	0.030	-0.027	-0.011	-0.016
Inshore trawl: effect on reef (habitat degradation)	0.000		0.000	0.000		0.000	0.000		0.0	0.000		0.000	0.000		0.000	0.000		0.000
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and highgrading)	0.000		0.000	0.000		0.000	0.000		0.0	0.000		0.000	0.000		0.000	0.000		0.000
Income (other sources)	-0.400	-0.443	0.043	-0.018	-0.006	0.012	0.000		0.0	0.000		0.000	0.000		0.000	-0.042	-0.015	-0.027
Injury at sea	0.000		0.000	0.025	0.011	0.014	0.000		0.0	0.000		0.000	0.000		0.000	0.060	0.030	0.030
Input costs (running costs and equipment for fishing)	0.762	0.762	0.000	0.000		0.000	0.000		0.0	0.000		0.000	0.000		0.000	0.000		0.000
Kob abundance	0.000		0.000	0.140	0.100	0.040	-0.299	-0.380	0.1	0.274	0.320	0.046	0.259	-0.299	0.040	0.028	0.016	0.012
Physical navigation dangers (river mouths)	0.000		0.000	0.000		0.000	0.000		0.0	0.000		0.000	0.000		0.000	0.291	0.245	0.046
Price of kob and other target species (price setting by fish mongers)	-0.000	-0.462	0.142	0.070	0.039	0.031	0.217	0.182	0.035	-0.000	-0.093	0.044	-0.000	-0.120	0.009	0.014	0.006	0.008

	60									13			12					
	4									7			9					
Unsafe operating conditions	0.000		0.000	0.085	0.045	0.040	0.000		0.000	0.000		0.000	0.000		0.000	0.201	0.122	0.079
Wave height	0.000		0.000	0.291	0.245	0.046	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000
	Convergence Value																	
	Commercial kob landings' fully activated			Commercial alternative landings' fully activated			Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated			Income (fishing)' fully activated			Kob abundance' fully activated			Sector-specific policy implementation' fully activated		
Component Affected	Base run 2	Sensitivity test	Column 1	Base run 22	Sensitivity test 2	Sensitivity test 22	Base run 24	Sensitivity test 3	Sensitivity test 3 2	Base run 26	Sensitivity test 4	Sensitivity test 42	Base run 28	Sensitivity test 5	Sensitivity test 52	Base run 21 0	Sensitivity test 6	Sensitivity test 7
Ability to secure a sustainable livelihood	0.479	0.538	-0.059	0.429	0.297	0.132	-0.388	-0.360	-0.028	0.762	0.762	0.000	0.480	0.496	-0.016	0.472	0.426	0.046
Access to craft	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.540	0.562	-0.022
Access to DFFE	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.291	0.245	0.046
Access to rights	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.000		0.000	0.604	0.635	-0.031
Commercial alternative landings	-0.000	-0.377	-0.057	1.000	1.000	0.000	-0.048	-0.057	0.009	0.000		0.000	-0.000	-0.032	-0.015	0.464	0.478	-0.014

	43 4											04 7						
Commercial kob landings	0. 00 0		0.00 0	0. 00 0		0.00 0	- 0.5 19	- 0.466	- 0.053	0. 00 0		0.00 0	0. 76 2	0.76 2	0.00 0	0. 42 3	0.41 8	0.00 5
Conflict between inshore trawl and linefishery	0. 00 0		0.00 0	0. 00 0		0.00 0	0.7 62	0.762	0.000	0. 00 0		0.00 0	0. 00 0		0.00 0	- 0. 90 1	- 0.89 9	- 0.00 2
Ecosystem health	- 0. 54 9	- 0.58 5	0.03 6	0. 00 0		0.00 0	- 0.6 78	- 0.693	0.015	0. 00 0		0.00 0	0. 60 4	0.63 5	- 0.03 1	0. 29 6	0.25 2	0.04 4
Income (fishing)	0. 52 2	0.60 2	- 0.08 0	0. 45 9	0.30 6	0.15 3	- 0.4 10	- 0.377	- 0.033	0. 00 0		0.00 0	0. 52 3	0.54 4	- 0.02 1	0. 51 2	0.45 5	0.05 7
Inshore trawl: effect on reef (habitat degradation)	0. 00 0		0.00 0	0. 00 0		0.00 0	0.6 04	0.635	- 0.031	0. 00 0		0.00 0	0. 00 0		0.00 0	- 0. 32 1	- 0.33 8	0.01 7
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0. 00 0		0.00 0	0. 00 0		0.00 0	0.0 00		0.000	0. 00 0		0.00 0	0. 00 0		0.00 0	- 0. 47 5	- 0.46 9	- 0.00 6
Kob abundance	- 0. 88 2	- 0.89 3	0.01 1	0. 00 0		0.00 0	- 0.5 75	- 0.504	- 0.071	0. 00 0		0.00 0	0. 00 0		0.00 0	0. 11 6	0.00 6	0.11 0
Minimum catch (size) limits for kob	0. 00 0		0.00 0	0. 00 0		0.00 0	0.0 00		0.000	0. 00 0		0.00 0	0. 00 0		0.00 0	0. 29 1	0.24 5	0.04 6
Price of kob and other target species (price setting by fish mongers)	- 0. 16 8	- 0.15 5	- 0.01 3	- 0. 29 1	- 0.24 5	- 0.04 6	0.1 69	0.130	0.039	0. 00 0		0.00 0	- 0. 21 1	- 0.18 0	- 0.03 1	- 0. 26 0	- 0.22 0	- 0.04 0
Surveillance (patrol vessels/aerial)	0. 00 0		0.00 0	0. 00 0		0.00 0	0.6 04	0.635	- 0.031	0. 00 0		0.00 0	0. 00 0		0.00 0	0. 35 2	0.37 9	- 0.02 7

In the third test, the initial categories used to determine if a relationship was low, medium, or high were altered. Specifically, the low quantification was adjusted from ± 0.3 to ± 0.25 , low medium to ± 0.5 , high medium to ± 0.75 , and high remained at ± 1

Table 44: Regional Prototype Model Quantification Category Sensitivity Test 3

Component Affected	Convergence Value																	
	External economic pressures' fully activated			Wind Strength' fully activated			Prevailing sea surface temperature range' fully activated			Wind events that drive upwelling' fully activated			Specific financial management skills' fully activated			Variability in rainfall patterns' fully activated		
	Base run 2	Sensitivity test	Change	Base run 22	Sensitivity test 2	Change 2	Base run 24	Sensitivity test3	Change 3	Base run 26	Sensitivity test 4	Change 4	Base run 28	Sensitivity test 5	Change 5	Base run 210	Sensitivity test 6	Change 6
Ability to secure a sustainable livelihood	-0.815	-0.824	0.009	-0.153	-0.128	-0.025	-0.447	-0.484	0.037	0.258	0.178	0.080	0.245	0.206	0.039	-0.069	-0.096	0.027
Access to capital (savings/investments/retirement income/loans)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.604	0.635	-0.031	0.000	0.000	0.000
Access to craft	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.443	-0.043	0.000	0.000	0.000	0.000
Alternative employment opportunities	-0.604	-0.635	0.031	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Available sea days	0.000	0.000	0.000	-0.196	-0.210	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Commercial alternative landings	0.000	0.000	0.000	-0.161	-0.168	0.007	-0.198	-0.225	0.027	0.311	0.179	0.132	0.295	0.306	-0.011	-0.032	-0.061	0.029
Commercial kob landings	0.000	0.000	0.000	-0.073	-0.073	0.000	-0.536	-0.634	0.098	0.148	0.155	-0.007	0.139	0.143	-0.004	-0.014	-0.026	0.012
Conflict between inshore trawl and linefishery	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Current strength	0.000	0.000	0.000	0.291	0.245	0.046	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Deterioration in sea state	0.000	0.000	0.000	0.283	0.284	-0.001	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Duration of fishing season	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.604	0.635	-0.031	0.000	0.000	0.000	0.000	0.000	0.000
Ecosystem health	0.000	0.000	0.000	0.098	0.122	-0.024	-0.206	-0.184	0.0	-0.189	-0.235	0.046	-0.180	-0.221	0.041	0.020	0.044	-0.024
Income (fishing)	-0.743	-0.725	-0.018	-0.135	-0.112	-0.023	-0.480	-0.529	0.0	0.263	0.180	0.083	0.249	0.210	0.039	-0.027	-0.040	0.013
Inshore trawl: effect on reef (habitat degradation)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Income (other sources)	-0.400	-0.443	-0.043	-0.018	-0.018	-0.000	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	-0.042	-0.056	0.014

Injury at sea	0.000	0.000	0.000	0.025	0.035	-0.010	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.060	0.113	-0.053
Input costs (running costs and equipment for fishing)	0.762	0.762	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kob abundance	0.000	0.000	0.000	0.140	0.163	-0.023	-0.299	-0.249	-0.1	0.274	-0.320	0.046	0.259	-0.299	0.040	0.028	0.059	-0.031
Physical navigation dangers (river mouths)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.462	-0.171
Price of kob and other target species (price setting by fish mongers)	-0.604	-0.462	-0.142	0.070	0.060	0.010	0.217	0.212	0.005	0.137	-0.083	-0.054	0.129	-0.112	-0.017	0.014	0.022	-0.008
Unsafe operating conditions	0.000	0.000	0.000	0.085	0.071	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.201	0.227	-0.026
Wave height	0.000	0.000	0.000	0.291	0.462	-0.171	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Convergence Value																	
	Commercial kob landings' fully activated			Commercial alternative landings' fully activated			Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)' fully activated			Income (fishing)' fully activated			Kob abundance' fully activated			Sector-specific policy implementation' fully activated		
Component Affected	Base run 2	Sensitivity test	Column 1	Base run 22	Sensitivity test 2	Sensitivity test 22	Base run 24	Sensitivity test 3	Sensitivity test 3 2	Base run 26	Sensitivity test 4	Sensitivity test 42	Base run 28	Sensitivity test 5	Sensitivity test 52	Base run 21 0	Sensitivity test 6	Sensitivity test 7

Ability to secure a sustainable livelihood	0.479	0.509	-0.030	0.429	0.297	0.132	-0.388	-0.332	-0.056	0.762	0.762	0.000	0.480	0.463	0.017	0.472	0.432	0.040
Access to craft	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.540	0.562	-0.022
Access to DFFE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.462	-0.171
Access to rights	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.604	0.635	-0.031
Commercial alternative landings	-0.434	-0.569	0.135	0.000	0.000	0.000	-0.048	0.059	-0.107	0.000	0.000	0.000	-0.047	-0.218	0.171	0.464	0.391	0.073
Commercial kob landings	0.000	0.000	0.000	0.000	0.000	0.000	-0.519	-0.466	-0.053	0.000	0.000	0.000	0.762	0.762	0.000	0.423	0.462	-0.039
Conflict between inshore trawl and linefishery	0.000	0.000	0.000	0.000	0.000	0.000	0.762	0.762	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.901	-0.914	0.013
Ecosystem health	-0.549	-0.585	0.036	0.000	0.000	0.000	-0.678	-0.693	0.015	0.000	0.000	0.000	0.604	0.635	-0.031	0.296	0.327	-0.031
Income (fishing)	0.522	0.561	-0.039	0.459	0.306	0.153	-0.410	-0.345	-0.065	0.000	0.000	0.000	0.523	0.501	0.022	0.512	0.462	0.050
Inshore trawl: effect on reef (habitat degradation)	0.000	0.000	0.000	0.000	0.000	0.000	0.604	0.635	-0.031	0.000	0.000	0.000	0.000	0.000	0.000	-0.321	-0.393	0.072
Inshore trawl: IUU fishery practices (fishing too close to the coast, targeting bycatch and high grading)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.475	-0.553	0.078

Kob abundance	- 0. 88 2	- 0.89 3	0.0 11	0. 00 0	0.00 0	0.00 0	- 0.5 75	- 0.50 4	- 0.071	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 11 6	0.06 0	0.05 6
Minimum catch (size) limits for kob	0. 00 0	0.00 0	0.0 00	0. 00 0	0.00 0	0.00 0	0.0 00	0.00 0	0.000	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 29 1	0.24 5	0.04 6
Price of kob and other target species (price setting by fish mongers)	- 0. 16 8	- 0.10 7	- 0.0 61	- 0. 29 1	- 0.24 5	- 0.04 6	0.1 69	0.10 1	0.068	0. 00 0	0.00 0	0.00 0	- 0. 21 1	- 0.13 5	- 0.07 6	- 0. 26 0	- 0.21 0	- 0.05 0
Surveillance (patrol vessels/aerial)	0. 00 0	0.00 0	0.0 00	0. 00 0	0.00 0	0.00 0	0.6 04	0.63 5	- 0.031	0. 00 0	0.00 0	0.00 0	0. 00 0	0.00 0	0.00 0	0. 35 2	0.52 6	- 0.17 4