Sustainability Science
https://doi.org/10.1007/s11625-024-01545-y

ORIGINAL ARTICLE

Mental models of aquaculture governance in Indonesia

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Received: 12 May 2023 / Accepted: 15 July 2024

Abstract

Aquaculture stakeholders have mental models, which are the internal cognitive representations of how they understand and prioritize the different features of their aquaculture systems. Individuals and stakeholder groups are likely to have different mental models, with implications for making cooperative governance work and guiding the rapidly emerging sector's sustainable development. We apply a participatory approach called fuzzy cognitive mapping to capture and compare the mental models of community-based coastal pond aquaculture stakeholders in Indonesia, including farmers, government managers, and researchers who need to work together to govern a rapidly expanding aquaculture sector which faces critical sustainability challenges. To conceptually structure our comparison, we use Elinor Ostrom's social–ecological systems framework. Our results highlight important differences between stakeholder group mental models which represent potential conflicts of interest and barriers for collaborative governance. Fish farmer models emphasize resource system challenges relating to production instability and risk, while government managers emphasize increasing production intensity to meet sectoral growth targets. Researchers, in contrast, tend to focus on pond waste treatment and water quality management. Governance attributes were consistently perceived as less frequent and less influential compared to other social–ecological dimensions, reflecting perceptions of weak governance in the sector. We identify a critical need for programs aimed at strengthening community-level institutional arrangements for governing shared aquaculture resources, increasing technical knowledge capacity, and managing financial risk. By merging all stakeholder models into a single "community" model, we identify key consensus action situations across the three groups as potential focal points for aquaculture development which may serve as a starting point for actors to work together to identify context-appropriate institutional solutions to these sustainability challenges.

Keywords Mental models · Social–ecological systems framework · Aquaculture · Fuzzy cognitive mapping · Indonesia

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Introduction

Fuzzy cognitive mapping (FCM) of mental models

"Mental models" are defined in the cognitive science literature as internal representations which structure people's understanding of the external world (Craik 1943; Johnson-Laird 1983). People's mental models are shaped by and continue to evolve based on interactions with the external world over time, acting as our primary internal reference for decision-making and reasoning (Jones et al. 2011). As our mental models structure our understanding of aspects of our environment, which in turn informs our decision-making, mental models shape and influence the external world (Gray et al. 2014a).

Natural resource governance often involves a wide range of stakeholders including direct resource users, surrounding communities, governments and private organizations who must make management decisions and rules together. Different stakeholder groups have their own distinct mental models of the social-ecological system (SES) they are embedded in, based on the different ways they interact with, use, and value the resource (Gray et al. 2017), and conflict in natural resource governance is often embedded in differences in perception of resource system structure and function (Levin et al. 2021). Management of shared natural resources, therefore, represents a potential collective action dilemma (Ostrom 1990), as different types of actors may hold diverse and potentially diverging mental models regarding the natural resource or how it should be used. At the same time, there is a growing consensus that integrating a diverse range of perspectives builds more complete understandings of complex social–ecological systems (Aminpour et al. 2020; Mohammadabadi 2020; Short et al. 2021). The development of shared mental models is critical for successful collective action and management of shared natural resources, and research and management approaches which integrate diverse knowledge types can improve collective decision-making and lead to more realistic policy and management decisions (Biggs et al. 2011; Stephenson et al. 2016).

Fuzzy cognitive mapping (FCM) is a participatory approach to map mental models through an interactive workshop activity where individuals or groups of respondents structure their knowledge about a given system in terms of the important concepts (variables) and directed causal relationships between them (Kosko 1986). Concepts are represented as nodes, and respondents typically assign a quantitative score (from −1 to 1) reflecting their perception of the direction and strength of each causal relationship. FCMs can, therefore, be interpreted as static external representations of our internal mental models at a particular place and time. As a “semi-quantitative” approach, FCMs combine and bridge qualitative visualization and exploration with a range of quantitative network metrics and simulation methods to model and predict system outcomes (Özesmi and Özesmi 2004; Jetter and Kok 2014). FCM has seen a variety of applications in science, engineering, and business management (Papageorgiou et al. 2014), but has been increasingly popularized as a participatory tool for participatory stakeholder modeling of social–ecological systems and natural resource management (Özesmi and Özesmi 2004; Mourhir 2021). A growing body of research in the past 20 years has demonstrated how FCM can be used to build detailed knowledge of an SES in otherwise information-scarce contexts based on local expert knowledge (Fairweather 2010; van Velden et al. 2020; Aminpour et al. 2021a) and to help build and test SES management scenarios (Gray et al. 2015; Devisscher et al. 2016). As an accessible participatory modeling tool, FCM can provide important insights into how people think about and interpret the systems they act within and influence, including key differences or similarities in the mental models guiding the actions, priorities, and decision-making of different social subgroups connected to a shared natural resource (Halbrendt et al. 2014; Drew et al. 2021). In doing so, FCM can facilitate social learning within and between researchers and stakeholder groups through transparent and easily interpretable models (Malek 2017).

Case context: coastal brackish pond aquaculture in Nusa Tenggara Barat, Indonesia

In Indonesia, aquaculture is rapidly expanding driven by national strategic plans to develop the sector as a sustainable livelihood and source of food security and nutrition (NUMBER 57/PERMEN-KP/2020), making use of the country’s abundant freshwater and marine resources. The Indonesian government has set major targets to increase farmed fish production at least through 2030 (Henriksson et al. 2019), and Indonesia is now the second largest aquaculture producer behind China (FAO 2022). Demand for affordable, viable protein and nutrition sources will continue to drive expansion. At the same time, aquaculture transformation introduces new sustainability challenges, including eutrophication, disease contamination, and feed production issues (Boyd et al. 2020; Gephart et al. 2021), and the capacity for aquaculture to deliver intended social benefits is uncertain (Ateweberhan et al. 2018). Aquaculture research has historically focused heavily on technical aspects of production, while needed governance and management literature critical for informing sustainable development of the sector is still lacking (Partelow et al. 2022).

Indonesian aquaculture production is highly dependent on government intervention or assistance. While central government policies are broadly driving expansion of aquaculture across the country, extensive government decentralization in recent decades gives some degree of autonomy regarding how to develop the sector to local governance arenas, from provinces and regencies (Indonesian: kabupaten, province subdistricts) to local communities. Local decision-makers—from government officials to researchers to fish farmers themselves—must make management or policy decisions in contexts involving a complex range of interacting social–economic and ecological processes, and a diversity of stakeholders with different goals and priorities. Still, aspects of environmental governance in Indonesia have been criticized as being too top-down and disconnected from local communities, and there is growing recognition for the need to improve public participation in natural resource decision-making in the country (Permana et al. 2023).

The province of Nusa Tenggara Barat (NTB), consisting of the islands of Lombok and Sumbawa, ranks fifth out of 38 provinces in Indonesia for overall aquaculture production. Coastal brackish pond aquaculture (Indonesian: tambak) has quickly expanded in recent decades to become the highest value aquaculture sector in the province (BPS 2020). These brackish pond systems consist of earthen ponds, connected through a network of canals and dikes which connect to the sea and freshwater sources. Commonly cultivated species include milkfish (*Chanos chanos*) which are primarily produced for domestic consumption, as well as high-value whiteleg shrimp (*Penaeus vannamei*) and tiger shrimp (*Penaeus monodon*) which are often exported to Western markets (Rimmer et al. 2013). Coastal pond aquaculture farmers rely on a diverse range of shared resources, which can lead to collective action challenges and require appropriate institutions to govern them (Partelow et al. 2022; Riany et al. 2023). In brackish pond aquaculture the most important shared resource is water, and the canal infrastructure used to distribute it and connect individual private ponds. Brackish pond farm networks can have common pool resource dilemmas relating to the provisioning of shared canal maintenance to maintain the common good of water quality (Partelow et al. 2018; Riany et al. 2023) and require a high degree of self-organization amongst farmers to coordinate the input and release of water to prevent the shared risk of disease outbreaks and cross-contamination (Galappaththi and Berkes 2015). Increasing pollution of the jointly used water body, maintenance of the canal infrastructure, low productivity, climate uncertainty, and environmental impacts are major governance problems facing the pond aquaculture sector in Indonesia (Rimmer et al. 2013; Ilman et al. 2016; Partelow et al. 2018; Riany et al. 2023).

NTB, outside the urban capital of Mataram City, is a predominantly rural province which is heavily reliant on paddy cultivation and other forms of agriculture as the primary livelihood source, while also having amongst the highest poverty rates in Indonesia (Butler et al. 2014; Supriaman et al. 2018). In this context, local government programs have attempted to support the development of pond aquaculture in rural, low-income coastal communities with the goal of providing greater economic opportunities and food security. Some communities have now been practicing brackish pond aquaculture for multiple generations but continue to have mixed or unsuccessful results (Partelow et al. 2018). Local government support primarily consists of aid programs which require farmers to self-organize into small farmer groups called pokdakan (KKP 2013) to access subsidies and loans, with the goal of incentivizing collective action to improve community outcomes. Extension officers from the Ministry of Marine Affairs and Fisheries (MMAF) also work in each province district to support and guide fish farming communities, but face capacity issues as there is often only one extension officer assigned to each district. The National Research and Innovation Agency (BRIN) has various research initiatives exploring innovative aquaculture livelihood technologies, including a research station in Lombok, although some previous pilot projects in NTB had mixed efficacy due to a lack of alignment between research program goals and community needs (Senff et al. 2018). A challenge for the sector is that the growth of the brackish pond sector has not been accompanied by a similar increase in effective management knowledge, training capacity or adequate spatial planning within aquaculture communities in NTB, leading to sustainability issues of production instability, disease outbreaks, and pond abandonment which communities and local governments have so far been unable to address (Partelow et al. 2018; Senff et al. 2018).

Problem orientation and research objectives

In the present context, the core problem orientation of this study is that while formal governance of the aquaculture sector has to an extent been decentralized to a local level in Indonesia, local fisheries and marine affairs departments have limited capacity and resources to develop locally meaningful policies and programs (Partelow et al. 2018; Riany et al. 2023). As a result, integration of community voices and needs is limited (Permana et al. 2023), and appropriate formal and informal institutional arrangements for governing the sector are lagging behind its development (Riany et al. 2023). There is a strong reliance on top-down "one-size-fits-all" programs and best management practices from MMAF which often do not fit to local needs, challenges, and goals for developing the sector due to mismatched between government goals and community needs (Paramita et al. 2023; Nagel et al. 2024).

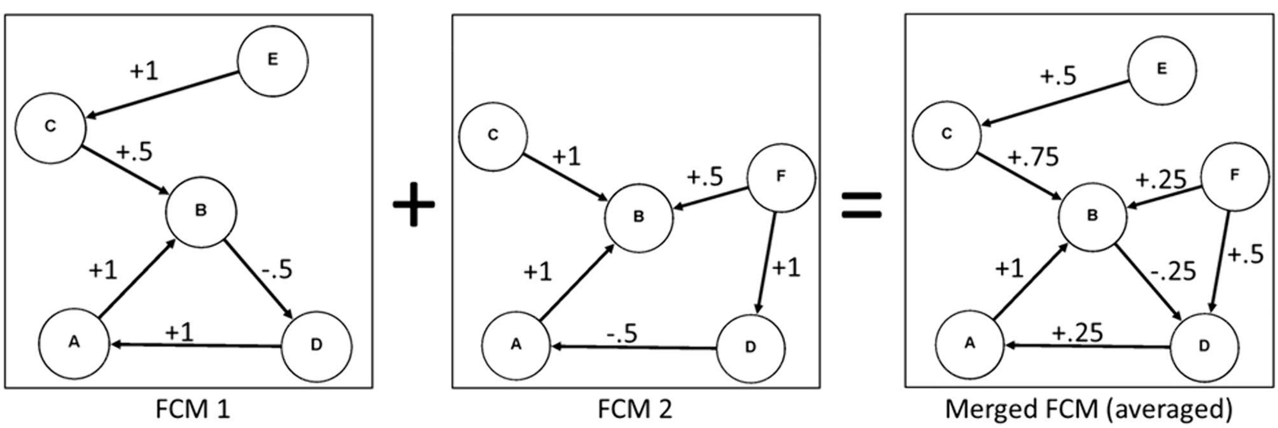
FCM has been increasingly investigated as a tool to support adaptive co-management and social learning within environmental governance by identifying conflicting views between groups such as resource users and government, as well as consensus areas which could be used as leverage points for developing more effective environmental policy (Gray et al. 2014b; Halbrendt et al. 2014; Christen et al. 2015; Drew et al. 2021). In the present study, we apply FCM to map and compare mental models of local fish farmers, government managers, and researchers. To achieve long-term sustainability in an emerging aquaculture sector and develop more locally adaptive policy, these groups need to work together to develop governance frameworks and institutions to solve the collective action problems which emerge from aquaculture production, intensification and expansion (Partelow et al. 2022). Having a "shared mental model" among aquaculture stakeholders is essential for this process to both avoid conflicts and to constructively work together. The main objectives of our study are to use FCM to (1) identify and interpret important similarities and differences which may represent collective action opportunities or challenges, respectively, and (2) develop a merged "community" FCM reflecting topics of majority agreement across stakeholder groups as leverage points to inform priority areas for addressing aquaculture development challenges in NTB. Among increasing calls for knowledge co-production approaches to inform future sustainability pathways (Norström et al. 2020), we demonstrate how our FCM results might be used to inform more locally adaptive environmental policy in NTB to more effectively address jointly understood problems.

To conceptually frame our findings, we organize the results into Elinor Ostrom's social–ecological systems framework (SESF) (Ostrom 2007, 2009; McGinnis and Ostrom 2014). Analyzing many FCM exercises involves dozens, sometimes hundreds, of raw concepts which must be standardized and compared. A common framework like the SESF helps organize the variables into meaningful conceptual categories for analysis and comparison of findings. We chose the SESF based on its extensive use in environmental governance and commons research as perhaps the most comprehensive framework for identifying social–ecological variables in a system, as well as our particular interest in studying mental models to identify collective action challenges and opportunities for collaboration in aquaculture development. The SESF was designed to guide research examining why in some natural resource management cases actors are successfully able to work together to solve collective action dilemmas, and in other cases not (Ostrom 2007). The SESF provides an extensive vocabulary of social and ecological variables, oriented around an "action situation", where interactions in the SES are transformed into outcomes which feed back into the system. The decomposable first- and second-tier variables of the SESF have been empirically identified as potentially influential for SES collective action outcomes (Ostrom 1990, 2007, 2009). Here, we apply the SESF to code the concepts from our FCM results and generally organize our analysis by interpreting how the different first-tier of the SESF are represented by different brackish pond aquaculture stakeholder groups.

Materials and methods

Fuzzy cognitive mapping as a tool to compare stakeholder group mental models

FCMs can be conducted individually or in groups, and individual FCMs can be mathematically aggregated into a single merged FCM to represent shared mental models of a stakeholder group or entire community (Fig. 1). To aggregate individual FCMs, adjacency matrices of all quantitative causal relationship values are summed and averaged across all individual FCMs in the group, combining knowledge on the important variables and causal relationships from all interviewed individuals, while reinforcing (increasing) values for causal relationships with consensus agreement



Adjacency matrix 1

	A	B	C	D	E
A	0	1	0	0	0
B	0	0	0	-0.5	0
C	0	0.5	0	0	0
D	1	0	0	0	0
E	0	0	1	0	0

Adjacency matrix 2

	A	B	C	D	F
A	0	1	0	0	0
B	0	0	0	0	0
C	0	1	0	0	0
D	-0.5	0	0	0	0
F	0	0.5	0	1	0

Merged adjacency matrix

	A	B	C	D	E	F
A	0	1	0	0	0	0
B	0	0	0	-0.25	0	0
C	0	0.75	0	0	0	0
D	0.25	0	0	0	0	0
E	0.5	0	0	0	0	0
F	0	0.25	0	0.5	0	0

Fig. 1 Example of FCM aggregation by averaging causal relationship weights, visualized as both FCM diagrams and quantitative adjacency matrices used for analysis

in the group. Concepts and causal relationships that are not frequently mentioned across individuals are still included, just not reinforced. FCMs can be analyzed via qualitative interpretation of the models, quantitative metrics derived from network analysis and graph theory, as well as steady-state analysis, which draws from neural network theory to simulate how FCM models predict the system to change (in terms of relative increase or decrease to all concepts) under multiple "what-if?" scenarios (Özesmi and Özesmi 2004; Jetter and Kok 2014).

Data collection

To analyze mental models of the coastal brackish pond aquaculture SES in NTB, we collected individual FCMs in one-on-one stakeholder interviews, the results of which were aggregated into merged stakeholder group FCMs during the analysis phase (Figure S1). All FCM data were collected from December 2021 to April 2022 with an additional phase from September to October 2022 to present and discuss preliminary results with stakeholders. Supporting information regarding study methods can be found in Appendix 1.

Stakeholder group and participant selection

Research with FCM does not typically aim for a representative sample of an entire population, but instead to capture a diversity of knowledge areas, with participants typically selected based on their expertise of a system (Olazabal et al. 2018). Environmental governance research with FCM typically aims for one of two approaches: representing and comparing mental models of one or more often deductively derived groups based on social identity (Gray et al. 2014a) or by often more inductively exploring patterns in mental model heterogeneity, which may be attributed to social identity or some other form of cognitive diversity (Aminpour et al. 2021b; Tessier et al. 2021). Our goal was to capture mental models from multiple pre-defined social groups with distinct and differing relationships to aquaculture governance in NTB, and create an aggregated FCM representing shared mental models of each stakeholder group. An initial phase of exploratory key informant interviews identified three key stakeholder groups central to aquaculture governance in NTB for comparison in our analysis: fish farmers, government managers, and researchers. Several other actor groups were considered during this phase but omitted due to lack of relevance or lack of access (Table S1). We identified respondents within each of these groups through a purposive, snowball sampling approach aiming to interview experts (1) with multiple years of experience with aquaculture in NTB, as a baseline for expert knowledge and understanding of the system, and (2) with the aim of selecting experts from multiple localities in both Lombok and Sumbawa islands to incorporate knowledge on SES dynamics from across the entire province. A summary of the total number, location, and additional characteristics of actors included in each of the three groups is provided in Table 1.

FCM activity

FCMs were collected from 37 individual interviews from January to April 2022 both in-person using a whiteboard and concept cards, and online using the web program "Mental Modeler" (Gray et al. 2013) (Fig. 2). This mixed data collection strategy was employed as the online tool helped extend the geographic reach of our sample and facilitate access to actors still facing COVID-19-related restrictions at the time of sampling. At the same time, the in-person tool was more accessible to farmer participants who often have limited technology access. The format of the interview was selected based on the respondent's preference and both formats were conducted using the same procedure. Following standard FCM procedures, an example FCM of an unrelated system (Figure S2 'example FCM') was presented to the respondent to explain the activity. Respondents were then asked to brainstorm any concepts that came to mind as important or influential to coastal pond aquaculture development in NTB, using several example concepts to help seed the discussion (see Appendix 1 for more information). Following the concept brainstorming, respondents mapped out what they perceived as the important causal relationships between these concepts, whether it was a positive (+) or negative (−) relationship, and ranked the perceived strength of each relationship ("strong"—1.00, medium"—0.66, "weak"—0.33), which were converted to quantitative values during analysis. Respondents also selected two concepts in their FCM most likely to change over the next 5 years, results of which were used to inform a small number of anticipated "what-if?" scenarios during the analysis phase. To determine an appropriate sample size of individual FCMs to represent collective group knowledge, we followed a standardized approach to whether a concept saturation point has been reached, called an "accumulation curve", suggesting that little new information is being added with consecutive FCMs (Özesmi and Özesmi 2004).

Data analysis

FCM homogenization and aggregation

To facilitate FCM aggregation and comparison across 417 raw concepts identified from interviews, similar concepts were merged and standardized through a qualitative process of FCM homogenization. As the process of FCM concept homogenization typically involves some degree of subjectivity and author judgment, we referenced

Table 1 Stakeholder groups connected to the coastal pond aquaculture SES in Nusa Tenggara Barat province

Group	Total no. of FCM interviews by group	Group description	No. of FCM by description sub-category	No. of FCM by gender	No. of FCM by location in province (Lombok or Sumbawa island)	No. of FCMs by interview mode (online vs. in-person)
Farmers	16	Community-based "traditional" tambak (large brackish water ponds, low stocking density, few inputs, few technologies) farm group leaders and secretaries	11	Men 15	Lombok 13	Online 3
		Community-based "semi-intensive" to "intensive" tambak (medium to small brackish water ponds, moderate to high stocking density, moderate to high technology use, moderate to high input use) farm group leaders and secretaries	5	Women 1	Sumbawa 3	In-person 13
Government managers	11	DKP (Regency level Department of Marine Affairs and Fisheries) officers	7	Men 9	Lombok 3	Online 11
		MMAF (Ministry of Marine Affaris and Fisheries) aquaculture extension officers	4	Women 2	Sumbawa 8	In-person 0
Researchers	10	Academic aquaculture researchers from local universities	9	Men 8	Lombok 8	Online 6
		Government fisheries and aquaculture scientists from NTB BRIN (Indonesia National Research and Innovation Agency)	1	Women 2	Sumbawa 2	In-person 4

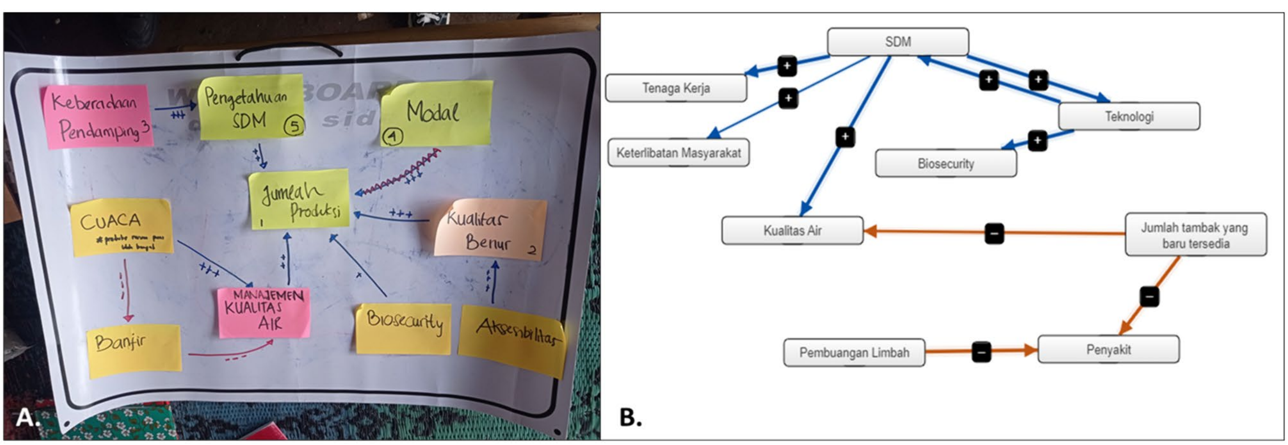


Fig. 2 **a** In-person FCM activity using portable whiteboard, sticky notes, and dryerase markers. **b** Online FCM activity using MentalModeler web-based application

existing recommendations for increasing FCM research transparency (Olazabal et al. 2018) and include a full list of all raw concepts alongside their homogenized definitions, along with notes regarding their interpretation

(Appendix 2). We additionally coded each concept to the first-tier components of the SESF. Adapting the approach of Ziegler et al. (2019), we used Hinkel et al.'s modified SESF coding procedure formalized specifically for model-based research (Hinkel et al. 2015), coding concepts into the SESF categories of "resource system (RS)" (merged with "resource units" as an attribute of the resource system), "actor (A)", "governance system (GS)", "(external) environment (E)" (consisting of both "social, economic, and political setting (S)" and "related ecosystems (ECO)"). Concepts were coded into the SESF based on attribution ("All Concept As have a Concept B") and subsumption ("All Concept Bs are one type of Concept A, but not vice versa") relationships (see Hinkel et al. (2014) for further explanation). The action situation of the SESF is not included as variables in Hinkel et al.'s modified SESF as in a scientific model, interactions are instead represented as processes or relationships. Within an FCM, we interpret the action situation as being explicitly modeled not as variables, but as causal relationships (interactions), the predicted emergent outcomes of which can then be analyzed via FCM steady-state simulation analyses. All individual FCMs from each stakeholder group were weighted equally and aggregated by averaging the adjacency matrices of quantitative causal relationship values across all individuals in each stakeholder group.

Descriptive metrics and comparisons of stakeholder group FCMs

To compare stakeholder group FCMs, descriptive node- and network-level metrics were calculated using the R package "FCMapper" (Turney and Bachhofer 2016). As FCMs are directed networks of causal relationships, we focus on comparing concepts across the first-tier SESF categories in terms of outdegree (measure of cumulative strength of outgoing causal relationships from a concept) and indegree (measure of cumulative strength of incoming causal relationships to a concept), the combined sum of which represents degree centrality (sum value of weighted causal relationships connected to a concept, a general indicator of connectivity and importance in a network). A high outdegree indicates a concept is acting as a driver, or highly influential variable, within the SES, while a high indegree indicates a concept is acting as a "receiver" or outcome variable, heavily influenced by other variables (Özesmi and Özesmi 2004; Gray et al. 2012). These metrics were analyzed alongside interview recordings and notes to identify the most central features of each model and develop a brief descriptive summary of each stakeholder group FCM.

Steady-state simulation analysis of stakeholder group FCM interactions and outcomes

To analyze how different groups modeled the "interactions and outcomes" tier of the SESF, we applied FCM steady-state analyses (Özesmi and Özesmi 2004; Gray et al. 2012; Jetter and Kok 2014), an approach which simulates how system conditions are predicted to change based on one or more hypothetical "what if?" scenarios. These simulations involve "clamping" (Kosko 1986) or fixing the value of one or more concepts to a "high" (1) or "low" (0) value (e.g., clamping "sea level rise" at 1 to represent a worst-case scenario of rising sea levels) to represent a particular scenario. This concept state change is then recursively iterated throughout the FCM network of concepts and relationships until a stable limit cycle is reached. The difference between the values from the "what-if" scenario and an initial steady-state "baseline" represents the predicted relative increase or decrease to each concept in that scenario. Steady-state scenarios model the emergent predicted outcomes of a dense number of interactions and feedback loops. By comparing simulation results, we can explore how stakeholder groups differently predict how the aquaculture SES is anticipated to react to a given pressure or intervention. To compare how different NTB stakeholder groups viewed key concepts as influencing aquaculture outcomes, we compared several "what-if?" scenarios selected from the concepts respondents reported as most likely to change in the next 5 years. All steady-state analyses were calculated in R using the "nochanges.scenario" and "changes.scenario" functions of the package "FCMapper" (Turney and Bachhofer 2016). See Aminpour et al. (2021a) for more information on the specific sigmoidal steady-state functions applied in this analysis.

Community FCM

In addition to modeling separate stakeholder group-specific FCMs, all FCMs can be aggregated together to represent the combined knowledge of an entire study population, referred to as "community" models or FCMs (Gray et al. 2012). There is no single consensus aggregation approach for developing a community FCM, but here we apply the two-step approach described by Aminpour et al. (2020), aggregating individual FCMs into stakeholder group FCMs by averaging the adjacency matrices, and then aggregate the stakeholder group FCMs into a single community FCM using the median rather than the mean of the adjacency matrices. Importantly for our research objectives, the first stage of aggregation identifies consensus areas within each stakeholder group by reinforcing recurring relationships, while the median approach to combine the stakeholder group FCMs results in a community FCM which represents shared understandings across stakeholder groups (as only those concepts and relationships reported by the majority of stakeholder groups are preserved).

Follow-up discussions and qualitative model validation

Preliminary findings from the data analysis, including the three aggregated stakeholder group FCMs and descriptive results, were presented back to 28 of 37 of the FCM respondents in September and October 2022. As the goal of our FCM aggregation was to develop combined FCM models of shared or consensus beliefs in each group, ideally some form of validation should be carried out to evaluate whether the aggregate models adequately reflect the views of the group (Jetter and Kok 2014). To qualitatively validate whether final models were representative of the shared views of each group, we started by asking whether the respondent viewed the aggregated stakeholder group FCMs as appropriately representative of their group, and if they would add or change anything. These semi-structured stakeholder discussions were also used as a preliminary stage of results dissemination and interpretation. The primary topic of discussion included respondent interpretations on the important similarities and differences between the stakeholder group models from their own perspective. Feedback and notes from these conversations contribute to the discussion of our findings by aiding the authors in the contextual interpretation.

Results

37 individual FCMs were collected and aggregated into three stakeholder group FCMs representing the primary stakeholder groups being compared. 417 raw concepts were homogenized into 68 aggregated concepts. A full list of original and transformed concepts is included in Appendix 2. An accumulation curve of concepts generated across individual FCM exercises suggests that a concept saturation point was reached (Figure S3).

Descriptive analysis of SES components in individual and group aquaculture FCMs

The homogenized concepts were coded into four slightly modified (Hinkel et al. 2015) first-tier components of the SESF: resource system (24 concepts), actors (22 concepts), governance system (13 concepts), and external environment (9 concepts) (Fig. 3). The three group FCMs each included a similar number of concepts, while the researcher model had a lower density of causal relationships than the other groups (Table 2). Across all stakeholder groups, FCMs had a consistently higher frequency and degree centrality of resource system and actor concepts compared to governance system and external environment concepts. The farmer FCM had the highest proportion of resource system concepts, while the government FCM had the highest proportion of actor concepts. The researcher FCM included the highest proportion of governance system and external environment concepts but was still dominated by resource system and actor concepts.

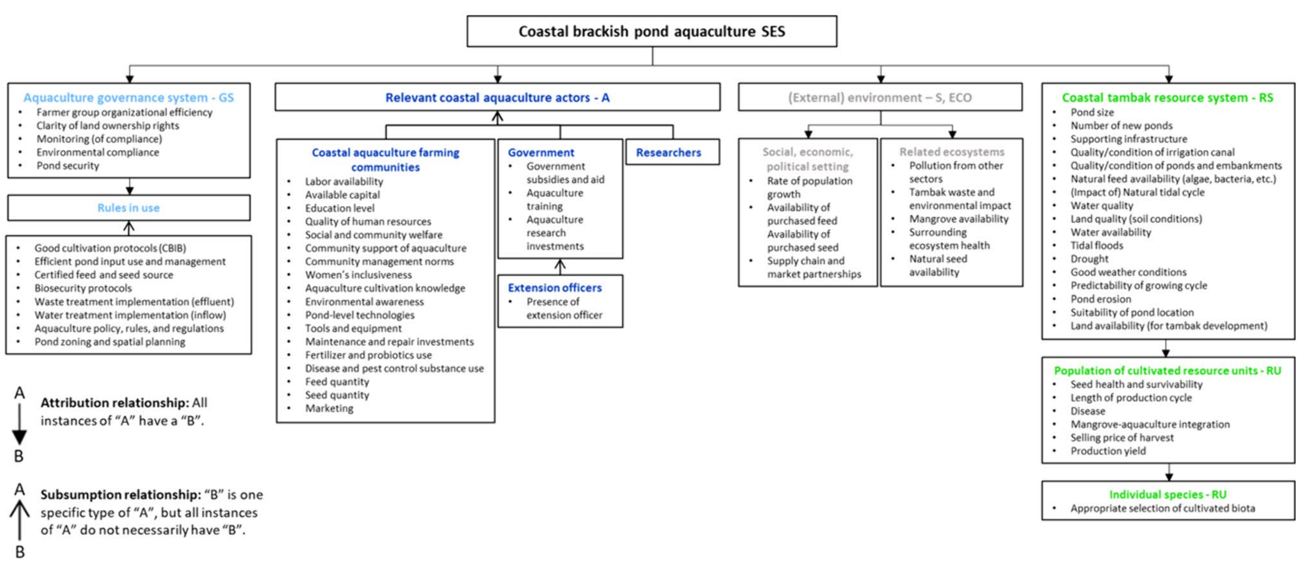


Fig. 3 All homogenized FCM concepts coded into the SESF first-tier categories using the approach of Hinkel et al. (2015). To facilitate comparisons with other SESF studies, we additionally coded concepts to the 2nd-tier variables of the SESF (Figure S4)

Table 2 Descriptive FCM metrics. All values for individual FCMs besides # of FCMs are denoted as mean values (standard deviation). All values for stakeholder group FCMs are raw values

	Individual FCMs ($n=37$)			Stakeholder group FCMs ($n=3$)		
	Farmer FCM	Government FCM	Researcher FCM	Farmer group FCM	Government group FCM	Researcher group FCM
No. of FCMs	16	11	10	–	–	–
Total components	10.19 (2.69)	11.91 (4.21)	9.80 (3.29)	48	48	50
Total connections	10.81 (3.62)	14.18 (4.85)	11.30 (5.70)	138	128	98
RS proportion	0.49 (0.12)	0.32 (0.15)	0.42 (0.16)	0.40	0.31	0.30
A proportion	0.33 (0.12)	0.41 (0.21)	0.26 (0.09)	0.38	0.40	0.32
GS proportion	0.07 (0.11)	0.15 (0.21)	0.21 (0.19)	0.13	0.17	0.22
E proportion	0.10 (0.12)	0.11 (0.14)	0.11 (0.10)	0.10	0.13	0.16

Across both individual and group FCMs, actor concepts had a significantly higher average outdegree than other concepts, meaning the aquaculture SES is perceived as most heavily influenced by actor-related factors (Figures S5, S6). Resource system concepts had a higher average indegree than other concepts, meaning these concepts are the primary "receivers" or outcomes within the SES. Outside of several significant differences in representation of the RS and A categories (Figures S11–S13) there were few major significant differences in between-group SESF first-tier frequency or centrality, although there is substantial variation at the level of individual concepts (Fig. 4). In the following sections, we descriptively characterize these variations in how the SES is modeled, across the three stakeholder group FCMs.

Farmer group FCM

The farmer FCM (Fig. 5a) had the highest number of resource system concepts of any group, including three RS concepts unique to the farmer FCM, "impact of natural tidal cycle", "drought", and "predictability of pond conditions". In addition to "water quality" and "production yield", which were some of the most central concepts across all stakeholder groups, the farmer FCM reflects the resource system risk-management challenges affecting the day-to-day operations of aquaculture production for farmers in NTB, including "tidal floods", "disease", "pond erosion", "good weather conditions", and "quality/conditions of ponds and embankments". The most central indegree concepts in the farmer model consisted almost exclusively of resource system concepts including "production yield", "water quality", "disease", and "seed health and survivability", suggesting that farmers view both overall production as well as the stability or predictability of the aquaculture resource system as the most important system outcomes. The farmer FCM had the lowest proportion of governance system and external environment concepts of any of the stakeholder groups. Meanwhile, the strongest driver concepts in the farmer FCM included several actor variables which are primarily related to the perceived importance of government support to improve resource system outcomes, notably "available capital", "aquaculture training", and "government subsidies and aid". Farmers also viewed water quality and impact of tidal flood events as important drivers of production outcomes, and were the only stakeholder group to explicitly touch upon gender issues within the coastal pond aquaculture sector, through the "women's inclusiveness" actor concept.

Government FCM

Stakeholders from local Departments of Marine Affairs and Fisheries (DKP) manage coastal pond aquaculture to meet central Ministry of Marine Affairs and Fisheries (MMAF) goals of increasing overall production capacity and efficiency by intensifying aquaculture production. These goals are reflected in the government FCM (Fig. 5b), which identifies concepts such as "production yield", "pond-level technologies" (technologies relating to production intensification), "quality of human resources", and "supporting infrastructure", as the most important receivers within the system. The most central drivers were entirely social concepts from the actor tier, including "aquaculture cultivation knowledge", "government subsidies and aid", and "aquaculture training". "Pond-level technologies" and "quality of human resources" were identified as both strong driver and receiver concepts. Important governance concepts for government stakeholders included the adoption of the Indonesian government's good aquaculture practices protocols (CBIB, Indonesian: Cara Budidaya Ikan yang Baik), and increasing the certification status of aquaculture seed and feed producers. Key external environment concepts included the overall market availability of purchased feed inputs, as well as increasing business partnerships between local farmers and other actors along the value chain (a concept unique to the government FCM). Additional unique concepts included "community management mindset", reflecting the

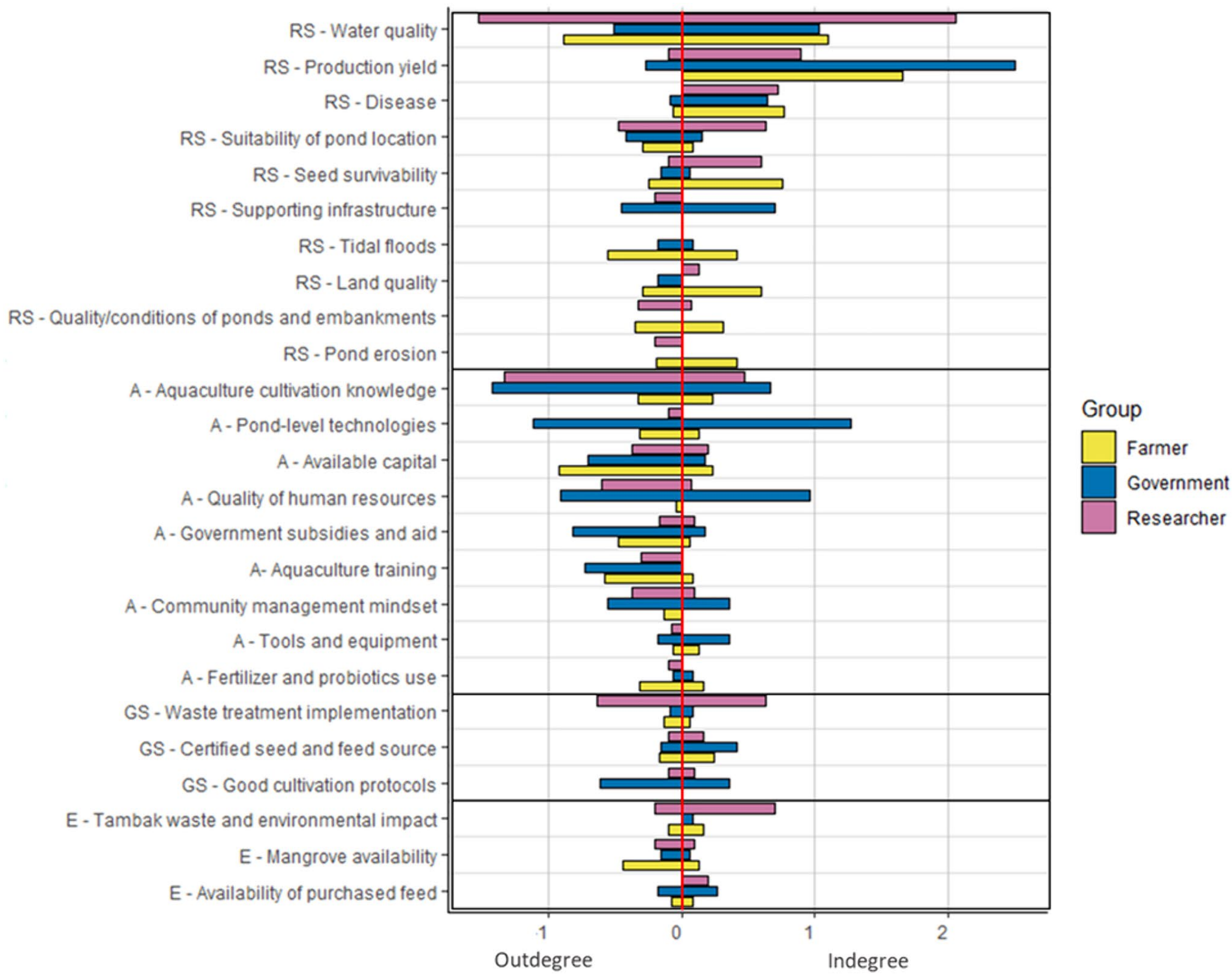


Fig. 4 Outdegree (left) and indegree (right) centrality values of 25 of the most central concepts across the three stakeholder group FCMs. Total length of each bar represents overall degree centrality

viewpoint that farmers should see aquaculture as a primary, and not only secondary livelihood.

Researcher FCM

In comparison to the farmer and government manager FCMs which viewed production yield as the most central receiver, the researcher community FCM (Fig. 5c) identifies water quality as both the most important driving and receiving concept, while also having the higher proportion of governance system and external environment concepts of any group. Like government managers, researchers also identified "aquaculture cultivation knowledge" and "quality of human resources" as key influencing concepts; however, researchers were the only group to identify "waste treatment implementation" as a highly central governance concept. This concept relates to government waste treatment rules meant to reduce wastewater impacts from pond aquaculture farms to the surrounding environment. Some researcher respondents, however, viewed current waste treatment regulations as insufficient and requiring strengthened "aquaculture policies, rules, and regulations" to improve. The researcher FCM placed the strongest emphasis on the connection of coastal pond aquaculture to related ecosystems in the external environment, including identifying "mangrove availability" and "tambak waste and environmental impacts" as some of the most central concepts. Additional concepts unique to the researcher FCM included "surrounding ecosystem health", "aquaculture research" and "environmental compliance".

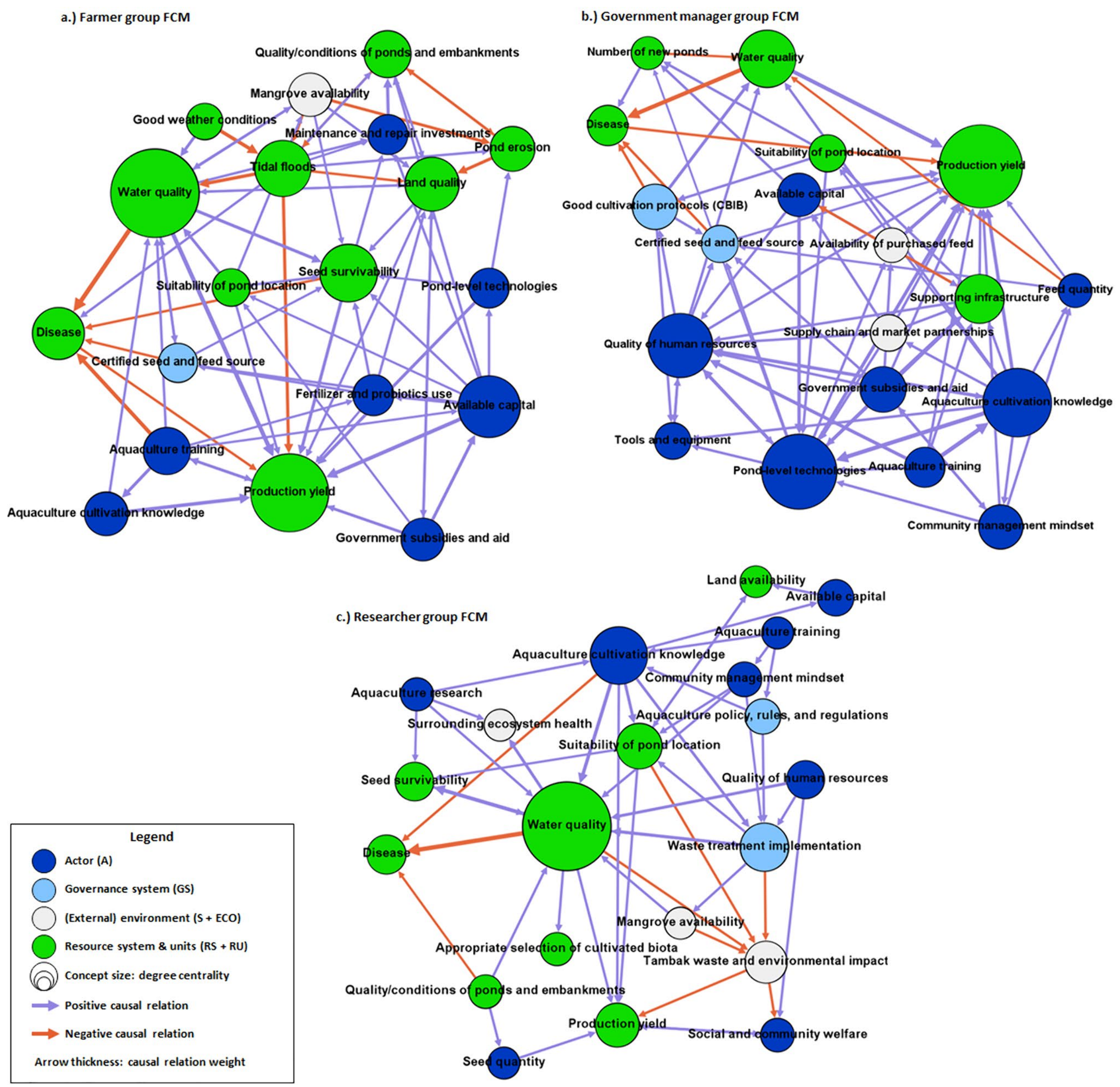


Fig. 5 Aggregated group FCMs of **a** farmers, **b** government managers, and **c** researchers. Visualizations reduced to circa 20 most central concepts to increase readability, see Supplementary Information for complete FCMs for each stakeholder group

Qualitative validation of representativeness of models

Qualitative feedback was acquired from 28 of the 37 original respondents in September–October 2022. All 28 follow-up respondents reported that the group FCMs adequately reflected the shared beliefs of their group. Two farmer and one government respondents suggested two important concepts were missing from the final models, which we discuss further in "Social drivers, limited governance: key patterns across stakeholder group FCMs" section.

Steady-state simulations of SES interactions and outcomes

To compare differences in perceived SES interactions and outcomes, we analyzed two "what-if?" simulation scenarios: (1) increase in aquaculture cultivation knowledge (A), and (2) decrease in water quality (RS), the two concepts generally viewed as the strongest actor and resource system drivers, respectively, and the two concepts identified by the most respondents as most likely to change over the next five years. Governance system (GS) and external environment (E) scenarios were explored but dropped as the weak influence (outdegree) of these concepts led to minimal predicted changes. We compared simulation outcomes across all concepts which were shared across all three stakeholder groups (Fig. 6). All simulations reached a steady state within 20 iterations.

In both scenarios, there was complete agreement across all three groups (in terms of both the existence and direction of predicted state changes) for only a handful of concepts, which were primarily outcomes relating to RS concepts such as water quality, disease, and production yield. At the same time, there were almost no cases of groups predicting opposite direction state changes, indicating a general degree of agreement on the dynamics of the SES. In the increased aquaculture cultivation knowledge scenario (A), all three groups perceived state changes in the system across all four first-tier SESF categories, suggesting that actor-related concepts are perceived as influential to all components of the SES. Researchers perceived the most state changes to RS concepts such as a decrease in disease and increase in water quality and suitability of pond location. The government FCM meanwhile produced the strongest state changes to actor concepts, including an increase in pond-level technology adoption and quality of human resources. In the decreased water quality (RS) scenario, all three stakeholder group FCMs predicted negligible state changes to any actor concepts, suggesting that the coastal pond aquaculture resource system is not perceived as influential to actor concepts by any of the stakeholder groups. Additional simulation analyses evaluated the average perceived influence of all variables from each SESF first-tier category and group FCM on simulation outcomes. Actor concepts were consistently the only SES category viewed as influencing the entire SES, while RS, GS, and E concepts were in most cases only perceived as influencing the RS (Figure S7).

Community FCM

The community FCM (Fig. 7), which includes only concepts and causal relationships agreed upon by the majority of stakeholder groups, is dominated by two resource system concepts, "production yield" and "water quality", as the most central concepts in the system, followed by "aquaculture cultivation knowledge" (A), "available capital" (A), and "disease" (RS). The majority of stakeholder groups perceived both water quality and production yield as each being casually connected to 15 other concepts, suggesting an agreement across stakeholder groups on not only the importance, but also complexity, of these topics. Consistent with stakeholder group FCMs, governance system and external environment concepts are lower in frequency and centrality than other SESF categories, but the community FCM demonstrates a majority agreement on the influence of 6 governance concepts and 4 external environment concepts to the coastal pond aquaculture SES.

Discussion

In the following sections, we first interpret important differences between-group FCMs which represent potential collective action challenges. We then highlight key trends across all stakeholder group FCMs in how aquaculture is

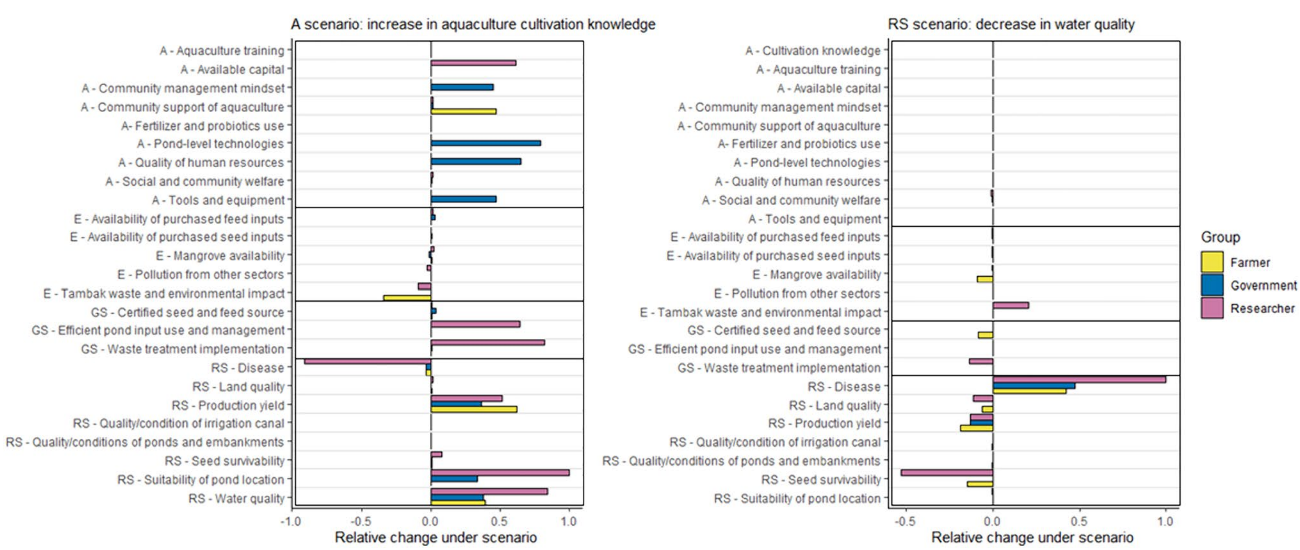


Fig. 6 Left: Actor-related scenario (increase in aquaculture cultivation knowledge.) Right: Resource system-related scenario (decrease in water quality)

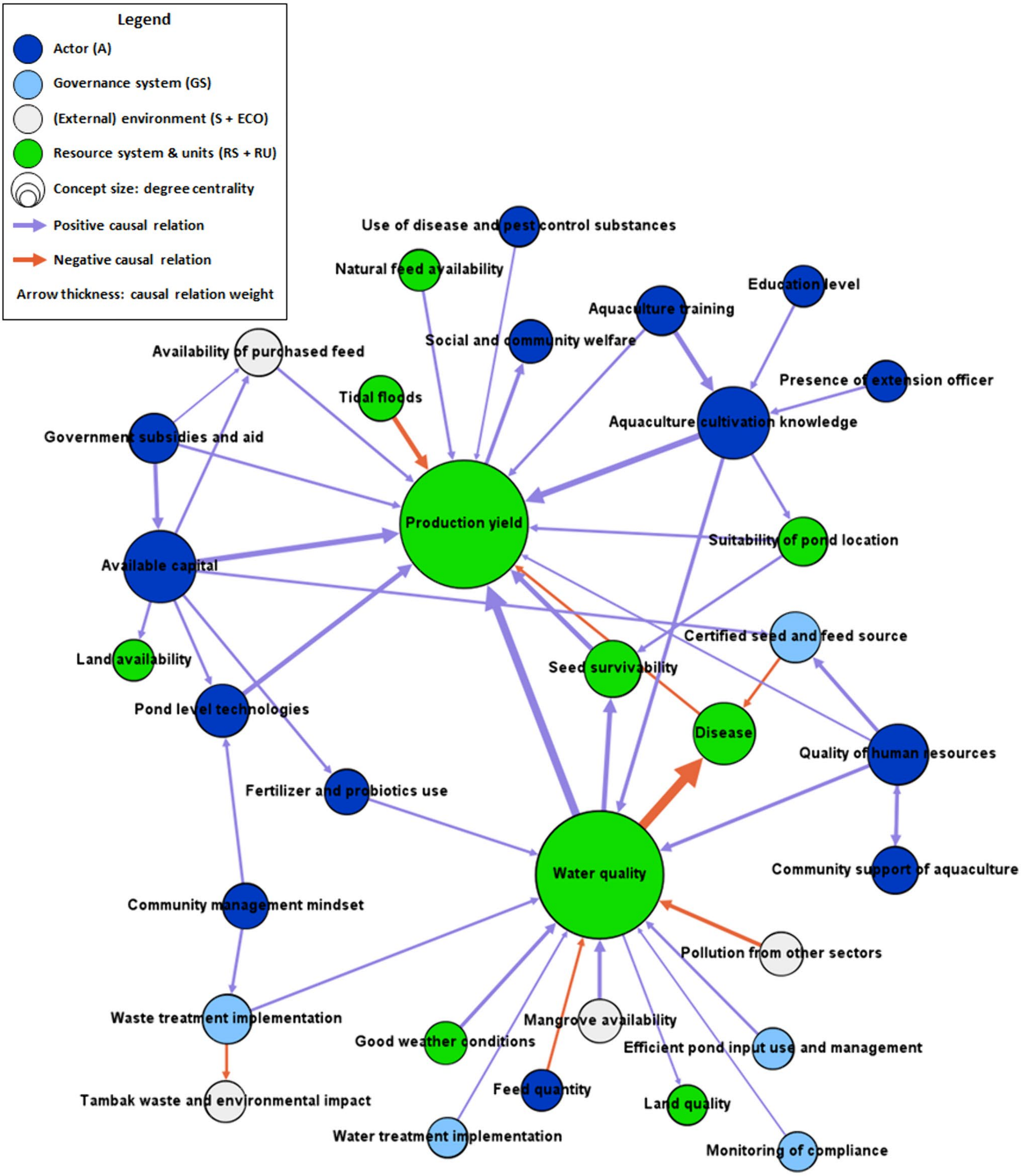


Fig. 7 Median-aggregated FCM of all three stakeholder groups. $n = 33$ concepts, $n = 48$ causal relationships

perceived as a SES. Finally, we discuss the community FCM as a starting point for informing collective action and developing a shared vision for pond aquaculture development in NTB.

Increase production, but how? Key differences in stakeholder group FCMs

We observe differences between the FMCs of the three stakeholder groups. But do these differences matter? Both farmers and government managers agreed that production yield is the most important receiver variable. However, their models identify very different causal pathways to increasing production. The government model is heavily oriented around actor-related issues which relate to central government development goals of 'modernizing' traditional pond systems through intensification. For example, in the simulation scenarios, government managers associated increased knowledge with increasing farmer adoption of pond-level technologies, improving the quality of human resources to meet the higher technical and maintenance requirements of intensive production, and improving the "community management mindset" to view pond aquaculture as a primary and not only supplementary livelihood. This approach is to some extent supported by research which suggests that if properly governed, increasing production intensification can increase land and water use efficiency and decrease mangrove deforestation. However, it is also likely to incur sustainability trade-offs such as increased disease impact and capital investment requirements (Rimmer et al. 2013; Henriksson et al. 2019), two factors which are highlighted in farmer FCM results as major existing issues in NTB.

The farmer model reflects more near-term challenges to stable production, such as "tidal floods" and "pond erosion" which represent major risks to whole harvests. Yet, these production risks to farmers marginally appear in the government FCM and are completely missing from the researcher FCM. The prevalence of disease outbreaks in NTB has also influenced many fish farmers to transition from more disease-prone shrimp production to lower-value but more stable milkfish and salt production. Due to these issues many fish farmers struggle to achieve financial independence and long-term profitability, relying on government subsidies and aid, and pond abandonment is widespread. These financing issues are reflected in the most central driver in the farmer FCM, "available capital". In follow-up discussions, all traditional farmer respondents reported a strong interest in adopting more intensive "pond-level technologies" but viewed the government focus on technology adoption for intensification as incongruent with the on-the-ground reality, where flooding, disease outbreaks, unstable production and lack of available capital are immediate barriers which need to be addressed. Government-driven trends towards intensifying production are often tied to increased industrialization which has the potential to leave smallholders behind (Belton et al. 2018), although this pattern is not universal (Ha et al. 2013). While both government and farmer mental models agree on increasing production yield and stability as long-term outcomes, there is a lack of consensus on what the short-term transitional steps should be to increase production efficiency while keeping small-scale farmers included.

Compared to other groups, the researcher FCM emphasizes water quality management and maintaining ecosystem health. In the simulation scenario, contrasting the other two groups, the researcher model captures the importance of developing institutions and adopting protocols and technologies to monitor and improve water quality. This is both to stabilize pond growing conditions and to mitigate harmful impacts of pond wastewater on the surrounding environment. At the same time, addressing these issues through stricter environmental compliance measures is perceived as incurring costs for the producers and might result in actual costs in the short-term. This trade-off represents a key tension point between groups in developing a shared vision for aquaculture. As noted by one researcher respondent, "how the three groups have to work together to align these two [water quality and production yield], I think that is the biggest challenge". Input from aquaculture researcher respondents, predominantly consisting of natural scientists, additionally emphasized a need for more social and economic aquaculture research which is currently lacking in the region to better inform local stakeholders regarding the costs, benefits, and trade-offs involved in developing stronger institutions for water quality management and environmental monitoring.

Certain differences in stakeholder group mental models represent potential conflicts of interests which need to be addressed and negotiated to develop shared goals amongst stakeholders. They also demonstrate that including knowledge from multiple types of stakeholders creates a more complete understanding of the aquaculture social–ecological system, such as the impacts of increasing tidal flood severity on pond aquaculture resource system dynamics captured only by farmers. In both cases, these findings suggest that collaborative governance involving local resource users is needed.

Social drivers, limited governance: key patterns across stakeholder group FCMs

Across all stakeholder groups, resource system concepts were not perceived to be as influential as the social ones. Aquaculture is viewed as a highly actor-driven development process. This pattern suggests that stakeholders identify social drivers, such as farmer actions and decisions, as more easily influenced or changed in comparison to ecological drivers which are difficult to control (e.g., climate conditions). In essence, our findings emphasize the perceived social challenges of NTB aquaculture development. Therefore, the desire to improve key resource system outcomes—such as water quality, disease mitigation and production—will largely depend on engaging with actor-related social issues. This includes, from our findings, the lack of aquaculture knowledge and training, financial risk and lack of capital, as well as addressing limited access to technologies to increase production efficiency. These central actor-related concepts can be thought of as the key action parameters, or leverage points (Leventon et al. 2021) for enabling collective action across NTB aquaculture stakeholders.

Addressing social challenges, however, requires governance in the form of appropriate institutions. Surprisingly, little emphasis was attributed to both the frequency and influence of governance-related factors on the aquaculture SES, particularly by government managers and farmers. The under-representation of governance factors at least partially reflects a lack of collaboration between actor groups, as well as a lack of collective action between farmers in some communities. In follow-up discussions, many farmers reported that the lack of governance concepts reflected their viewpoint that the government was not adequately involved in their livelihoods, farmers were not being engaged in aquaculture policy-making and program development, and that rules and policies for aquaculture were unclear or not relevant to them. For example, some farmers reported that the concept CBIB (MMAF best aquaculture practices) was only useful for large-scale shrimp producers and not relevant for the challenges in their communities. We interpret these findings as at least in part reflecting stakeholder experience that governance in the sense of government or active regulation of Indonesian aquaculture, does not become apparent in daily life, a challenge often noted in the wider Indonesian natural resource governance literature (Riggs et al. 2018; Nurlinah and Haryanto 2020; Putri et al. 2022). Most interviewed farmers are dependent on government subsidies but otherwise reported minimal government influence. Government natural resource policy in Indonesia has often been criticized as being highly disconnected from local communities (Talib et al. 2022), and better integration of local actors into decision-making and deliberation processes with local governments are needed to foster shared understandings regarding the need for strong locally adapted governance to improving aquaculture outcomes. Of the governance concepts that were present, nearly all related to top-down government rules and policies, while concepts related to the role of community or farm-level governance were largely missing. The Indonesian government uses aid and subsidies to incentivize farmers to self-organize into farmer groups (POKDAKAN) to encourage local, bottom-up group management of shared aquaculture challenges, but it remains unclear to what extent farmers in these groups are actually self-organizing to develop institutions for managing CPR dilemmas (Partelow et al. 2018). Still, during follow-up discussions, some farmer and government respondents reported that the final FCMs were missing important concepts relating to community-based natural resource governance, including "gotong royong" (Indonesian societal concept of "working together", with parallels to the concept of collective action) and "awig-awig" (customary community-based natural resource management rules) in brackish pond aquaculture management (Feruzia and Satria 2016; Lukiyanto and Wijayaningtyas 2020). Two farmer respondents in separate regions attributed the collapse of neighboring pond aquaculture networks entirely to the lack of awig-awig in those communities. Further research is needed to explore the extent to which collective action is (or is not) emerging to solve shared resource dilemmas in Indonesian smallholder fish farming communities, and how existing customary community-based institutions can be leveraged to improve bottom-up aquaculture governance (Partelow et al. 2022).

Moving forward: community FCM of shared aquaculture knowledge

Governing aquaculture systems requires collective action to meet sustainability goals, and the more consensus there is regarding how the aquaculture system functions—and its problems to be addressed—the more likely collective action is. The community FCM highlights areas of majority agreement across the actor groups, allowing us to identify three central governance challenges that stakeholder groups generally agree upon (Fig. 8). We adopt the Ostrom terminology of the 'action situation' to describe them, within the context of aquaculture governance and deliberation, as three key issues regarding provisioning challenges within which these actors are acting and influencing each other and must collectively act to solve. We also briefly summarize how these action situations might be used as leverage points to adjust local aquaculture policy to address jointly understood local challenges.

The first action situation regards the issue of water quality. A common expression shared by respondents from all three groups said "aquaculture farmers cultivate water, not fish". Indeed collective action challenges relating to the management of water quality and provisioning of canal systems have been frequently linked to stock collapse and pond abandonment (Rimmer et al. 2013; Henriksson et al. 2017). The community FCM indicates strong causal relationships between water quality, disease and production yield, making it a central, complex and multidimensional challenge with social and ecological variables. In the community FCM, this is the only action situation with a clear agreement regarding the role of governance and appropriate governance interventions, including the need for waste treatment regulations and compliance, as well as efficient operational rules regarding use of pond inputs. Follow-up discussions highlighted that some respondents viewed current pond water and waste management regulations as insufficient and ineffective, and that farmers have little incentive to move beyond the bare minimum in implementing waste treatment facilities. Interventions in the form of institutions

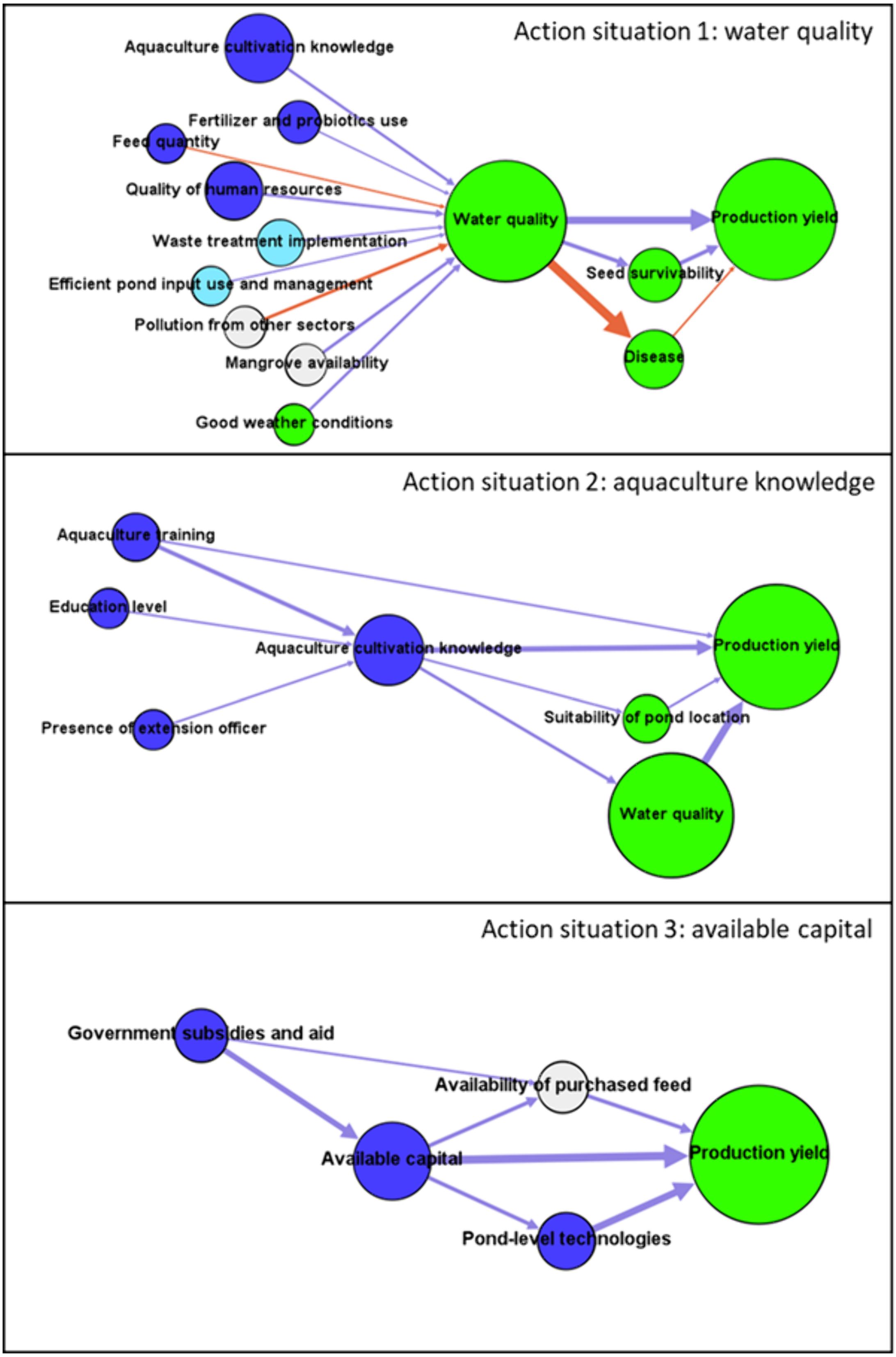


Fig. 8 Three action situations (important interactions and outcomes) in the coastal pond aquaculture community FCM

regarding the provisioning of canal maintenance, a critical issue for maintaining pond water quality (Partelow et al. 2018; Senff et al. 2018), also seem to be missing from the community model.

The second action situation encompasses the provisioning of aquaculture knowledge. While training is commonly understood as key to provisioning knowledge, local governments and extension officers often lack capacity to provide extensive technical training programs to communities. Most farmer respondents reported limited access to technical training, and unlike more established sectors there is often little community-based generational knowledge to turn to. In some cases this leads to the inability of farmers to recognize important shared resource dilemmas leading to reduced incentives for collective action (Partelow et al. 2018; Senff et al. 2018). The aquaculture knowledge action situation reflects the shared understanding of stakeholders that limited technical knowledge capacity is a critical barrier for development of the sector, but what types of knowledge and how to provision it are key challenges missing from the community FCM which stakeholders will need to address.

The third action situation involves access to and provisioning of available capital. Farming capital and financing are a major social challenge for farmers, who often lack initial investments into pond technologies which government programs and strategic plans would prefer. Farmers also have limited financial safety nets to deal with production instability and high risks of disease and pond collapse, contributing to widespread production failure and pond abandonment which still persists. The government subsidizes pond inputs such as feed and seed which helps support a business-as-usual trajectory, but moving forward stakeholders need to identify appropriate institutional solutions for financing and risk-management from widespread production uncertainty.

Aquaculture development programs in Indonesia are heavily government-dominated and scholars are increasingly advocating to improve public participation and knowledge co-production in environmental governance (Talib et al. 2022; Permana et al. 2023; Salman and Mori 2023). Our results demonstrate how FCM can be useful as a starting point for this process as a tool for structuring and comparing stakeholder social–ecological system knowledge which could be integrated into future processes of shared deliberation and decision-making.

The community FCM can be directly used as an applied tool for multi-stakeholder collaborative governance in the region. It summarizes the main findings of the project into a simple visual image that can be used for discussing governance pathways among the three groups. We, as external actors to the system, cannot decide or say how the system can be most effectively governed to meet the needs of each group. We can, however, provide tools such as the community FCM to help facilitate constructive deliberation on potential paths forward on the relevant identified topics. The three action situations offer starting points to focus discussion. Moving forward to address each likely involves tradeoffs in where to focus often limited time and financial resources. The FCMs help to identify potential effects of variable changes within the complex system, helping to make the different groups aware of what can or could be changed, but also how the other groups perceive the importance of those potential changes. Potentially important questions to consider include the following: how is technical training and knowledge provisioned, who has access, and who provides it? How is financial risk managed or adoption of intensive pond technologies financed? How is shared canals' maintenance incentivized? What rules are needed to coordinate release of polluted pond water and mitigate disease spread between ponds?

We presented these findings in workshops, seminars, and follow-up discussions with NTB actors from the three studied groups in May and June 2023. While only a starting point, these activities suggested a strong interest and support regarding the three action situations, which helped prompt discussions between respondents and researchers regarding how policy could be adapted to address them, and have further informed the development of an Indonesian-language policy brief. For example, potential future directions for adapting policy to address water quality could include the implementation of management training programs aimed at improving capacity of pond farming communities to coordinate and self-organize their own rules for provisioning shared canal maintenance and mitigating disease cross-contamination. Shared understandings regarding the importance of mangroves for stabilizing water conditions additionally suggests that some aquaculture communities may be receptive to mangrove restoration and silvofishery programs (Basyuni et al. 2018; Susilo et al. 2018). Regarding provisioning aquaculture knowledge, possible policy adjustments could include aquaculture farm surveys or workshops with aquaculture community leaders in each district to develop training programs more directly targeted at local needs and aquaculture development goals. For example, farmers in one workshop suggested that capacity-building programs in their district would be improved by emphasizing business management training which is lacking in their community, rather that technical production training. Finally, regarding financing and access to capital, one potential policy pathway is to explore how long-established crop insurance schemes common in the agriculture sector might be adapted to aquaculture as a strategy to support farmers in dealing with the severe challenges of production risk.

Primary reported feedbacks from respondents on the FCM exercise included the visual interpretability of the exercise, and as a learning and communication tool specifically in the way the exercise encouraged a "systems thinking" approach focused on relationships between factors. Future research might further explore how FCM can be applied to directly support environmental management and inclusive governance, such as recent studies applying FCM to support selection of appropriate environmental management indicators (Game et al. 2018) or to support community decision-making (Mehryar and Surminski 2022).

Study limitations and reflections

Sampling issues are challenging in rural contexts, particularly among groups that have histories of conflict and sentiments of distrust among public officials, foreigners and prior research projects. Our government sample was skewed towards Sumbawa participants due to an increased willingness of these respondents to participate, potentially due to differences in scheduling, availability, or incentives to participate between officials in the more populated and urbanized Lombok island, which has historically received relatively more research attention, and the more rural and sparsely populated Sumbawa island. Conversely, our reliance on in-person FCM for farmer interviews led to an over-representation of Lombok farmers in our sample, who were more geographically accessible. It is thus difficult to evaluate how representative our results are of coastal pond aquaculture governance issues across the entire province. Gaining access to large industrial shrimp farming operations might have allowed a clear understanding of potential future development scenarios of aquaculture in NTB, as the high economic value of this export-oriented subsector means that these industrial farms will likely continue to expand and pay a key role in the province. We primarily collected FCMs from groups with a vested interest in expanding the aquaculture sector, and gaining access to more diverse stakeholders may have better highlighted social and ecological trade-offs or conflicts associated with aquaculture expansion in Indonesia (Table S1; Rimmer et al. 2013; Diedrich et al. 2019). Due to reduced scope of our data collection period due to the COVID-19 pandemic which limited the number of FCM interviews we conducted, we only evaluated one consolidated farmer group, but further disaggregating this large and diverse population may have provided a more detailed and nuanced understanding of the diversity of fish farmer mental models involved in multi-stakeholder governance of brackish pond aquaculture in NTB (e.g., wealthier intensive shrimp farmers vs lower-income traditional tambak farmers). For example, Aravindakshan et al. (2021) identified six typologies of agricultural farmers in south-central Bangladesh which were then compared using FCM. We also identify a need for further methodological reflection regarding how FCMs structure and represent stakeholder group knowledge, which is explored further in Appendix 1.

Critical reflections are additionally warranted regarding our positionality. Three of five co-authors, including the lead author, are western white non-Indonesians, which is certain to have influenced our interpretations of the final data (including our choice to interpret our findings through a predominantly western-derived framework). For example, mental models are likely influenced by a range of social–cultural factors, a stronger understanding of which may have added additional interpretation to our findings. We also faced limitations in our ability to interact with local actors included in our study in particular due to international travel restrictions due to COVID-19. More transdisciplinary integration of local actors throughout the entire study period as originally envisioned in our project would have allowed respondents a stronger voice in the problem orientation of the study and facilitated more opportunities to apply FCM as a tool for discourse around potential future development scenarios and adaptation pathways (Gray et al. 2019). Attempts taken to minimize (though certainly not erase) the negative impacts of parachute science within our project context included (1) developing our project from the proposal stage in close cooperation with local partners (two of five co-authors), (2) exploring opportunities to train and assist in career development of local research assistant team, (3) conducting student workshops at local partner universities to contribute to building local research capacity, and (4) coordinating dissemination activities at multiple project stages, including preliminary and final results, to discuss and inform policy recommendations with local government.

Conclusions

Fuzzy cognitive maps can provide powerful governance insights because they reveal how actors in a system think about how the system functions and its problems. Our study examined the similarities and differences in mental models between farmers, government officials and researchers, highlighting the influential and interconnected social and ecological factors in pond aquaculture systems. Our findings show that there are important differences between the mental models of each group with implications for governance. Farmers emphasized the need to address high short-term financial risks from a lack of resource system predictability and stability. Government managers focused on intensifying production, while researchers tended to indicate the importance of waste treatment implementation and reducing environmental impacts of aquaculture expansion. A singular aggregate model was created by combining the FCMs from all three groups. This community model shows key areas of agreement for making governance progress in the region focus around three action situations: (1) water quality, (2) aquaculture knowledge and (3) available capital. Policy and decision-makers should focus on strengthening institutions to govern these three action situations.

More broadly, pond aquaculture systems carry the burden of shared risk (e.g., flooding, disease, water quality, market changes), which is distributed among all farmers at the community level in different ways. To mitigate shared risk and to collectively make progress towards sustainable development, collective action needs to become a pillar of governance. However, it is unclear to what extent farmers are aware of their shared risk or the capability of customary or modern governing institutions in addressing these issues. What is clear is that increasing public participation and harnessing existing cultural customs for natural resource management may be important activities for government programs seeking to improve production outcomes through governance. We recommend that NTB decision-makers focus on capacity-building projects which emphasize improving water quality, building system knowledge and gaining access to capital. Finally, increasing production is viewed as the most important development outcome. It is also the only performance indicator reported by administrative districts about aquaculture development to the central government (MMAF). Our study suggests that there is a strong need to diversity the types of indicators that are measured and reported to improve the understanding of production trends and value of other development indicators from the sector such as income and financial risk on the social side, and environmental quality and impacts on the ecological side. This should be done in tangent with investments into more locally based social and economic research on the aquaculture sector in Indonesia.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-024-01545-y.

Acknowledgements We are grateful to all of our respondents who shared their time and knowledge for this study. We acknowledge and thank all our research assistants for their contributions to our data collection, dedication, and friendship. This study was made possible by funding from the German Ministry of Research and Education (BMBF) under the project COMPASS: Comparing Aquaculture System Sustainability (grant no. 031B0785). All data were collected under an Indonesian foreign research permit (No. 75/SIP/IV/FR/12/2021, No. 5/SIP.EXT/IV/FR/3/2023).

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability Data supporting the findings of this study are available in the Supplementary Information. Data for all individual FCM models analyzed in this study are available at: 10.6084/m9.figshare.26580295.

Declarations

Conflict of interest The present work has not been previously published, and does not contain any conflicts of interest. Financial support has been appropriately stated in the acknowledgements.

Ethical approval A standardized prior informed consent statement was read to each respondent in Bahasa Indonesia at the beginning of the survey, under the conditions that the data will be used for scientific purposes and individually identifying information would be kept confidential. Prior informed consent to participate was verbally received from all respondents before starting the survey. The study did not include minors. The study design and data collection methods were approved by the Ethics Committee of the Leibniz Centre for Tropical Marine Research (ZMT), in alignment with the standards of the German Research Foundation (DFG).

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