ZMT LEIBNIZ-ZENTRUM für Marine Tropenforschung

Verbundschlussbericht: COMPASS: comparing aquaculture systems sustainability to inform sustainable bioeconomy development

Kurzbericht

Vorhabenbezeichnung:	COMPASS: Comparing Aquaculture Systems Sustainability
Förderkennzeichen:	031B0785
Laufzeit des Vorhabens:	01.03.2020 - 31.12.2023
Berichtzeitraum:	01.03.2020 - 31.12.2023

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Part I: Short Summary

The project “COMPASS: Comparing Aquaculture Systems Sustainability” aimed to assess how the rapidly expanding aquaculture sector can transition towards coastal and marine sustainability to contribute as a central pillar to the global food bioeconomy. COMPASS explored and informed sustainability pathways for coastal aquaculture development through research in Indonesia, where the aquaculture sector plays a critical role in economic growth, livelihoods, and food and nutrition security. Through mixed-methods and an interdisciplinary social, economic, and ecological framework, COMPASS sought to provide problem-driven and solution-oriented research to inform transition of aquaculture towards sustainability through the case study of Indonesian coastal pond aquaculture. COMPASS is organized according to four working packages (Figure 1).

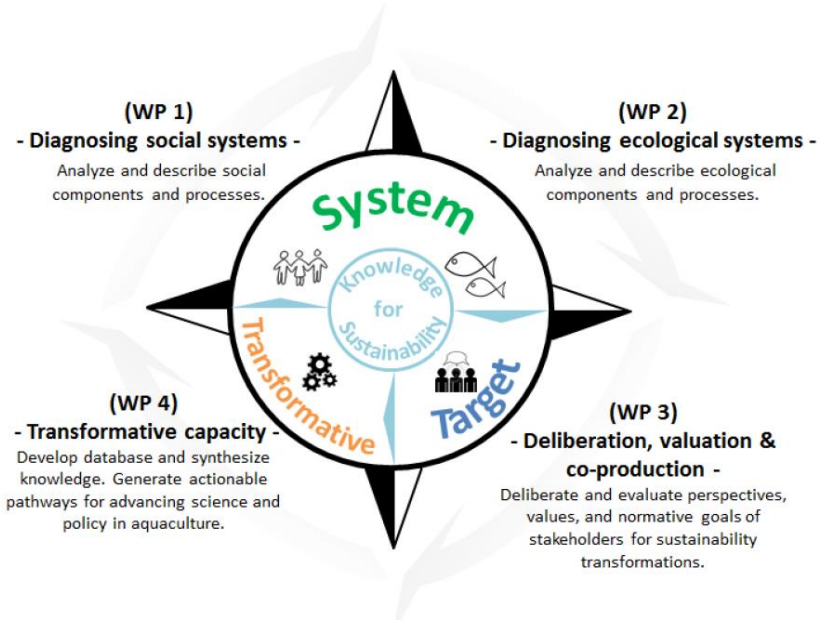

Figure 1. Working packages 1-4 of the Transitioning Aquaculture Ponds towards Sustainability: COMPASS project and the related system, target and transformative knowledge types for sustainability they aim to generate.

In WP1, research articles synthesized the diverse types of shared resources, or commons, that emerge in aquaculture governance, and reviewed the latest methodological trends with the social-ecological systems framework used in our research. These insights informed a diverse range of empirical research exploring Indonesian coastal pond aquaculture, which is dominated by small-scale community-based practices and relies on a diverse range of commons. Participatory modeling exercises with diverse local aquaculture experts in Indonesia developed models of the key social-ecological components and processes driving coastal aquaculture development outcomes, highlighting key collective action challenges for the sector while also reflecting the normative perspectives of different stakeholder

groups. Key issues drawn from the models include governance dilemmas around water quality management and disease outbreaks, aquaculture knowledge gaps, financial risk and lack of capital within farming communities. In-depth qualitative research and analysis of large-scale survey data further identified critical gaps in the lack of appropriate institutions for governing aquaculture, and mapped diverse combinations of collective action barriers and opportunities which vary across the heterogeneous context of small-scale coastal aquaculture communities.

In WP2, aquaculture community surveys connected these social and governance challenges with patterns in widespread issues of disease outbreaks, flooding, and mangrove deforestation, major environmental challenges for aquaculture communities. Additionally, research diagnosed the impacts of coastal shrimp farming in Indonesia on the surrounding ecosystem, by assessing waste discharge from coastal aquaculture and the impact on the surrounding coastal ecosystem. Addressing the social and ecological governance dilemmas identified requires coordination and collective action between relevant actors, and WP3 synthesized literature on deliberation in coastal contexts and investigated the role of deliberation and Indonesian cultural norms for collective action (Gotong-Royong) in informing sustainable development of pond aquaculture. A case study of several aquaculture communities involved in a government aquaculture irrigation policy program identified issues of fit between top-down program goals of strengthening Gotong-Royong and the diverse social-ecological realities of local communities, highlighting the need to better adapt policy to local conditions enabling or hindering collective action. An experimental study further explored how the social-ecological systems framework might be used as a deliberation tool for local stakeholder discussions around aquaculture governance, and reflected on how social and political culture in Indonesia influences deliberation processes in aquaculture communities. In WP4, reduced fieldwork due to the COVID-19 pandemic facilitated the development of additional synthesis research to advance aquaculture science and policy, including a keystone publication in Current Opinion in Environmental Sustainability combining insights from 30 aquaculture experts to define five key engagement arenas for aquaculture governance. Then, in the final project stages (May-June 2023), empirical “system” and “target” knowledge insights from WP 1-3 informed a range of workshops, Q&A sessions, lectures to discuss and deliberate COMPASS findings, which further informed targeted policy recommendations aimed at supporting actionable pathways for the sustainable development of the coastal pond aquaculture sector.

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Teil II: Eingehende Darstellung

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Part II: detailed report about the findings of Compass

The major results and outcomes of each WP are summarized below. A list of key academic and public outreach outputs is further provided in the Appendix.

WP1: Diagnosing aquaculture "social"-ecological system

WP1 is highly interlinked with WP2, and aims to build interdisciplinary social-ecological system knowledge of aquaculture systems with an emphasis on key **socio-economic** components and processes of aquaculture systems and appropriate methods for measuring them. Pond aquaculture, which dominates the aquaculture sector in Indonesia and much of the world, is highly reliant on commons or shared resources which create collective action problems that in turn require appropriate institutions to govern. In our case region in Indonesia, for example, large canal networks connecting ponds for water input and output are a critical common resource which requires coordination to manage and maintain. However, surprisingly little is known about the types of commons and governance arrangements that aquaculture relies on in comparison to other natural resource sectors. We developed a framework (Partelow et al. 2022) which helps conceptualize the types of collective action problems which can emerge from diverse combinations of commons that exist across the extremely heterogeneous aquaculture (Figure 1). Aquaculture systems rely on a range of first-order commons such as water quality, shared infrastructure, and disease mitigation, all of which require second-order commons (rules and norms, markets, property rights) to govern their use. Through four case examples, we demonstrated how the extreme heterogeneity of commons in the aquaculture sector means that the best combination of appropriate institutions is highly context-dependent. Insights from this article were applied in the empirical components of COMPASS which investigated the types of commons governance dilemmas emerging in Indonesian pond aquaculture, and potential pathways to address these dilemmas. In the future, our framework can be used to guide institutional analysis and diagnostic research in future aquaculture research to help fill this important knowledge gap.
A literature review was also conducted early in the project of the social-ecological systems (SES) framework being utilized to synthesized methodological trends with the social-ecological systems (SES) framework being utilized, and developed a methodological guide of best practices for improving knowledge synthesis and case comparability in social-ecological research (Nagel and Partelow 2022). This guide informed the design of the empirical research in this WP applying the SES framework to Indonesian pond aquaculture, where few studies have analyzed aquaculture from an interdisciplinary social-ecological perspective. Interactive participatory "mental modeling" activities were conducted to develop system dynamics models of the Indonesian coastal pond aquaculture system based on the expert knowledge of 37 local aquaculture stakeholders including farmers, government, and researchers (Nagel et al., in review, Figure 2).

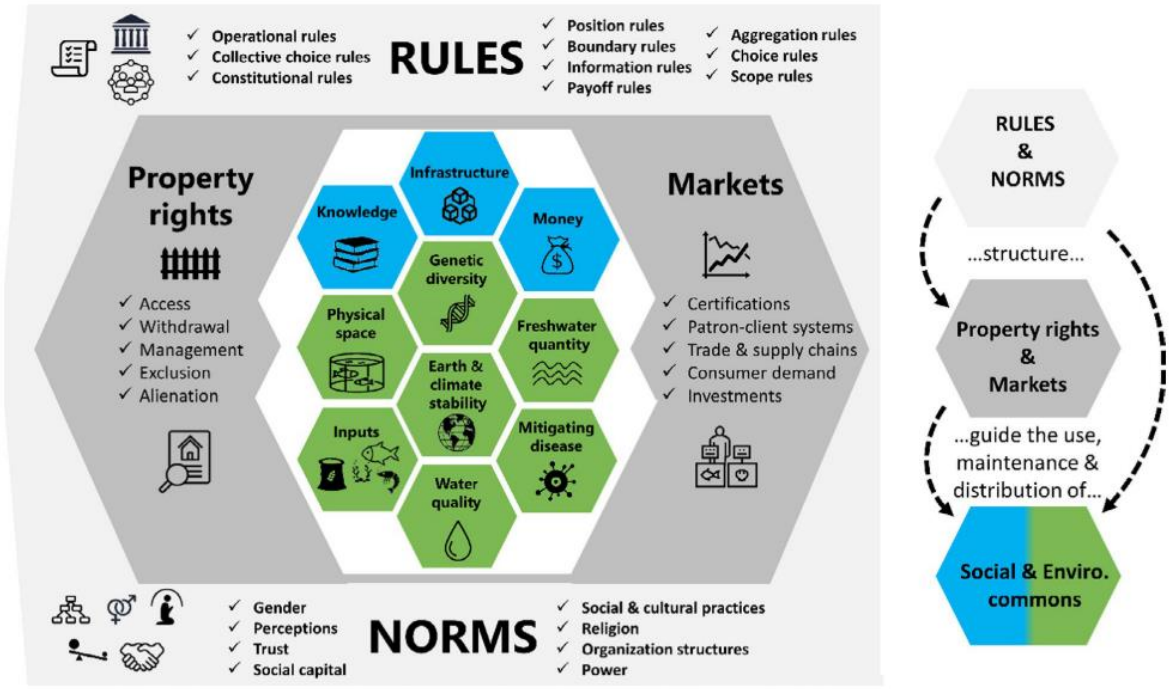

Figure 1. Conceptual framework for studying aquaculture commons. Rules and norms structure property rights and markets, which then guide the use, maintenance and distribution of shared resources. Rules and norms can also directly guide the use, maintenance and distribution of shared resources. Social and environmental commons are considered first- order collective action problems. The provision of institutions (rules, norms, property rights, markets) are considered second- order collective action problems that need to be provided in order to solve first- order collective problems of specific shared resources. The right side of the framework indicates the relationship between items. Numerous icons sourced from the Noun Project under a Creative Commons License.

In connection to COMPASS goals, these activities developed "system" knowledge about the aquaculture SES and how it functions, while also integrating "target" knowledge, as the models are developed entirely by stakeholders and include their own normative perspective about the system. The results highlighted key patterns in the social-environmental relationships and feedbacks driving widespread aquaculture challenges in the case region, leading to frequent production collapse and pond abandonment. Our findings demonstrated differences in how groups modeled the system which represent potential challenges for collaborative decision-making, particularly tensions between the government pushing for high financial investment and intensification of pond production, and the on-the-ground reality of many traditional, extensive pond farmers who lack the capital, knowledge, or risk support to make this transition. The models reflect perceptions of weak governance in the sector, and also highlighted consensus on several core governance challenges such as water quality management, lack of knowledge capacity, and financial risk and lack of capital, which could be used as leverage point issues for informing future aquaculture programs. Modeling of social-ecological systems is an immense challenge due to the often lack of information to inform the model, and the mental modeling tool demonstrated a promising approach for building complex aquaculture system models in data-scarce contexts through participatory knowledge co-production.

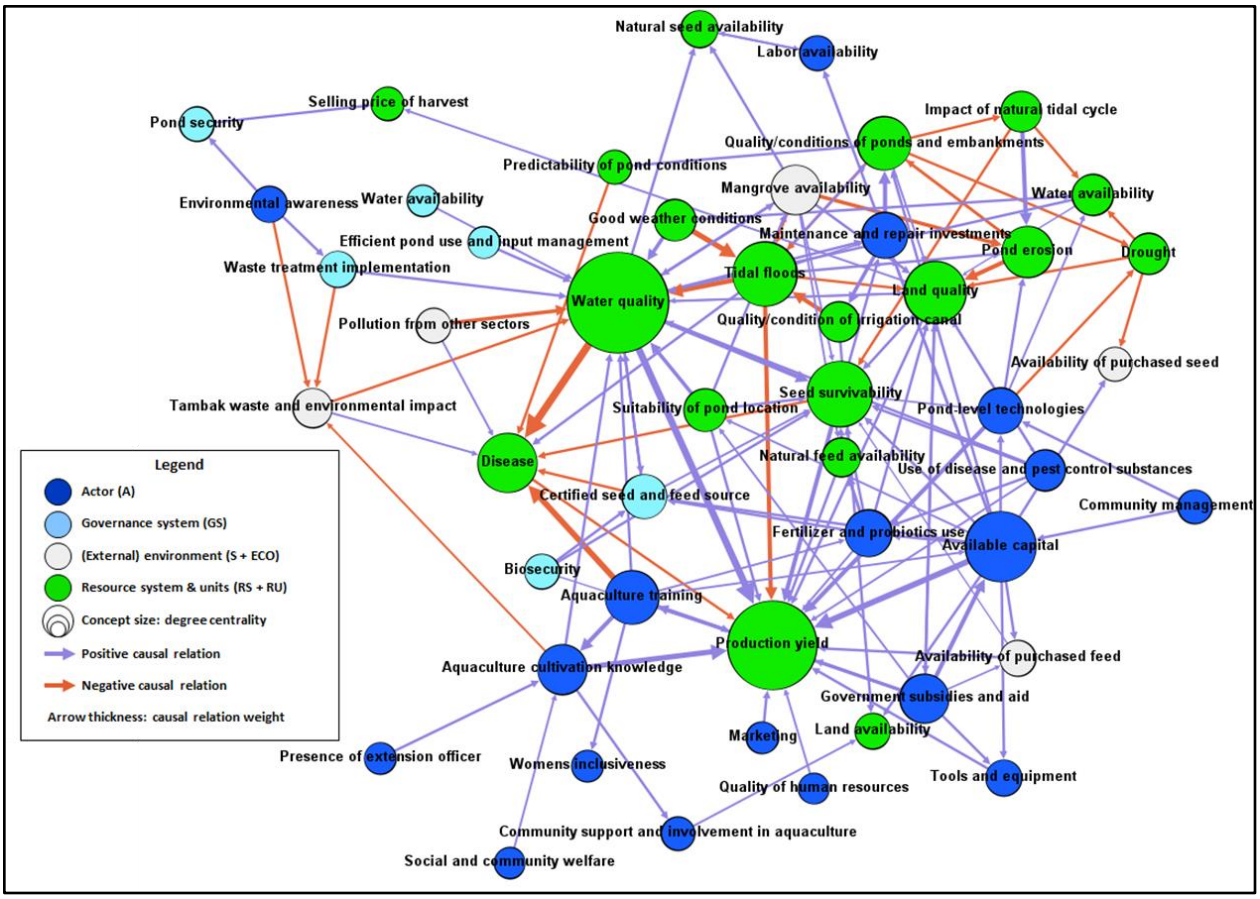

Figure 2. Shared fish farmer mental model of coastal pond aquaculture system, based on the inputs of 16 fish farmers in Nusa Tenggara Barat province, Indonesia.

We then empirically diagnosed pond aquaculture commons governance challenges at two different scales. First, we conducted an in-depth qualitative case study analysis of an aquaculture village in Gresik, Indonesia (Riany et al. 2023), to diagnose commons governance challenges using the SES framework. This study was led by a Master's student with a close familiarity with the study area, and outputs included both a research publication as well as a Master's thesis. Our results highlighted key governance issues as barriers to collective action: (1) limited access to capital and dependence on patrons, (2) lack of institutions for governing shared resources, (3) frequent failure of government aquaculture programs to meet goals, (4) lack of community leadership, and (5) lack of motivation and incentives to collectively act, as well as potential policy solutions (Table 1). We then conducted a large-scale survey across Nusa Tenggara Barat province to collect data on 26 social-ecological sustainability indicators from 85 pond aquaculture farmer groups called POKDAKAN, formation of which is encouraged by the government with the goal of fostering collective action (Nagel et al. 2024, Figure 3). We then applied the emerging archetypes approach from the sustainability science literature to help identify generalizable patterns in this highly large and dimensional dataset. Our findings demonstrated high heterogeneity in social-ecological sustainability challenges across groups, but we were also able to identify five typologies, or archetypes, of farmer groups which each share a similar "footprint" of commons governance challenges and opportunities. These results importantly demonstrate how top-down aquaculture policy prescriptions can be better adapted to the local context through a feasible middle-range of

generalizability such as our archetypes. Taken altogether, this empirical work demonstrated the important role of institutions for governing aquaculture commons and also the diversity of social and governance processes and challenges facing the sector, and that fostering collective action to improve the widespread production challenges facing pond farmers requires adjusting generic government programs to fit local needs. The research of WP1 was further developed as a part of a PhD thesis which has recently been successfully defended.

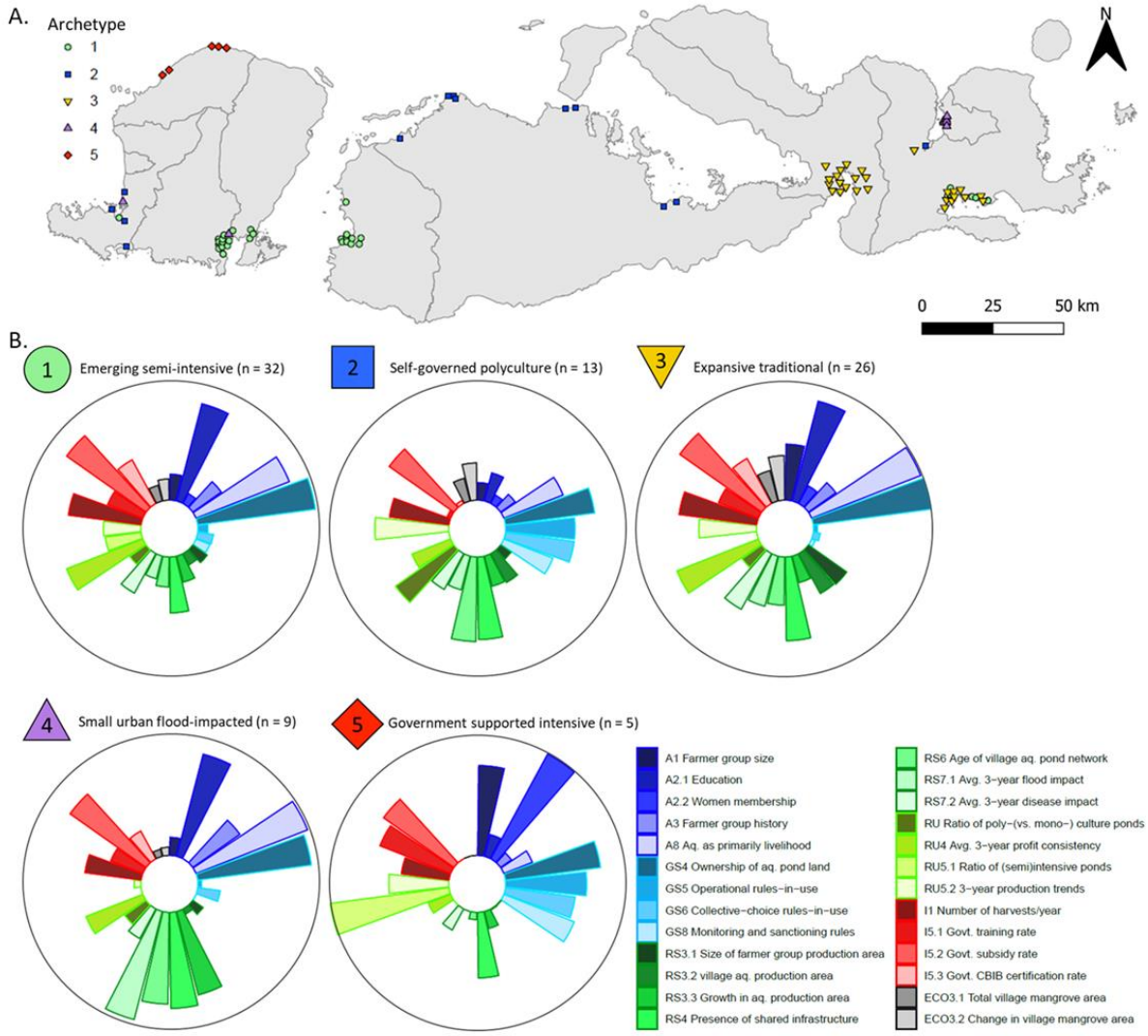

Figure 3. (A) Spatial distribution of farmer group archetypes across NTB province based on clustering analysis results. Farmer group locations are accurate to the nearest village district boundaries. (B) Flower diagrams for each archetype representing the average 0:1 normalized values of all indicators per archetype. Bars reaching the circle perimeter represent an average normalized value of 1 for that indicator. Different bar outline colors correspond to the 1st-tier SES framework categories.

WP2: Diagnosing aquaculture social-"ecological" system

WP2 is highly interlinked with WP1, aiming to build interdisciplinary social-ecological system knowledge of aquaculture systems with an emphasis on key **ecological** components and processes of aquaculture systems and appropriate methods for measuring them. Through the lens of social science methods implementing the social-ecological systems framework, empirical work of WP1 also directly informed the goals of WP2: (1) Our participatory modeling study (Nagel et al. in review) developed complex system models showing the highly interconnected processes influencing water quality, fish health and productivity, and disease outbreaks. Key identified drivers of environmental aquaculture outcomes including the quality and conditions of shared canal infrastructure and governance decisions, and to a lesser extent the availability and quality of surrounding mangrove forests. (2) Our large-scale survey (Nagel et al. 2024) showed that different typologies of aquaculture groups are impacted by varying combinations of environmental challenges which include disease outbreaks, flooding, production intensivity, monocultures vs polycultures, and mangrove deforestation. (3) Our in-depth qualitative research (Riany et al. 2023) found a critical lack of awareness of farmers regarding the link between shared canal upkeep and water quality conditions. Through the social-ecological lens, these findings mapped out how environmental challenges relate to different commons dilemmas and governance challenges, making top-down aquaculture policy a challenge as effective policy somehow needs to adapt to the varied contexts of pond aquaculture communities in order to be effective.

The objective of Work Package 2 (WP2) is to identify the primary ecological components and processes within aquaculture systems and to employ appropriate methodologies for their measurement. Consequently, researchers conducted several investigative activities at shrimp farming sites on Lombok Island and Sumbawa Island (Figure 4, Table 1). These activities included: 1) Assessing the relationship between the biodiversity of intertidal biota and the age and size of shrimp farms, 2) Determining the distribution patterns of water quality around shrimp farm effluent discharge areas and investigating their potential impact on substrate characteristics in the intertidal zone, 3) Evaluating the effects of shrimp farming effluents on intertidal biota using histological methods with the indicator species *Monetaria annulus*, and 4) Analyzing the diversity of intertidal biota using a DNA Barcoding approach to assess the effectiveness of this technique in elucidating the phylogenetic relationships among biota within the intertidal ecosystem at shrimp farm sites.

1. In the initial phase of our study, we collected data on the diversity of intertidal biota, with a particular focus on gastropods, situated in front of the outlets of shrimp ponds with varying operating ages and areas. Variations in age and area result in different discharges of liquid and solid waste, which, over time, reduce the dissolved oxygen content of the receiving waters, create hyper-nitrification leading to eutrophication, increase sedimentation loads, and potentially cause alterations in the resident organisms. Our findings indicate that the biodiversity of intertidal biota is greater in the dry season. Conversely, shrimp ponds that have been operating for extended periods exhibit reduced biodiversity, and those located in bay areas also show relatively low biodiversity.

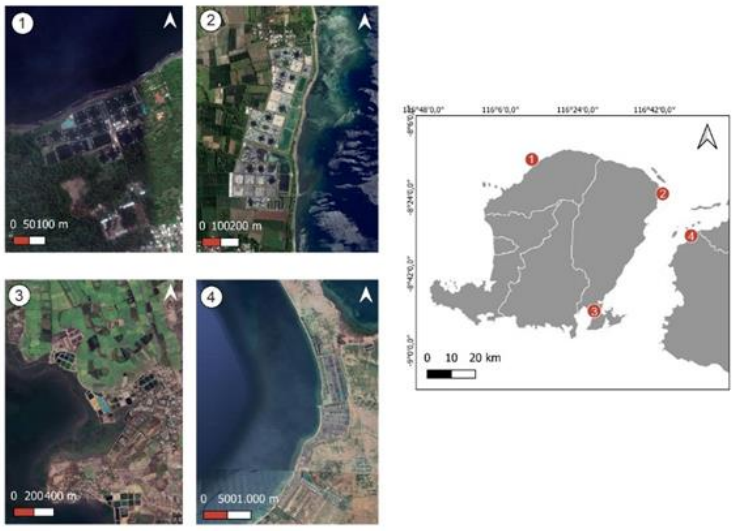

Figure 4. Sampling site; 1) Mumbul Sari, North Lombok 2) Sambelia, East Lombok 3) Pemongkong, East Lombok 4) Poto tano, West Sumbawa

Table 1. Diversity of intertidal biota (gastropods) and ecological index at each research site.

No	Sites	Familia	Genus	Species	Diversity Index (H')	Dominance Index (D)	Uniformity Index (E)
1	Mumbul Sari, North Lombok	10	14	22	2,264	0,129	0,836
2	Sambelia, East Lombok	16	19	27	2,708	0,103	0,821
3	Pemongkong, East Lombok	6	8	17	2,582	0,100	0,835
4	Poto Tano, West Sumbawa	9	10	16	1,768	0,255	0,624

2. The second study aimed to analyze the distribution pattern of water quality in areas surrounding discharges from shrimp farms and to investigate the potential impact of these discharges on substrate characteristics in intertidal waters (Figure 5). Discharges from *Litopenaeus vannamei* shrimp farming activities include solid and liquid wastes containing phosphorus, nitrogen, and organic carbon, while the liquid waste specifically contains ammonia (NH3-N), nitrite (NO2-N), nitrate (NO3-N), and phosphate (PO4). Generally, the water quality conditions at locations directly in front of the shrimp pond outlets are poorer than at surrounding sites. Additionally, the substrate in these areas is more clayey, which contributes to alterations in the biota community in these waters.

Figure 5. Outlet of shrimp pond waste from the research site.; A) Mumbul Sari, North Lombok B) Poto tano, West Sumbawa C) Sambelia East Lombok D) Water quality sampling

3. The histological method (Figure 6) utilizing the digestive gland of the mollusk *Monetaria annulus* as a test material to evaluate the impact of water condition changes at shrimp pond discharge sites has proven to be effective. This species was selected due to its consistent presence in the intertidal areas near the shrimp pond outlets observed during the study. The advantage of this method lies in its capability to microscopically analyze the tissue structure of marine animals, thereby identifying the accumulation of pollutants, such as heavy metals, and detecting dietary changes within the organisms. The results section demonstrates distinct histopathological differences in *Monetaria annulus* specimens collected from locations exposed to shrimp farming effluents in Lombok, Indonesia, highlighting the extent of the impact. Previous research has also indicated that the presence of shrimp farm effluent significantly affects water quality and the surrounding ecosystems.

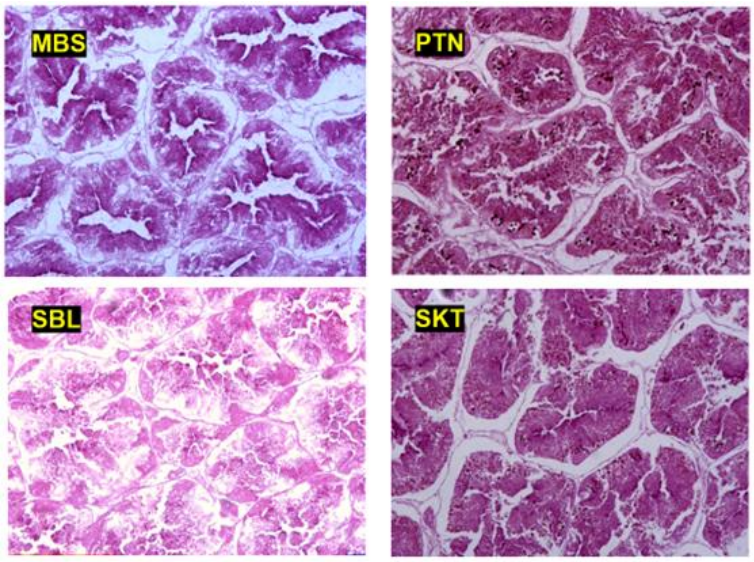

Figure 6. Image of histopathology results of the Monetaria annulus digestive gland obtained from the outlet location; MBS (Mumbul Sari), PTN (Poto Tano), SBL (Sambelia), SKT (Sekotong)

4. Initially, the study intended to employ the Environmental DNA (eDNA) method to explore the biodiversity of intertidal biota around the shrimp pond outlet locations, with the aim of comparing these results to those obtained using quadrant transects in the initial study. However, upon reviewing databases on platforms such as NCBI (National Center for Biotechnology Information) and BOLD (Barcode of Life Data) system, it was found that there was insufficient data on intertidal biota, rendering a comparative analysis impractical. Consequently, the decision was made to utilize DNA barcoding, focusing specifically on the genus *Cypraea* spp.. This genus was selected due to its consistent presence across all intertidal conditions at the study sites. The DNA barcoding method will facilitate a deeper understanding of intertidal biota biodiversity and their phylogenetic relationships. Currently, the research is in the preliminary stage of biota sampling in the field.

WP3 - Deliberation, valuation and knowledge co-production

The overall research objective of WP 3 is to evaluate perspectives, values, and normative goals of stakeholders to transform aquaculture governance towards sustainability. The research comprises four primary studies to achieve its aims. First, it sought to comprehend the utilization of the deliberation process in marine and coastal research based on existing literature. Second, it sought to evaluate the implementation of aquaculture policy programs, specifically examining their effectiveness in addressing the issue of fit. Third, it sought to develop an effective deliberation tool based on a scientific framework to guide discussion on collective action problems. Fourth, it sought to assess the differences between women and men salt farmers in exercising their agency to sustain their livelihoods. In addition to the publications highlighted below, this research contributed to the development of a PhD thesis which was recently successfully defended.

The first study (Paramita et al. 2023a) delved into the state of deliberation by employing a systematic literature review to synthesize existing knowledge in marine and coastal research. Marine and coastal systems were selected for the scope of the systematic literature review because brackish pond aquaculture is an inherent component of these systems. A systematic literature review conducted during this phase offers insights into the role of deliberation in research and its practical applications within the scope of marine and coastal governance. The findings indicated that there is an uneven spatial distribution of studies between the Global North and Global South. Most researchers have been actively participating in solving real-world problems by designing an effective deliberation process. The majority of case studies recommended deliberation to enhance participatory governance and science-policy integration. The findings of this review are relevant for understanding governance problems and challenges related to deliberation processes in the context of marine and coastal systems (second study). Furthermore, the findings offer insights into the development of an effective deliberation process (third study).

The second study (Paramita et al. 2023b) focused on understanding the social and ecological factors that influence collective action in the implementation of environmental governance at the local level, utilizing a case study approach (Figure 7). A case study was conducted using qualitative approaches to analyze the social and ecological factors that influence the outcome of collective action and the influence of an aquaculture policy program to solve collective action problems. Further analysis was conducted to examine the influence of monetary incentives, monitoring, and sanctioning mechanisms in the PITAP program on intrinsic motivations for collective action, utilizing the motivational crowding theory. Participatory Pond Irrigation Management Program (*Pengelolaan Irigasi Tambak Partisipatif*, PITAP), supports traditional aquaculture farmers with limited funding to repair irrigation canals that are vital for pond aquaculture. The findings of this case study are crucial for comprehending the challenge of the policy program's fit in addressing collective action problems. Based on the results, it is evident that the social and ecological conditions across four aquaculture villages have led to different outcomes of the PITAP program (Figure 8). Due to the diversity of social and ecological conditions, there is a need for a local adaptation mechanism in policy design and implementation to improve outcomes.

The third study (Paramita et al., in review) aimed to develop an experimental deliberation process that could effectively guide discussions among resource users. This experimental study was designed to explore the application of the SESF (McGinnis & Ostrom, 2014) as an image-based deliberation tool to facilitate in-depth and complex discussions among resource users to address collective action problems. The assumption is that the image-based SESF deliberation tool can enhance the depth and complexity discussion of the participants. This experimental study was conducted in the field by involving research participants in their environment. Irrigation canal maintenance by the PITAP program was used as the topic of discussion to represent a policy program to solve collective action problems. The quantitative findings indicated that the experimental study did not yield clear evidence to support these assumptions. However, there was a potential for the image-based SESF deliberation tool to facilitate resource users to discuss more about “Actors.” The quantitative findings were reflected on the political culture in Indonesia to provide contextual understanding of local deliberation processes.

The fourth study (Paramita et al., manuscript in development) is a gender study that aimed to understand differential factors that influence the agency of rural women and rural men to support their

livelihood through visual data of Photovoice. Photovoice is a participatory action research method and is typically used in research which involves marginalized populations who are typically excluded in decision making processes. By understanding and supporting the agency of both rural women and men, policies and interventions can be designed to promote more inclusive and participatory development, resulting in a more equitable and sustainable future for rural communities.

Figure 7. Images of collective action to maintain the irrigation canals in: (A) Lembar in 2022 and (B) Sekotong in 2022. Images of (C) Jerowaru and (D) Sambelia, were taken in 2021 after collective maintenance was completed. From Paramita et al. (2023).

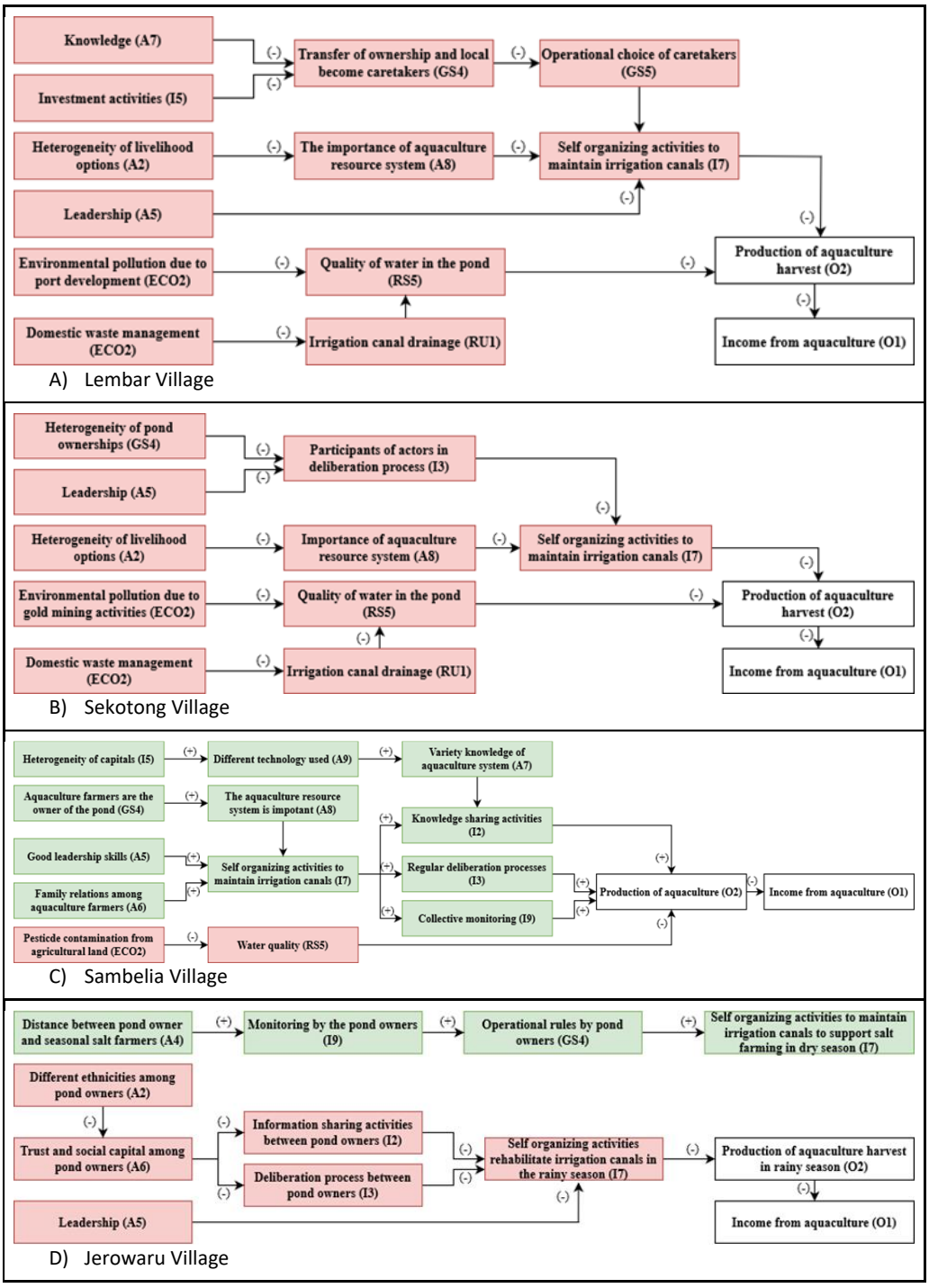

Figure 8. Key social-ecological interactions influencing collective action in four study locations. Arrows indicate interactions between variables. A green box indicates a positive influence of a variable on collective action. A red box indicates a negative influence on collective action. A white box indicates the final outcomes. Codes (A7, etc.) align with the 2nd-tier variables of the SES framework. From Paramita et al. (2023).

WP4 - Synthesis and transformation

WP4 delivered synthesis knowledge in two ways, through several comprehensive synthesis publications and through targeted empirical synthesis activities in Indonesia aimed at identifying actionable pathways for sustainable aquaculture development. First, due to the impact of the COVID-19 pandemic and related travel restrictions, COMPASS shifted to an expansion in desk-based synthesis work seeking to develop guides and frameworks as tools which can support the development of a more robust literature on the role of commons and institutions in aquaculture governance. This includes the development of two literature reviews previously summarized from WP1 (Nagel and Partelow 2022) and WP3 (Paramita et al. 2023a). In particular, the core framing paper of our COMPASS project has been published in Current Environment and Sustainability (Partelow et al. 2023a). With an extensive range of 30 intersectional aquaculture expert co-authors, this study combined a review with expert-elicitation to identify five key engagement arenas to advance a focus on governance for sustainable aquaculture transformation (Figure 9). As directions forward, the study concludes by summarizing a key set of action items which should be operationalized by aquaculture researchers, practitioners, and policymakers within their respective domains.

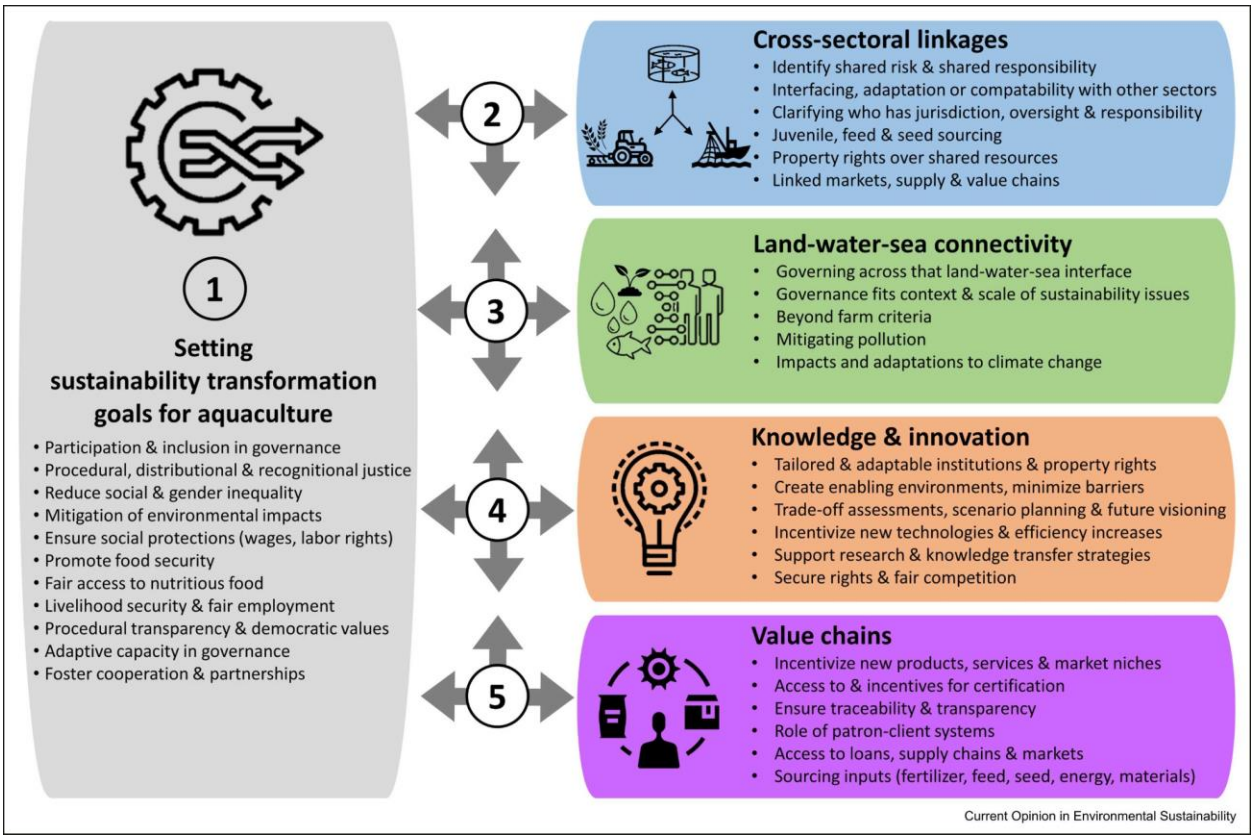

Figure 9. Five key engagement arenas for aquaculture governance that can foster sustainability transformation.

In what is to our knowledge the first social-ecological study of aquaculture governance at this scale, we further conducted a large-scale analysis of several dozen social, ecological, and governance indicators of

aquaculture development across 150 countries (Partelow et al., manuscript in review). Expanding beyond Indonesia to explore how to support sustainable bioeconomy development for aquaculture globally, we applied archetypes analysis to explore the social-ecological factors shaping aquaculture development trends around the world. We identified four country-level archetypes of global aquaculture development: (1) Emerging aquaculture producers, (2) Limited aquaculture engagement, (3) Developing economy producers, and (4) Wealthy economy producers, each reflecting a particular range of risks and opportunities for aquaculture development which are interpreted within the paper. The archetypes, which are characterized by 45 indicators including governance indices, seafood consumption, available production area, and environmental performance, inform development trade-offs while also moving beyond production-dominated characterizations of aquaculture sustainability.

Two other synthetic articles provided key publication contributions to WP4. First, a meta-analysis of the SES framework applied by COMPASS explored if different archetypical configurations of SES variables can be linked to sustainability outcomes across cases applying the framework, thus serving as building blocks for theory and policy (Partelow et al., 2024). This study contributes to the key gap in SES research and connects to a recurring theme of our COMPASS outputs: how to build generalizable findings out of heterogeneous individual SES cases? Additionally, a recent publication in njp Sustainability (Partelow et al., 2023b) reviews the literature on social science contributions to ocean sustainability, finding that social science contributes to only 7% of existing marine science literature. The review charts out five intervention areas whereby social science can provide key contributions to improve benefits (and reduce harms) to ocean sustainability projects.

While COVID-19 travel restrictions limited the transdisciplinary ambitions of COMPASS, generating transformative knowledge for sustainable aquaculture development not just for science, but for policy and practice, remained a core pillar of the project's outputs. A series of workshops, lectures, and policy briefs were developed and presented to aquaculture policymakers, communities, and researchers in 2022 and 2023 to share and discuss how empirical findings of WP1-3 can inform actionable sustainability pathways.

Policy recommendations and briefs

Targeted policy recommendations based on WP1-3 results were developed aimed at multiple levels and target groups, from local aquaculture communities (Table 1) to two Indonesian national programs aimed at supporting collective action in aquaculture: PITAP (Pond aquaculture irrigation management program) and POKDAKAN (aquaculture farm group program). Local governments and ministries may be able to improve PITAP program outcomes and aquaculture production by considering the following:

- Use deliberation processes with diverse stakeholders as a way to adapt the PITAP program to local contexts.
- Facilitate regular communication forums.
- Provide a moderator to facilitate deliberation.
- Provide capacity building such as cooperation options and technical skill trainings for farmers instead of monetary payments.
- Support the establishment of aquaculture farmer cooperatives to encourage self-organized mechanisms.

Regarding the POKDAKAN fish farmer group program, results of research led by WP1 showed that POKDAKAN programs are in most cases failing to meet their goals of fostering collective action between neighboring farmers. With findings from our archetypes results (Figure 4) and insights from follow-up interviews, recommendations for POKDAKAN included:

- Shifting government POKDAKAN support from only material support to a larger focus on capacity-building (technical and management training, knowledge capacity).
- Better integrate social-ecological indicators of governance challenges and broaden the current heavily production-oriented success indicators to a broader range of social and governance sustainability indicators.
- Apply these additional indicators to shift from top-down incentives to more locally adapted best management practices shaped by local problem contexts and community development goals, a strategy with some demonstrated success in other southeast Asian countries.
- Develop knowledge-sharing networks and platforms to improve coordination and communication between aquaculture communities and highly decentralized government offices. Key organizations such as the province-level fisheries and aquaculture department, or local universities, could serve as important bridging organizations.

These recommendations were shared by WP1-3 leads via in-person meetings with local aquaculture communities and government offices individually, as well as with public lectures and Q&A sessions at University of Mataram with diverse aquaculture stakeholders in attendance (Figure X). Insights from these discussions have so far informed the development of two Indonesian-language formal policy briefs which have been distributed to provincial and district level government offices, and we anticipate at least one more formal brief will be developed based on the outputs of WP2. Despite the limitations of COVID-19, our fieldwork and reliance on knowledge co-production methods helped build a strong network of local contacts which facilitated strong participation in these activities and from our perspective, strong interest in our research findings.

Main problems	Policy solutions	Target group
Lack of institutions amongst heterogeneous farmers to govern shared aquaculture commons	Bring different farmer groups together in workshops to help understand each other. Form groups around farmers with similar backgrounds. Motivate farm group formation and rule development that leverage existing norms of best practice and collaboration.	Local village leadership; milkfish community organizations; government extension officers
Limited access to capital and dependence on patrons	Increase access options to financing and basic infrastructure like roads. Explore pathways to more directly integrate wealthy fish farmer patrons into formal governance strategies.	Regional and national governments; patron communities
Continued government program failure	Increase monitoring of program implementation and iterative learning to improve program designs in ways that meets local needs. Align policy program ambitions with sufficient implementation resources, particularly increased field extension officer capacity to serve in a bridging role to improve uptake of government best aquaculture practice strategies. Extension programs incentivizing monitoring by farmers themselves which can in turn strengthen norms of trust and reciprocity.	All levels of government
Lack of leadership skill at the community level	Include leadership and administrative training in policy programs. Develop knowledge exchange and transfer initiatives to improve transitions between community aquaculture leaders.	Local village leadership; government extension officers: local universities
Lack of motivation and incentives to collectively act	Develop training programs to improve knowledge capacity regarding shared goods and shared risks of common water bodies such as irrigation canals. Find context appropriate incentives that reward cooperative behavior. Invest in capacity building trainings coupled with research.	All levels of government; Local village leadership; milkfish community organizations; government extension officers; local universities

Table 1. Policy recommendations for improving aquaculture governance in Gresik, Indonesia. From Riany et al. 2022.

Figure X. COMPASS dissemination activities. Left: Discussion workshop with West Sumbawa district fisheries and aquaculture office, June 2023. Right: COMPASS Dissemination day at University of Mataram, June 2023.

Public lectures

Numerous public lectures were given by COMPASS scientists during the duration of the project, in particular with our Indonesian university partners at IPB Bogor and University of Mataram, highlighted in the Appendix. Topics ranged from ocean governance to social-ecological systems.

Student workshops and activities

In addition to public lectures, additional student activities within COMPASS have been an important opportunity for our scientists to share with and mentor students interested in sustainability research. Several interactive student workshops with COMPASS university partners at IPB Bogor and University of Mataram shared our research methods and introduced students from often disciplinary backgrounds to interdisciplinary SES research methods used in our project. Topics included participatory modeling in SES research, as well as how and why to write a policy brief. Several recent graduates from University of Mataram also joined COMPASS as research assistants helping to facilitate fieldwork for WP1 & 3 over the span of multiple years, and are now themselves experts on the interdisciplinary research methods applied by COMPASS.

Appendix

Publications & publications in review

WP1&2

Nagel, B., E. Anggraini, N. Buhari, S. Gray, S. Partelow, and A. Schlüter. (In review). Mental models of aquaculture governance.

Nagel, B., N. Buhari, and S. Partelow. 2024. Archetypes of community-based pond aquaculture in Indonesia: applying the social-ecological systems framework to examine sustainability tradeoffs. Environmental Research Letters 19(4):044026.

Riany, C. F., S. Partelow, and B. Nagel. 2023. Governance challenges for Indonesian pond aquaculture: a case study of milkfish production in Gresik. Frontiers in Aquaculture 2.

WP1

Nagel, B., and S. Partelow. 2022. A methodological guide for applying the social-ecological system (SES) framework: a review of quantitative approaches. Ecology and Society 27(4):art39.

Partelow, S., A. Schlüter, A. Manlosa, B. Nagel, and A.O. Paramita. 2022. Governing aquaculture commons. Reviews in Aquaculture 14(2):729–750.

WP2

Al-Aqsha, L. M. R. R., A. A. Damayanti, E. Jefri. 2023. Keanekaragaman dan kelimpahan gastropoda di perairan Teluk Swage, Desa Pemongkong, Kecamatan Jerowaru, Lombok Timur. Jurnal Ilmu Kelautan Kepulauan, 6 (2) ; 917-927.

Maylanda, D.A., Paryono, I. Rahman. 2023. Studi Kandungan dan Sebaran Nutrien pada Perairan Teluk Swage, Lombok Timur. Journal Perikanan 13 (4) : 1225-1234.

Jefri, E., *et al.* Biodiversity of Intertidal Zones Adjacent to Effluent Discharge from Litopenaeus vannamei Shrimp Ponds: An Analysis of Habitat Variability (peer-review article in development).

Jefri, E., *et al.* Spatiotemporal Analysis of Coastal Water Quality at Shrimp Pond Effluent Discharge Sites with Varied Coastal Characteristics in Lombok (peer-review article in development).

Jefri, E., *et al.* Histology and biomarker of pollutant impacts from shrimp pond aquaculture effluents in Lombok with *Monetaria annulus* as an indicator species (peer-review article in development).

Jefri, E., *et al.* DNA Barcoding *Cypraea* spp. (Gastropoda: Cypraedae) from Intertidal Beach of Lombok, Indonesia, base on COI gene molecular marker (peer-review article in development).

Dewi, S.A.S., C.E.Larasati, N. Buhari. Komposisi Jenis Fitoplankton di Perairan Teluk Swage, Desa Pemongkong, Kabupaten Lombok Timur. Accepted in Jurnal Ilmu Kelautan Lesser Sunda.

WP3

Paramita, A. O., S. Partelow, and M. Fujitani. 2023a. A systematic review of deliberation research in marine and coastal case studies. Frontiers in Marine Science 10:1178453.

Paramita, A. O., S. Partelow, M. Fujitani, N. Buhari. (In review). Improving the depth and complexity of stakeholder deliberation using images: experimental evidence from Indonesia.

Paramita, A. O. et al. (In development). Gender and agency in rural salt farming in Indonesia: A photovoice study.

Paramita, A. O., S. Partelow, A. Schlüter, and N. Buhari. 2023b. Can the Indonesian collective action norm of Gotong-Royong be strengthened with economic incentives? Comparing the implementation of an aquaculture irrigation policy program. International Journal of the Commons 17(1).

WP4

Partelow, S., F. Asif, C. Béné, S. Bush, A. O. Manlosa, B. Nagel, A. Schlüter, V. M. Chadag, A. Choudhury, S. M. Cole, R. S. Cottrell, S. Gelcich, R. Gentry, J. A. Gephart, M. Glaser, T. R. Johnson, M. Jonell, G. Krause, A. Kunzmann, H. Kühnhold, D. C. Little, M. J. Marschke, D. D. Mizuta, A. O. Paramita, N. Pin, N. D. Salayo, G. D. Stentiford, J. Stoll, M. Troell, and G. M. Turchini. 2023a. Aquaculture governance: five engagement arenas for sustainability transformation. Current Opinion in Environmental Sustainability 65:101379.

Partelow, S., A. Schlüter, N. C. Ban, S. Batterbury, M. Bavinck, N. J. Bennett, R. Bleischwitz, J. Blythe, T. Bogusz, A. Breckwoldt, J. E. Cinner, M. Glaser, H. Govan, R. Gruby, V. Hatje, A.-K. Hornidge, G. K. Hovelsrud, J. N. Kittinger, L. C. Kluger, S. Kochalski, A. Mawyer, E. McKinley, J. Olsen, J. Pittman, M. Riechers, M.-C. Riekhof, K. S. Manez, R. J. Shellock, R. Siriwardane-de Zoysa, N. A. Steins, K. Van Assche, and S. Villasante. 2023b. Five social science intervention areas for ocean sustainability initiatives. npj Ocean Sustainability 2023 2:1 2(1):1–11.

Partelow, S., S. Villamayor-Tomas, K. Eisenack, G. Epstein, E. Kellner, M. Roggero, and M. Tschopp. 2024. A meta-analysis of SES framework case studies: Identifying dyad and triad archetypes. People and Nature 00:1–19.

Partelow, S., B. Nagel, R. Gentry, J. Gephart, J. Rocha. (In review). Archetypes of aquaculture development across 150 countries.

Theses

Jefri, E. 2024. (In development). Biodiversity and Environmental Impact Assessment of Intertidal at Shrimp Aquaculture Discharge Sites: A Comprehensive Assessment of Intertidal Biota, Water Quality, Histopathology, and DNA Barcoding. PhD thesis, University of Mataram.

Nagel, B. 2024. Advancing quantitative methods for complex social-ecological system research: a case study of aquaculture. PhD thesis, Constructor University.

Paramita, A.O. 2024. Analyzing deliberation and collective action problems in environmental governance: a case study of aquaculture policy program. PhD thesis, Constructor University.

Riany, C.F. 2022. Diagnosing Milkfish Aquaculture Governance Challenges in Gresik: Apply Socio-Ecological System Framework. Master's thesis, University of Bremen.

Conference contributions

Nagel, B. 2021. Operationalizing the social-ecological systems framework to assess and map aquaculture sustainability. ZMT Annual Conference (ZAC) 2.

Nagel, B. 2021. Operationalizing the social-ecological systems framework as a methodological tool to assess and map aquaculture sustainability. 2021 IASC Fisheries & Aquaculture Conference.

Nagel, B. 2021. A participatory modeling approach to analyze and compare perceptions of aquaculture social-ecological systems. 2021 MARE conference.

Nagel, B. 2021. A participatory modeling approach to analyze perceptions of aquaculture as a social-ecological system. 2021 ICYMARE conference.

Nagel, B. 2021. Operationalizing the social-ecological systems framework to assess and map aquaculture in Nusa Tenggara Barat, Indonesia. 2021 KDM Meeting.

Nagel, B. 2022. Conference session organizer: Adaptive place-based research during the COVID-19 pandemic: Perspectives and praxis. ZAC 3 conference.

Nagel, B. 2022. Mapping social-ecological archetypes of community-based aquaculture in Nusa Tenggara Barat, Indonesia. 5th International Workshop on Archetypes in Sustainability Research.

Nagel, B. 2023. Exploring stakeholder mental models to understand coastal pond aquaculture governance in Nusa Tenggara Barat, Indonesia. 2023 IASC Conference.

Nagel, B. 2023. A methodological guide for applying the social-ecological system (SES) framework: a review of quantitative approaches. 2023 IASC Conference.

Jefri, E. 2022. Diversity and Abundance of Intertidal Biota in front of Shrimp Pond on Lombok and Sumbawa Island. 5th International Marine and Fisheries Symposium. Hasanuddin University.

Jefri, E. 2024. Histology and biomarker of pollutant impacts from shrimp pond aquaculture effluents in Lombok with *Monetaria annulus* as an indicator species. 19th ISLAND OF THE WORLD CONFERENCE "Islands and Resilience: Global Opportunities".IPB University and University of Mataram

Paramita, A.O. 2021. Deliberation and collaborative governance: examining aquaculture on Lombok, Indonesia. 2021 IASC Fisheries & Aquaculture Conference.

Paramita, A.O. 2021. Understanding the women's challenges in aquaculture and aquaculture governance. 2021 MARE conference.

Paramita, A.O. 2022. International Conference on Environment, Earth Science, and Sustainability (ICES), 7th Annual International Institute for Environmental Studies (IIES) Science and Policy Workshops in Ho Chi Min and Phu Quoc, Vietnam from 24th – 28th October, 2022.
Presentation: Deliberation and collaborative governance. Examining aquaculture on Lombok, Indonesia.

Paramita, A.O. 2023. The International Association for the Study of the Commons (IASC) Conference: "The Commons We Want" in Nairobi, Kenya from 19th – 24th June, 2023.
Presentation: Can the Indonesian collective action norm of Gotong-Royong be strengthened with economic incentives? Comparing the implementation of an aquaculture irrigation policy program.

Paramita, A.O. 2023. MARE Conference XII: "Blue Fear – Navigating Ecological, Social, and Existential Anxieties during the Anthropocene" in Amsterdam, the Netherlands from 26th – 30th June, 2023.
Presentation: Operationalizing agency in gendered practices of salt farming and climate adaptation. A Photovoice study in Sekotong, Indonesia.

Partelow, S. 2022. A meta-analysis of SES framework archetypes. 5th International Workshop on Archetypes in Sustainability Research.

Partelow, S. 2022. Aquaculture governance: five engagement arenas for sustainability transformation. 2023 IASC Conference.

Partelow, S. 2022. Aquaculture governance: five engagement arenas for sustainability transformation. 2023 MARE Conference.

Rahmi, D.A.,, E. Jefri, Destikawati, F. Akbar, M. Hidayatullah, Rahfika, N. Buhari. Keanekaragaman Makroalga di Perairan Sambelia, Kabupaten Lombok Timur. 2023 Semnas Pengelolaan Perikanan dan Kelautan FIP2B.

Riany, C.F. 2022. Diagnosing Milkfish Aquaculture Governance Challenge in Gresik, applying Social Ecological System Framework. 2022 ICYMARE conference.

Communication & outreach events

Nagel, B. 2024. Policy brief: How to improve tambak aquaculture management in Nusa Tenggara Barat. Target group: Province and regency DKP offices in Nusa Tenggara Barat, Indonesia.

Nagel, B. 2022. Academic workshop: Tools & methods for participatory modeling of social-ecological systems. University of Mataram.

Nagel, B. 2022. Academic workshop: Tools & methods for participatory modeling of social-ecological systems. IPB Bogor University.

Nagel, B. 2023. Community workshop: Insights from Project COMPASS. West Sumbawa.

Paramita, A.O., Nagel, B., Jefri, E. Stakeholder Q&A event. ZMT Project COMPASS: Dissemination event: Insights from COMPASS Project. University of Mataram.

Paramita, A.O., Partelow, S., Schlüter, A. 2024. Policy brief: How to strengthen Gotong Royong to rehabilitate the irrigation canals among traditional aquaculture farmers without monetary incentives? https://doi.org/10.21244/zmt.2024.003

Paramita, A.O., Partelow, S., Schlüter, A. 2024. Policy brief: Bagaimana memperkuat Gotong Royong untuk merehabilitasi saluran irigasi antar petambak budidaya tradisional tanpa insentif moneter? https://doi.org/10.21244/zmt.2024.004

Paramita, A.O. 2023. Academic workshop: How to design policy brief effectively. University of Mataram.

Partelow, S. Public lecture: Frameworks! and Ostrom in the Ocean. Leuphana University.

Partelow, S. Public lecture: Coastal governance and environmental theory. University of Costa Rica.

Partelow, S. 2023. Public lecture: Governing the Commons. University of Bonn.

Partelow, S. Invited talk: Social-ecological system frameworks. Earth System Governance SES Group.

Partelow, S. 2023. Invited talk: Environmental Governance and the Commons. IBM company.

Schlüter, A. 2023. Public lecture: Governing aquaculture commons. University of Mataram