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Exploring the Social-Ecological System Connectivity of a Small-Scale Coral Reef Fisheries: The Case of Ranobe Bay, Madagascar

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ABSTRACT
On the southwest coast of Madagascar, the small-scale coral reef fisheries (SSCRFs) play a crucial role in local fishing communities' daily lives and economy. Understanding all about the components of these SSCRFs, the nature of their interactions, and the resulting outcomes is crucial for designing policies that promote equitable and sustainable fisheries. This research aims to explore the SES structure and the characteristics of Ranobe Bay CRFs in Madagascar, using the Social-Ecological Systems (SES) framework and network analysis. We conducted this research from September to October 2024, requiring primary data from field observations, interviews involving the fisheries stakeholders, and secondary data from literature studies. We carried out the Socio-Ecological Network Analysis (SENA) to analyze the connectivity of the CRFs in this region. The research findings of the SENA results showed that this fishery is heavily centered around the fishermen's community: the Masikoro and the Vezo as the main actors of this activity. Nevertheless, the clustering analysis reveals a high number of clusters, highlighting a fragmented SES structure and low system connectivity. Ranobe Bay's CRFs' sustainability depends on fishermen's central connectivity within the network, which can be strengthened through improved policies and management to ensure effective governance.

Keywords: Madagascar, Ranobe Bay, Small-Scale Coral Reef Fisheries (SSCRFs), Social-Ecological Network Analysis (SENA), Social-Ecological System (SES)

INTRODUCTION

In tropical coastal locations, especially in the Global South, small-scale coral reef fisheries (SSCRFs) are essential for livelihoods, food security, and cultural identity (Pauly and Zeller, 2016; Cinner *et al.* 2016; FAO 2020). One of the most biodiverse marine habitats in the Western Indian Ocean (WIO) region is Madagascar, an island that is home to several small-scale coral reef fishermen due to its enormous coral reef systems (Harris 2011; Cripps and Gardner, 2016). An artisanal fishing community that mostly relies on CRF for revenue and subsistence is based in the South-West region of Madagascar, specifically in the Ranobe Bay coastal area. A complex Social-Ecological System (SES) with intricately intertwined ecological and social components is exemplified by the small-scale fisheries (SSFs) (Adrianto 2023), including CRFs (Cinner *et al.* 2009). However, they are also extremely vulnerable to external pressures, such as coastal development, climate change, and unsustainable harvesting practices, which threaten marine biodiversity and the local communities that depend on it (Hicks *et al.* 2016; Hughes *et al.* 2017; IPCC 2021). A multidisciplinary SES strategy that incorporates social and ecological aspects to advance sustainability is necessary to address these issues (Berkes *et al.* 2003; Ostrom 2009). The intricacies of social-ecological interactions have frequently been overlooked by the conventional command-and-control methods of fisheries management (Westley *et al.* 2002). To better understand and manage coastal and marine resources, academics have increasingly resorted to integrated frameworks, like the SES approach, in recognition of these enduring problems (Folke *et al.* 2003). This viewpoint emphasizes the need for comprehensive governance measures by highlighting the dynamic and interrelated links between human populations and marine ecosystems (Ostrom 2009). The SES framework enables a nuanced investigation of how ecological changes impact human behavior and vice versa (Cumming 2011) by providing insights into adaptive governance mechanisms that can improve sustainability.

In recent years, Social-Ecological Network Analysis (SENA) has become a potent instrument for studying the structural characteristics of SES. It enables researchers to map the connections between stakeholders, governance institutions, and ecological resources (Bodin and Crona, 2009; Sayles and Baggio, 2017). In fisheries management, network techniques offer insights into resilience, adaptive capacity, and vulnerabilities by examining the connectedness and interactions between various system components (Barnes *et al.* 2019). The WIO region's small-scale CRFs, where socioeconomic and ecological interactions are especially complex and dynamic, still lack a substantial application of SENA, even though it has been used more and more for fisheries governance and marine resource management (Wamukota *et al.* 2017; Cinner and Barnes, 2019). Although these fisheries are ecologically and economically important, there has been little research on how the social and ecological connections within the system shape its resilience and sustainability. A complex combination of national legal frameworks, community-based conservation programs, and traditional resource management characterizes the governance of Ranobe Bay's fisheries (Westerman and Gardner, 2013; Benbow *et al.* 2014). Socioeconomic disparities, a lack of institutional support, and the division of governance players hamper effective fisheries management. Finding leverage points that can improve sustainability and adaptive capability requires an understanding of the structural connections among fishers, governance institutions, and ecological resources.

To examine the relationships within the Ranobe Bay fishing system, a network-based viewpoint is especially helpful (Mahon and McConney, 2013). Fishermen, traders, and other stakeholders' social networks have an impact on knowledge sharing, resource access, and decision-making (Bodin and Crona, 2009). Similarly, the resilience and productivity of the fishery are shaped by ecological networks, which include habitat connectivity and species interactions (Janssen *et al.* 2006). By mapping these networks, researchers can identify key actors, governance gaps, and potential intervention points to strengthen resource management efforts (Carlsson and Sandström, 2008). Designing policies supporting fair and sustainable fisheries requires understanding these relationships. This research aims to explore the structure and key features of the SES-CRFs in Ranobe Bay by applying the SES framework and network analysis. By providing useful suggestions for enhancing fisheries management in Madagascar, the findings will aid in the creation of policies that strike a balance between the ecological system and the socioeconomic dynamics of the SES-CRFs.

MATERIAL AND METHOD

Research Time and Location

This research was carried out from September to October 2024 in the coastal village of Ranobe Bay, in the southwest region of Madagascar, where the coral reef fishing activity is mainly centered (Figure 1).

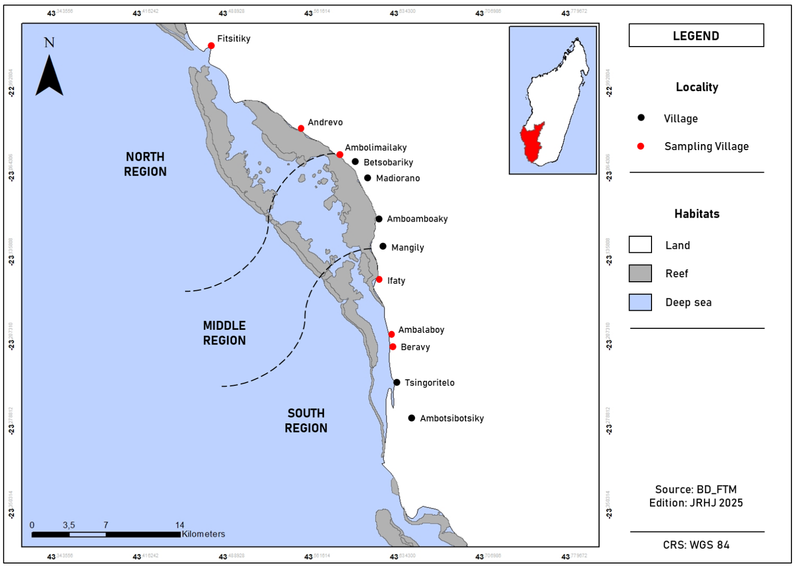

Figure 1. Research Location Map

Located along the Mozambique Channel between 22°25' to 22°55' S latitude and 43°00' to 43°30' E longitude, Ranobe Bay is a coastal region in Madagascar, covering an area of approximately 400 to 450 km², depending on the ecological boundaries applied (Harris 2007). The bay is located in the broader Toliara region, where the landscape and means of subsistence are shaped by the semi-arid climate and seasonal monsoons. It is well-known for its varied marine environments, which sustain a thriving fishing industry. Ranobe Bay is composed of 13 coastal villages, namely Fitsitiky, Andrevo, Ambolimailaky, Betsibaroky, Madiorano, Amboaboaky, Mangily, Ifaty, Ambalaboy, Beravy, Tsingoritelo, Ambotsibotsiky, and

Belitsaky. It is an essential environment for marine biodiversity, including a variety of fish species, sea turtles, and other animals that depend on reefs because it is home to large coral reefs, seagrass beds, and mangroves. This environment provides benefits for the fishermen's community, which relies heavily on the coral reef ecosystems. Indeed, traditional sailing pirogues and hand-line fishing are still the main sources of income for the local fishing community. However, the bay is subject to a growing number of environmental stresses, such as sedimentation brought on by deforestation and coastal expansion, climate change, and coral reef deterioration brought on by overfishing.

Research Framework

The SES represents the holistic approach of integrating both human and natural systems in the analysis, and the "Butterfly Model" (Higgins *et al.* 2020) likely illustrates the interconnections between different components of the system, emphasizing their interdependence and the need for a holistic approach (Figure 2).

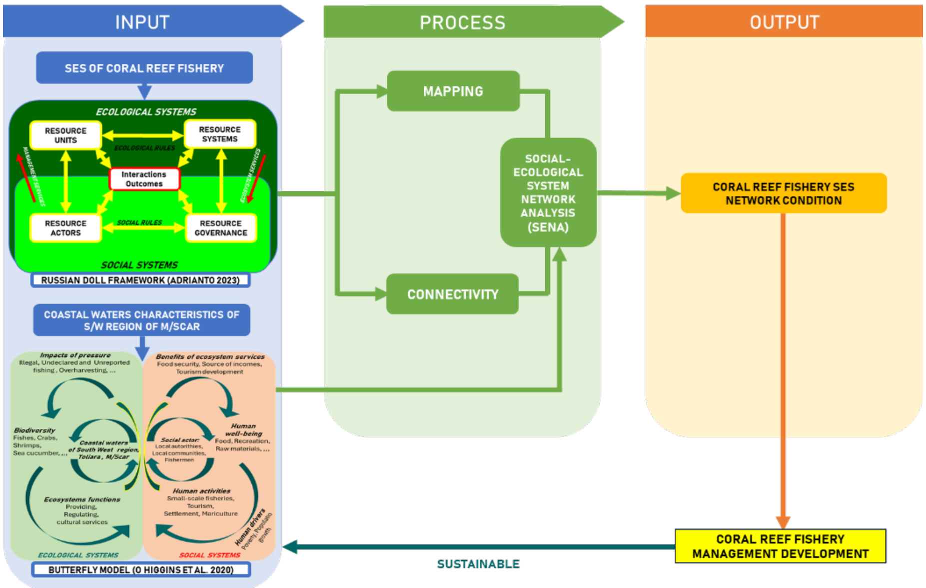

Figure 2. Research Framework Conceptualization

Our primary objective was to evaluate the condition of the CRFs in Madagascar's southwest while considering the sector's socio-ecological environment. Data and information regarding the fishing system, including its natural and human components, were gathered for this procedure. The second objective was to understand the connection within the SES, we employed the Social-Ecological Network Analysis (SENA) frameworks using the gathered SES components mapping data. This analytical method made it easier to create the conceptual model that systematically depicts the network topology, interaction dynamics, and functional linkages between the main CRFs system components. Therefore, to give a numerical assessment of their importance and strength, this research looked at the connection patterns and network indicators between ecological and social actors. Enhancing our knowledge of resource sustainability, governance, and the resilience of CRFs can help us develop conservation and management plans that can be more successful.

Data Collection

The data collection procedure was undertaken in six coastal villages of Ranobe Bay: Fitsitiky, Andrevo, Ambohilimailaky, Ifaty, Ambalaboy, and Beravy. These sites were chosen because CRFs are the main livelihood activity, ensuring a real focus on the social-ecological dynamics that sustain local fisheries. Both primary and secondary data sources had to be gathered and analyzed for the study (Table 1).

Table 1. Data collection process

Objective	Parameters	Data Sources	Methods
Socio-ecological system (SES) mapping related to coral reef fisheries (CRF) in the South-West region of Madagascar	Resource Systems (RS), Resource Units (RU), Resource Actors (RA), Resource Governance (RG), Interactions (I), Outcomes (O), and External Factors (EF).	Primary and secondary data	-Interviews, on-site observation, Focus Group Discussions (FGDs) with stakeholders -Documentation (strategic and technical documents, institutional and juridical tools)

Assessment of the connectivity network related to the CRF taking into account the social-ecological context of the sector	-Basic Conceptual model: nodes, edges -Network connectivity: centrality degree (Cd), centrality betweenness (Cb), centrality cluster (Cc), Hubs and Authorities	Primary data	-Interviews, FGDs

The data collection encompassed the coral reef fisheries activity in this area. The selection of research locations during primary data collection was determined by field observations and interviews with respondents purposively selected based on criteria to understand the coral reef fisheries dimensions so that the data obtained are more informative according to the research objectives (Puspitawati *et al.* 2022). The primary data were obtained through interviews and Focus Group Discussions (FGDs) with the concerned respondents and the secondary data were obtained through literature studies and the availability of documents from various supporting sources. The interviews were conducted with a total of 90 respondents from all of the sampling villages, including fishermen, the local community, the chief village, Non-governmental organizations (NGOs), and government institutions to identify the interconnections among components of the SES. These initial observations and interviews are conducted simultaneously with all of the respondents. The FGDs were also conducted as a confirmatory technique per village with a several size of 15 respondents per village.

Data Analysis

The data analysis components of this research used indicators from the social-ecological system (Ostrom 2009; Biggs *et al.* 2021; Kusuma *et al.* 2024). Thereby, it is possible to depict the model of the SES based on the elements and interactions that take place inside the system network by effectively mapping the system and the interconnection value of coral reef fisheries in Ranobe Bay following the SES framework. To address the goal of this research, three steps are taken in the analysis of the data components: the first step was to identify every element (system and subsystem) that makes up the social-ecological system; in the second step, the mapping findings of the SES components served as the foundation for discussion which attempts to confirm the fundamental conceptual network created by. In the third step, the connectivity analysis was conducted using the basic conceptual network of links among all the SES components as input to determine the value of connectivity of each part of the socio-ecological system of the CRFs in Ranobe Bay.

Mapping of the social-ecological system components

According to Kluger *et al.* (2015), the process of mapping the natural and human dimensions involves identifying components with differing degrees of complexity and importance, necessitating accuracy. The identification of the socio-ecological system involved mapping all the components of the Resource Systems (RS), Resource Units (RU), Resource Actors (RA), and Resource Governance (RG), including also the Interactions (I) between the components, the Outcomes, and the External Factors (EF) (Kusuma *et al.* 2024). This identification process was carried out through interviews and observations, where the subsystem components were grouped or scoped to describe and depict the condition of the social-ecological system of CRFs in Ranobe Bay (Kusuma *et al.* 2024). After identification, the mapping visualization of all components and their relative interactions was derived using DIA software (available from http://live.gnome.org/Dia).

Developing the basic conceptual network model

The basic network concept was developed using the interview data inventory process (Baird *et al.* 2014), which aims to gain a general perspective in mapping the basic network model. To increase consistency and lower errors, the basic network was shown during Focus Group Discussions (FGDs) as a confirmatory technique. FGDs with 15 respondents per village including fishermen, the head of an association, a village official, and a community leader were used to conduct the confirmation steps. The link between all of the components is examined in the FGDs questions. They look at whether a connection exists, what kind of relationship it is, how each respondent views it, and how it is doing right now. After confirmation and revision, the basic network conceptual model was derived using R-Studio software, employing the “igraph” package and the “scale” function (Csardi and Nepusz, 2006), with the DIA mapping file serving as the primary data source.

Analysis of the system connectivity

The substance of this analysis is to examine the relationships formed within a relation between subsystem components (Kusuma *et al.* 2024). So, the Social-Ecological Network Analysis (SENA) was used to analyze the patterns of interaction in each relationship by evaluating the connectedness of the components in the social-ecological system with the help of the R-Studio application (R Core Team 2021). To read the basic network input from the DIA file (available from https://bit.ly/GitHub-SENA), the analysis was done using R software with the aid of the "igraph" and "scale" packages (Csardi and Nepusz, 2006).

The components of the analysis should be arranged into a folder within the working directory of R-Studio algoritm modification using the framework of Melbourne-Thomas *et al.* (2012) for the community matrix and function matrix analysis.

For this analysis, the attributes of the system's connectivity evaluated include network size in the form of nodes, density in the form of edges, centrality in the form of degree centrality and betweenness, and eigenvector centrality values in the form of hubs and authorities, as well as community detection or clustering (Luke 2015; Biggs *et al.* 2021).

Calculating the value total of "Centrality Degree" (Cd) is estimated algoritm adoption using the following formula (Biggs *et al.* 2021; Munawar 2021):

$$C_d(n_i) = \frac{\sum_1^j e_{ij}}{N-1} \qquad (1)$$

Where Cd(ni) of corresponds to the centrality degree on the network, j represents the number of connected nodes in this network, N is the total number of nodes in the system, and $^e ij$ is the edge between the i-th node and the j-th node.

The value total of "Centrality Betweenness" (Cb) is estimated using the following formula (Biggs *et al.* 2021; Munawar 2021):

$$Cb\ (ni) = \sum g_{jk\ (ni)} / gjk \qquad (2)$$

Where Cb(ni) represents the centrality betweenness of this node in the network (edgepoint), $\sum g_{jk\ (ni)}$ the number of shortest paths through the *ni node* and *gjk* the total number of shortest paths between the j-th node and the k-th node.

"Community Detection" is estimated using the "Centrality Cluster" value based on the following formula) where Cc(ni) is the centrality cluster (group), d(ni,nj) representing the distance between *ni* and nj nodes, and N is the number of *nodes* contained in the network (Setatama and Tricahyono 2017; Biggs *et al.* 2021):

$$Cc\ (ni) = \frac{N-1}{\sum_{j \neq i}^{n} d(ni,nj)} \qquad (3)$$

"Hub" value is a measure that quantifies the number of links from a node to other nodes in the network. Nodes with high hub centrality are considered to be significant sources of information (Newman 2010). This centrality metric emphasizes outgoing links from a node, calculated using the following formula (Luke 2015):

$$AA^t\ y = \lambda y \qquad (4)$$

"Authorities" value is a measure that quantifies the number of links from other nodes to a specific node in the network. Nodes with high authority centrality are considered beneficiaries, indicating their importance in receiving information or influence from other nodes (Newman 2010). This centrality metric focuses on incoming links to a node, calculated using the following formula (Luke 2015):

$$A^t A x = \lambda x \qquad (5)$$

where A refers to the adjacency matrix, A^t represents the transpose matrix, represents the largest eigenvalue, y represents the eigen vector of hubs, and x represents the eigenvector of authorities.

RESULT AND DISCUSSION

Results

Social-Ecological System Components Mapping

The results of the research on the identification of the SES elements of CRFs Ranobe Bay are laid out in this table as follows (Table 2).

Table 2. Social-ecological system components keys of Ranobe Bay's CRFs

Components	Symbol	Sub-systems
Socio-Economic Political Setting (S)	S1	Conditions of Small-Scale CRF
	S2	Community Welfare
	S3	Fishery Regulations
Resources Systems (RS)	RS1	Ranobe Bay Ecosystem Services: Coral Reefs (CoRf)
	RS2	System Boundaries: Ranobe Bay (RaBa)
	RS3	Natural Habitat Area (NtAr)
	RS4	Artificial System Area (AtAr)
	RS5	Threats of Ranobe Bay Coral Reef Ecosystem (Thrt)

	RS6	Fishing Ground (FiGd)
	RS7	Water Quality (WtQl)
Resource Units (RU)	RU1	*Octopus* spp. (Octo)
	RU2	Fish Resources (FiRe)
	RU3	Target Fish Commodities (TgFi)
	RU4	Fishing Gears (FGear)
	RU5	Fish Distribution (FiDb)
	RU6	Markets (Mrkt)
	RU7	Fish Prices (FiPr)
	RU8	Trip Cost (Tpct)
Resources Actors (RA)	RA1	VEZO community (Vezo)
	RA2	MASIKORO community (Mskr)
	RA3	Collectors (Clctr)
	RA4	Fishmongers (Fmgr)
	RA5	DRPEB Technicians (RTch)
	RA6	Village Head (SefoFKT)
	RA7	Associations and NGOs (NGOs)
	RA8	Revenues (Rvne)
	RA9	Incomes (Incm)
Resources Governance (RG)	RG1	MPEB: National Level
	RG2	DRPEB: Regional Level
	RG3	Fokontany (FKT): Village level
	RG4	Community-Managed Marine Reserve (CMMR)
	RG5	Law No 2015-053/2018-26 : Code de la Pêche et de l'Aquaculture (CPA)
	RG6	Ministerial Decree (MDec)
	RG7	Traditional Law Enforcement: DINA
Interactions (I)	I1	Catch Dynamics (CtDm)
	I2	Conflicts (Cftl)
	I3	Conservation Efforts (CEff)
Outcomes (O)	O1	Socio-Economic Conditions (SECd)
	O2	Environmental Quality (EnQl)
External Factors (EF)	EF1	Climate Patterns (Clmp)
	EF2	Pollutions Patterns (PolP)
	EF3	Population Growth (PoGr)

The SES methodology for the assessment of CRFs in Ranobe Bay, South-West region of Madagascar, categorizes key elements and their interactions, grouped into sub-systems influencing sustainability and management. The Socio-Economic and Political Setting (S) defines the broader context affecting small-scale fisheries. Key factors include the economic viability of CRFs, resource access, and community dependence on fishing (S1). The well-being of local communities is also critical, encompassing livelihoods, health, and socio-economic stability (S2). Furthermore, fishery regulations, including legal and policy frameworks, play a significant role in shaping sustainability resource use (S3).

The Resource System (RS) represents the physical and ecological aspects of Ranobe Bay's fisheries. Coral reefs provide essential ecosystem services, including marine habitat support, coastal protection, and tourism (RS1). The system's geographical and ecological limits define its operational boundaries (RS2). Within the bay, the natural habitat areas (RS3) support biodiversity, while artificial system areas (RS4) include aquaculture zones and artificial reefs. However, threats such as overfishing, coral bleaching, and habitat destruction pose significant risks to ecosystem stability (RS5). Fishing grounds (RS6) are critical operational zones for fishers, and the overall water quality (RS7) influences marine productivity.

The Resource Units (RU) category focuses on marine resources and the economic aspects of the fishery. Octopus species (RU1) are a key target for both local consumption and export, while diverse fish resources (RU2) support the community. Commercially valuable fish commodities (RU3) drive the local economy, with various fishing gears (RU4) employed, such as nets, traps, and spears. Fish distribution networks (RU5) and markets (RU6) determine trade dynamics, influenced by fish prices (RU7), which fluctuate based on demand, seasonality, and external markets. The costs incurred per fishing trip (RU8) further shape economic sustainability.

The Resource Actors (RA) are the different groups of people involved in fishing activities around Ranobe Bay. The Vezo community (RA1) is the main fishing group, well known for their deep connection to the sea and their traditional fishing knowledge. The Masikoro community (RA2), who were traditionally farmers, now also fish and are actively involved in trade. The Collectors (RA3) help move the fish from the shore to markets or buyers, while fishmongers (RA4), often including fisherwomen, are responsible for the distribution and selling of the fish locally. Government staff, like technicians from the regional fisheries department (DRPEB) (RA5), help manage and monitor fishing activities. Local leaders, such as village heads (RA6), play an important role in solving problems, making decisions, and keeping order in the community. Fishermen's cooperatives and local organizations (RA7) support sustainable fishing, offer training, and work with NGOs on conservation projects. Finally, economic factors like shared revenues (RA8) and people's daily earnings (RA9) directly affect how families make a living and how much they rely on fishing.

The Resource Governance (RG) section includes institutions and policies regulating fisheries. National oversight is managed by MPEB (RG1), with regional implementation by DRPEB (RG2). Local governance occurs at the Fokontany level (RG3), complemented by community-managed marine reserves (RG4) for conservation. Legal frameworks such as Law No. 2015-053/2018-26 (RG5) and ministerial decrees (RG6) establish regulatory guidelines, while traditional law enforcement (RG7) ensures compliance through customary practices. This research generates a visualization mapping network for all SES-CRFs components in Ranobe Bay (Figure 3).

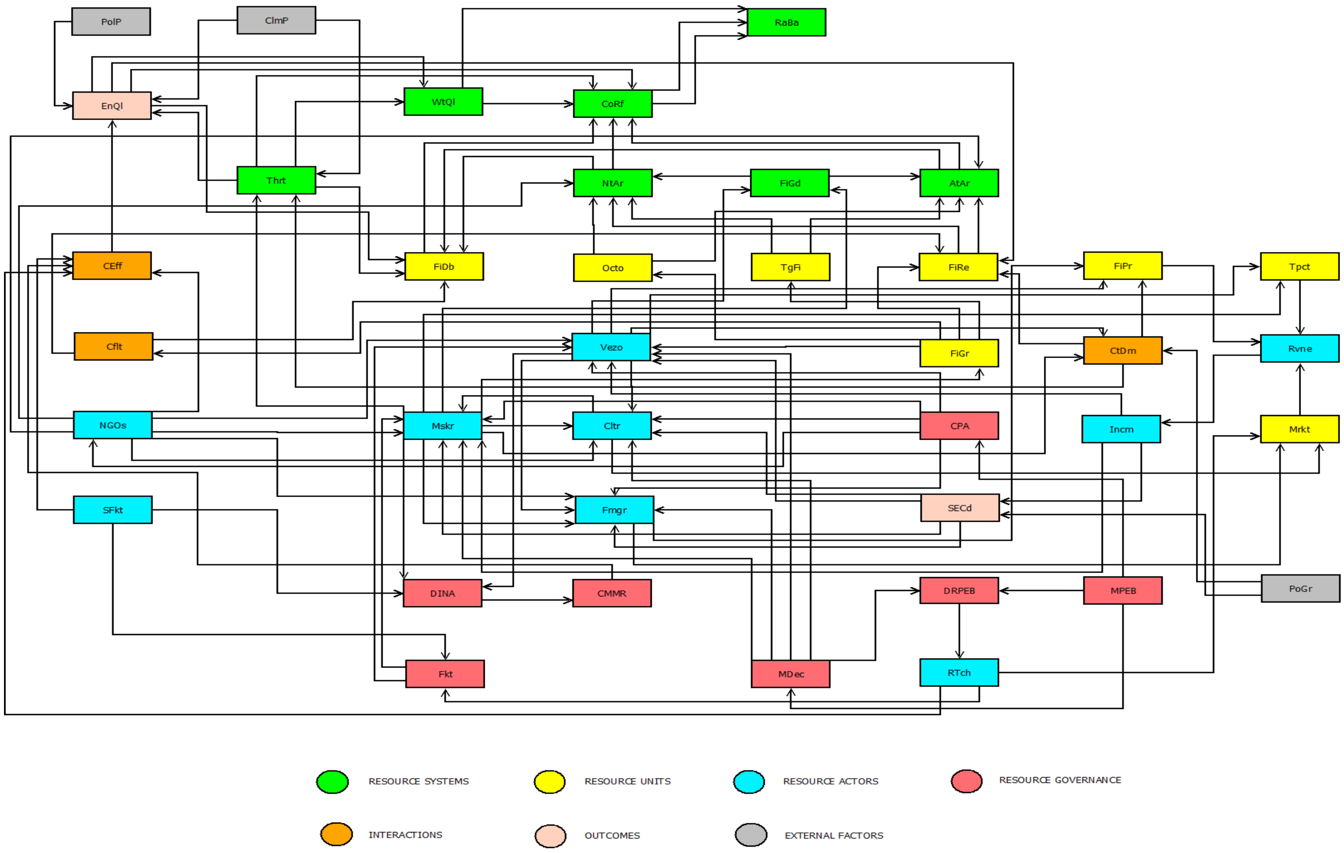

Figure 3. SES mapping undirected model of CRFs in Ranobe Bay

The Interactions (I) within the system include catch dynamics (I1), which track stock availability, fishing intensity, and seasonal variations. Conflicts (I2) arise over resource access and governance disputes, while conservation efforts (I3) focus on protecting biodiversity and promoting sustainable fishing. The Outcomes (O) reflect socio-ecological conditions, including socio-economic stability (O1) and environmental quality (O2), which assess coral reef health, water conditions, and biodiversity status. Finally, External Factors (EF) influence the system beyond local control. Climate patterns (EF1) affect fish stocks and fishing activities, while pollution (EF2) from agricultural runoff, plastic waste, and industrial discharge threatens water quality. Population growth (EF3) increases pressure on fisheries due to demographic expansion and migration. These interconnected components collectively determine the sustainability and resilience of Ranobe Bay's coral reef fisheries. Connectivity in fisheries requires an interdisciplinary approach to embrace the complexity of SES interconnects as nodes and edges in nature and human components.

Resource Systems are labeled Ranobe Bay Ecosystem Services: Coral Reefs (CoRf), System Boundaries: Ranobe Bay (RaBa), Natural Habitat Area (NtAr), Artificial System Area (AtAr), Threats of Ranobe Bay, Coral Reef Ecosystem (Thrt), Fishing Ground (FiGd). The resource units are Octopus spp. (Octo), Fish Resources (FiRe), Target Fish Commodities (TgFi), Fishing Gears (FGear), Fish Distribution (FiDb), Markets (Mrkt), Fish Prices (FiPr), Trip Cost (Tpct). The resource actors are labeled as VEZO community (Vezo), MASIKORO community (Mskr), Collectors (Clctr), Fishmongers (Fmgr), DRPEB Technicians (RTch), Village Head (SefoFKT), Associations and NGOs (NGOs), Revenues (Rvne), Incomes (Incm). For the resources governance: MPEB: National Level, DRPEB: Regional Level, Fokontany (FKT): Village level, Community-Managed Marine Reserve (CMMR), Law No 2015-053/2018-26: Code de la Pêche et de l'Aquaculture (CPA), Ministerial Decree (MDec), Traditional Law Enforcement: DINA. The network displayed is an undirected type that signifies a relational network of all nodes. The results indicate that the strongest and most numerous relational networks are found in nodes associated with the coral reef fishing activity in this region.

Basic Conceptual Model

The basic of social-ecological system (SES) connectivity for CRFs in Ranobe Bay has a strong directed network, as evidenced by the presence of links in the case of basic model this study result (Figure 4).

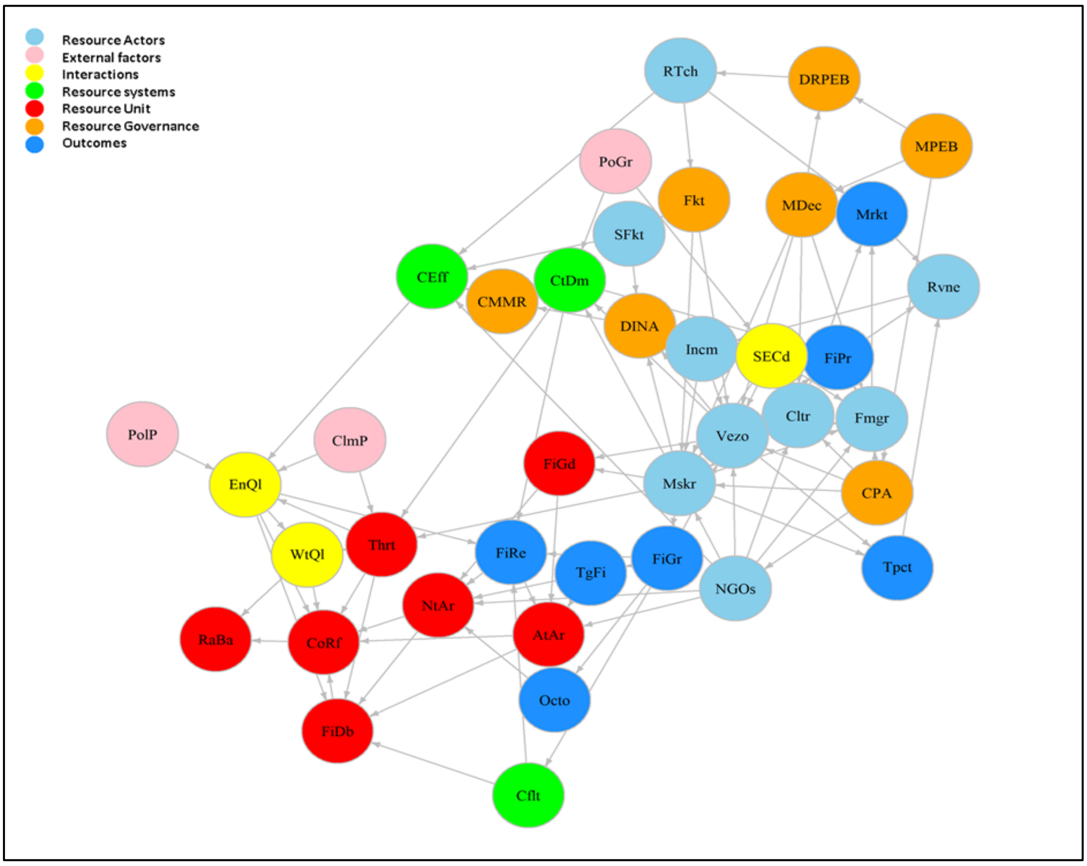

Figure 4. Basic Conceptual Model of CRFs connectivity in Ranobe Bay

Confirmation approach of ensures that the initial stage identification can be assessed with certainty, without any doubt following the study network's conditions. The basic network model of the total overall system consists of 39 components (nodes) and 101 components interactions (edges) in Ranobe Bay, Madagaskar.

Centrality Degree

The value of the network produced in the form of centrality is based on the social-ecological system. The centrality of all resources produces values in the form of degrees (Figure 5).

The analysis of the system's degree values based on centrality shows that RA2, the node of the fishermen community, namely Masikoro, has the highest degree value of 15, with 7 flows in and 8 flows out. RA1 or Vezo, the node of the second fishermen community, holds the second highest value with 14 degrees: 7 flows in and 7 flows out. These 2 nodes are the most crucial components of the SES-CRFs in Ranobe Bay according to their centrality degree value. They are followed by the Collectors (Clctr), Fishmongers (Fmgr), and the

Associations of Non-Governmental Organizations (NGOs) with a value of 8 degrees for each one.In Ranobe Bay Fisheries, RA components have a higher centrality degree value than the other SES components. According to the SES connectivity study, if these keystone nodes are lost, meaning that the highest-degree components of the SES network are removed from the system, it can cause the fragmentation of this one, reducing resilience, disrupting the information flow, and potentially leading to the collapse of the social-ecological system (SES).

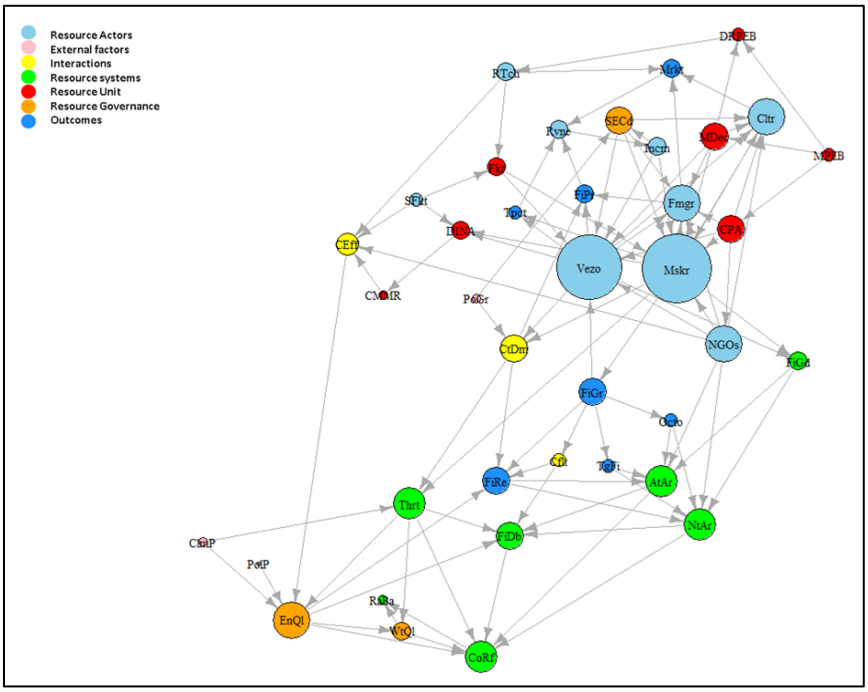

Figure 5. Value of centrality degree

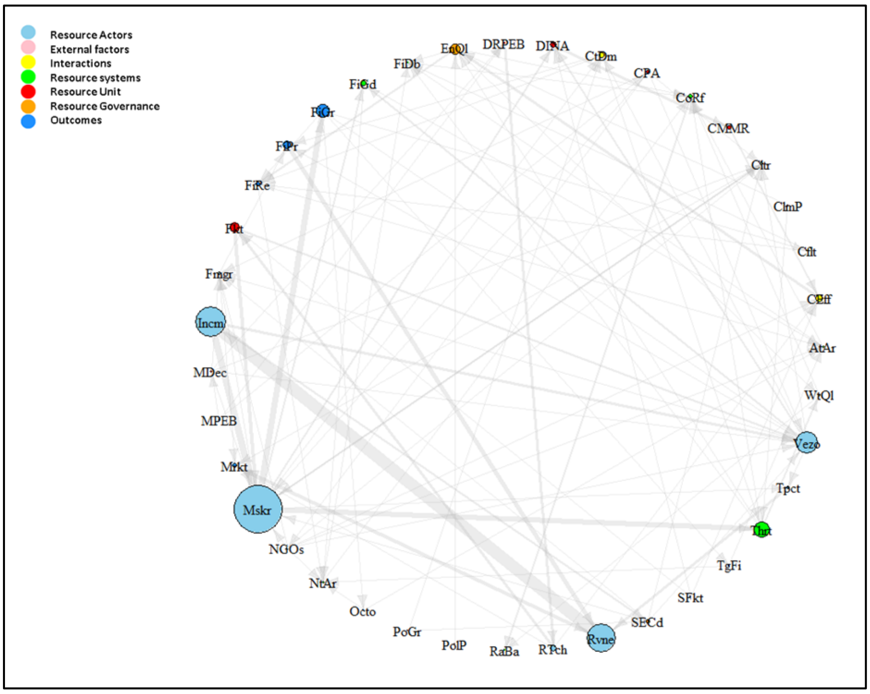

Figure 6. Centrality Betweenness of CRFs in Ranobe Bay

Centrality Betweenness

The size of the nodes and thickness of the edges represent their importance compared to the betweenness centrality measure, which indicates the number of times a node acts as a bridge between 2 nodes (Brandes 2001). The network value produced in the form of centrality betweenness is shown as follows for the CRFs of Ranobe Bay (Figure 6).

The analysis of the degree values of the system based on the centrality betweenness shows that RA2, the node of the fishermen community, namely Masikoro, has the highest betweenness centrality with a value of 239. The next highest value is held by RA8, RA9, and RA1, which are the nodes of the Resource Actor, respectively: the Income with a value of 151, the Revenue with 144, and the "Vezo" fishermen with 107. These components likely play crucial roles in bridging various subsystems within the SES-CRFs of Ranobe Bay. Nodes with high betweenness centrality are potential leverage points for interventions since their removal or disruption could fragment the system. Indeed, a high betweenness centrality means that the node plays a key role as a go-between, helping to connect different parts of the system. This makes it important for understanding how resilient or vulnerable the system is overall.

Clusterization

The analysis of the CRF connectivity groups is further presented in the form of clusters, which indicate the presence of 5 network groups (Figure 7). The resulting cluster shows 5 groups due to the similarity in field conditions where key stakeholders are involved in the fisheries activity and management. The clustering of components was performed using the walktrap algorithm based on the similarity of structure, patterns, and characteristics of relationships that often appear together (Munawar *et al.* 2020).

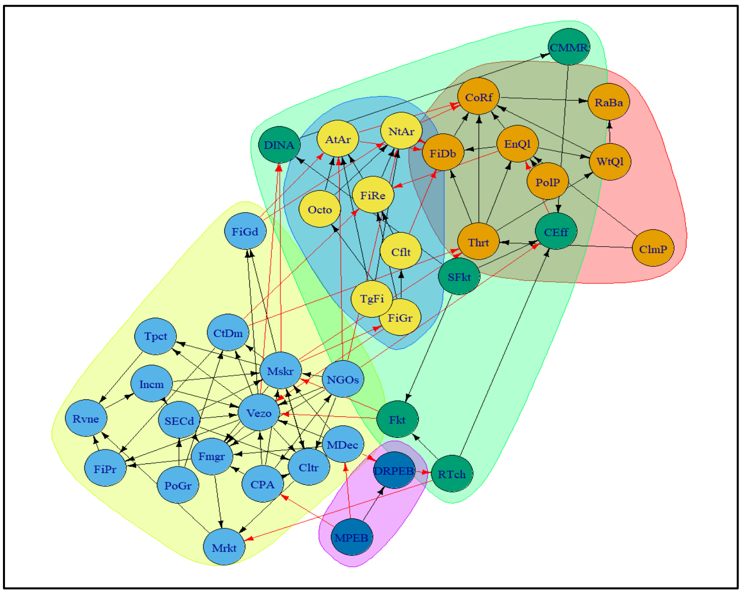

Figure 7. Clusterization of SES connectivity of CRFs in Ranobe Bay

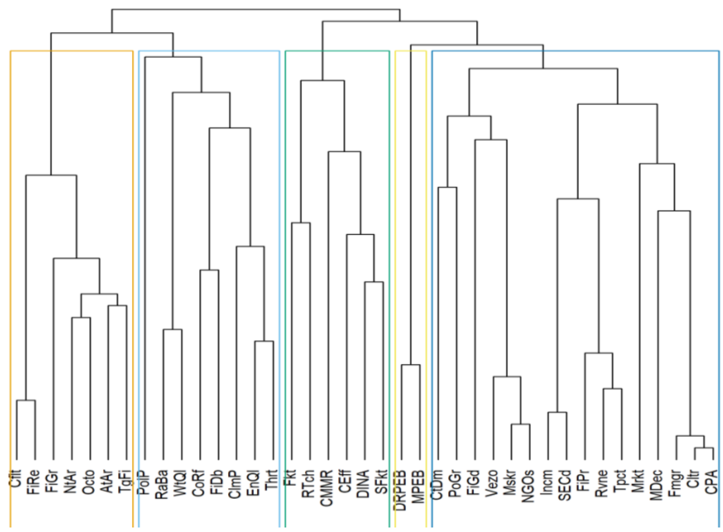

Figure 8. Dendrogram of the CRFs cluster in Ranobe Bay

The first group consists of "ClmP", "CoRf", "EnQl", "FiDb", "PolP", "RaBa", "Thrt", and "WtQl", which are the ecological components and external factors that appear in Ranobe Bay. The second group consists of "Cltr", "CPA", "CtDm", "FiGd", "FiPr", "Fmgr", "Incm", "MDec", "Mrkt", "Mskr", "NGOs", which are institutional structures, interactions, and fishing communities. The third group consists of "PoGr", "Rvne", "SECd", "Tpct", "Vezo", which are composed of the community welfare and a fishermen community. The fourth group consists of "CEff", "CMMR", "DINA", "Fkt", "RTch", and "SFkt", which are the governance forms present in this region.

The biggest group is the second group formed by "Cltr", "CPA", "CtDm", "FiGd" "FiPr", "Fmgr", "Incm", "MDec", "Mrkt", "Mskr", and "NGOs", and the little one consists of "PoGr", "Rvne", "SECd", "Tpct", and "Vezo" (Figure 8).

Value of Hubs and Authorities

The results of the relationship between nodes based on the direction of centrality towards SES-CRFs are presented in the size of the node value formed from each component type (Figures 9 and 10). The RA7, RG5, and RG6 nodes, as a structure and institutional typology, have more outgoing links based on the results of hub centrality. The value of the RG5 and RG6 hub size indicates that the node is crucial in influencing the other components it connects, as the main institutional governance system that influences this CRF.

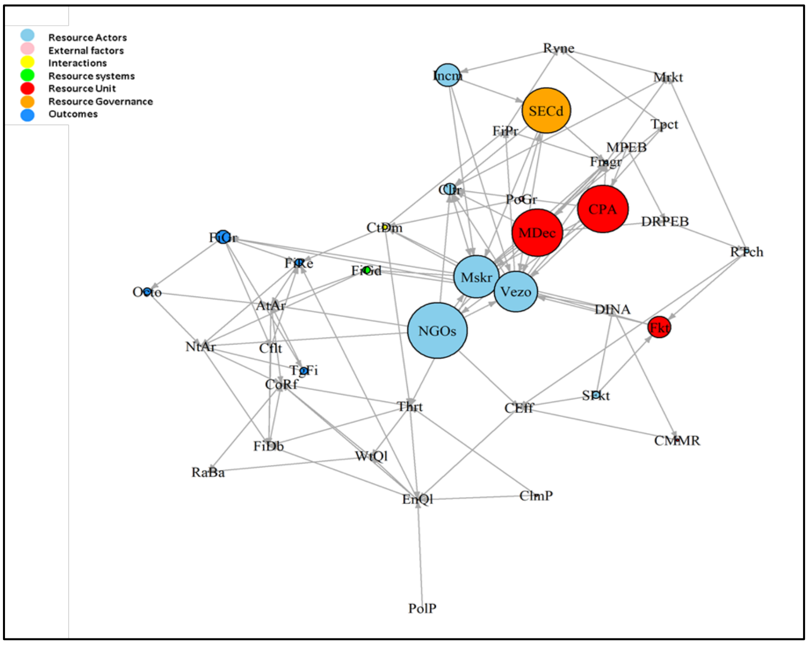

Figure 9. Hubs value of CRFs in Ranobe Bay

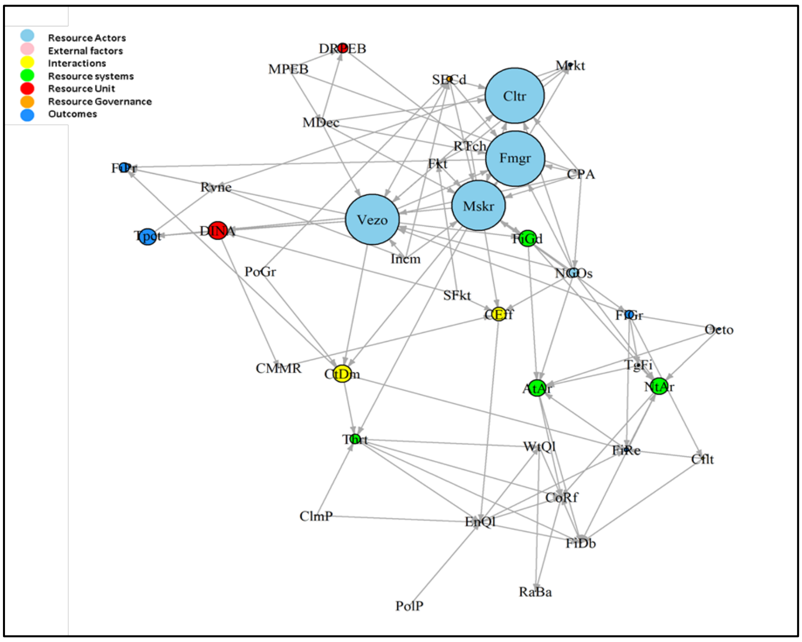

Figure 10. Authority value of CRFs in Ranobe Bay

On the other hand, the centrality of authorities has a significant number of incoming links particularly to RA1, RA2, RA3, and RA4. Based on their authority level, components play a significant role in the SES.

Discussion

Social-Ecological Systems Conditions Aspects

The assessment of coral reef fishing activity in Ranobe Bay through the SES framework provides a comprehensive understanding of the dynamic interactions among ecological, economic, and governance components. This research highlights key challenges and opportunities in managing small-scale fisheries, particularly in balancing livelihood sustainability with conservation goals.

The findings are consistent with other studies on small-scale fisheries in tropical marine ecosystems, emphasizing the interdependence of socio-economic conditions, governance structures, and environmental health (Cinner *et al.* 2012; McClanahan *et al.* 2015). A critical factor influencing the sustainability of SSCRFs in Ranobe Bay is the condition of small-scale fisheries and community welfare. Our analysis shows that the Vezo and Masikoro communities rely heavily on fisheries for subsistence and income, similar to patterns observed in other small-scale fisheries-dependent communities in the Western Indian Ocean (WIO) region (Cinner *et al.* 2009). However, the increasing pressures from overfishing, habitat degradation, and climate change have led to declining fish stocks, a trend also reported in Kenya and Tanzania (Hicks *et al.* 2013). The dependency on octopus (*Octopus* spp.) and commercially valuable fish species, alongside fluctuations in fish prices, further complicates economic stability for fishers.

Governance structures play a crucial role in shaping fishery sustainability. This study identifies a multi-level governance framework, including national institutions (MPEB), regional institutions (DRPEB), and local governance through Fokontany and Community-Managed Marine Reserves (CMMRs). Similar governance structures have been documented in Madagascar's Locally Managed Marine Areas (LMMA), where customary law enforcement (DINA) has been effective in regulating fishing practices (Andriamalala and Gardner, 2010). Nevertheless, enforcement challenges remain due to limited institutional capacity and resource constraints, as observed in other community-based fisheries management settings (Gutiérrez *et al.* 2011). Strengthening community engagement and integrating traditional knowledge into policy frameworks could enhance regulatory compliance and resilience in the SSCRFs system.

Another significant finding of this research is the role of environmental threats, including overfishing, coral bleaching, and pollution. The degradation of Ranobe Bay's coral reefs mirrors trends reported in other parts of the WIO, where coral loss has been linked to both local stressors (e.g., destructive fishing practices) and global climate change impacts (Obura *et al.* 2017). Water quality degradation due to pollution and agricultural runoff further exacerbates the vulnerability of the marine ecosystem. Previous research in the Seychelles and Mauritius has also shown that reduced water quality correlates with declines in fish productivity and biodiversity (Graham *et al.* 2015). Addressing these threats requires a multi-faceted approach, including improved waste management, the promotion of sustainable fishing techniques, and adaptive marine spatial planning.

The interactions between fishers, market dynamics, and governance mechanisms illustrate the complexity of managing CRF in Ranobe Bay. The presence of conflicts between different stakeholder groups, including fishers, traders, and conservation organizations, is consistent with other case studies in the region (Berkes 2006). Effective conflict resolution strategies, such as participatory decision-making and equitable benefit-sharing mechanisms, are essential for fostering cooperation and ensuring long-term resource sustainability.

Social-Ecological Systems Connectivity Aspects

Looking at fisheries in Ranobe Bay through a SES lens helps us better understand how the environment, people, and governance interact. But the findings show that connections within the system, especially in SSCRFs, are weak. The most connected and central actors are the Masikoro and Vezo fishing communities, which isn't surprising. These groups play a vital role in linking fishing activities with markets, gear, and even some governance processes. This supports earlier research showing how essential local communities are in managing marine resources (Cinner *et al.* 2012; Basurto *et al.* 2013).

What's especially important is the role of traditional systems. Local leaders, respected elders, and informal rules like dina (customary law) are still very influential. These traditional roles help guide who gets to fish, settle disputes, and keep the community united. They also play a big part in encouraging people to follow rules, something formal institutions often struggle to do effectively in remote areas. These informal systems often work better than official ones when it comes to day-to-day governance and passing on local ecological knowledge. Indeed, informal and traditional roles, such as those played by village elders, customary law (DINA), and respected fishing community members, are central to how fisheries are managed on the ground. These actors often compensate for the limited presence and capacity of formal institutions, guiding access to fishing grounds, enforcing local rules, and mediating conflicts through well-established social norms (Andriamahefazafy *et al.* 2019; Harris 2007). Their authority is grounded in cultural legitimacy and everyday interactions, which often leads to higher compliance and social cohesion, factors that are essential for sustainable resource use in small-scale fisheries (Cinner and Aswani, 2007; Ostrom 1990).

At the same time, the analysis shows that formal institutions like DRPEB and MPEB aren't very central in the network. This is quite different from other places, like parts of East Africa or the Pacific Islands, where government bodies often take the lead in managing fisheries (Evans *et al.* 2011; Cohen *et al.* 2012). In Ranobe Bay, this may be due to weak institutional presence or simply because people rely more on their community systems. Instead of a top-down approach, governance here seems to be more of a blend: a mix of official structures (like Ministerial Decrees and CPAs) and traditional governance (like community rules and DINA). This kind of hybrid system can be a strength local customs and practices are deeply rooted and often more responsive to change than rigid bureaucratic systems.

When researchers looked at how the network is structured, they found 5 separate clusters of actors. That means the different parts of the system aren't well connected. This kind of fragmentation can make it harder to manage resources effectively and increase the risk of conflict or inefficiencies. Still, the biggest cluster, which includes both institutions and communities, shows how closely social and economic factors are tied together in local fisheries governance. This is similar to what's been seen in other places, like Chile's coastal fisheries, where local fishers work closely with NGOs and government agencies (Castilla and Defeo, 2001).

There's also a notable cluster centered around community-managed marine reserves and traditional law enforcement. This highlights how much local governance still matters. In Madagascar, community-led marine reserves have helped both conservation and livelihoods (Harris 2007; Andriamahefazafy *et al.* 2019), though challenges remain, especially when traditional and formal systems clash or when enforcement is weak. Compared to more successful cases like the Locally Managed Marine Areas (LMMAs) in the Pacific (Jupiter *et al.* 2014), Madagascar still has work to do.

Ideally, formal governance institutions should be better connected, with stronger roles in sharing information, setting policy, and managing resources. But in Ranobe Bay, it's the Vezo and Masikoro communities that are driving change. They've taken leadership roles in improving governance, and they bring valuable knowledge and commitment to sustainable practices. This reflects broader thinking in resilience and sustainability: strong systems are those that allow for both coordination and local leadership (Folke *et al.* 2005; Ostrom 2009).

In short, the fisheries system in Ranobe Bay faces challenges like weak links between actors, enforcement gaps, and limited government involvement. But there's also a strong foundation in the form of traditional roles, local knowledge, and community leadership. If future efforts can strengthen the connections between formal institutions and these local systems without overriding or ignoring them, there's real potential for more effective and sustainable fisheries management.

CONCLUSION

In conclusion, this research provides a valuable contribution to the understanding of small-scale coral reef fisheries in Ranobe Bay through the SES framework. The findings highlight the complexity of fisheries connectivity, revealing that the Masikoro and Vezo are the primary actors in this activity, and the fishermen's community is largely concentrated around this fishery according to their centrality value. However, the results of the cluster value analysis suggest that the system is divided into a high number of clusters, showcasing that the SES-CRFs of Ranobe Bay have a poor connection and less compact structure. So, the SES-CRFs of Ranobe Bay is relatively low in connectivity and need more policy formulation and strong management to face the challenges and adapt to the situation that occurs in the region. Hybrid governance systems, incorporating both formal and traditional management practices, play a crucial role in sustaining CRFs, yet challenges remain in ensuring effective enforcement and balancing power dynamics between institutional and community actors. Future research should explore the effectiveness of existing conservation initiatives and investigate adaptive governance mechanisms that enhance the resilience and sustainability of small-scale fisheries in Madagascar and beyond under changing environmental and socio-economic conditions.

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