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Archetypes of community-based pond aquaculture in Indonesia: applying the social-ecological systems framework to examine sustainability tradeoffs

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Abstract

We analyze archetypes of farmer groups conducting pond aquaculture across the province of Nusa Tenggara Barat, Indonesia using Ostrom's social-ecological systems framework. Pond aquaculture farmers share coastal irrigation infrastructure as common property, among other resources, and are encouraged by the government to organize into groups with varying sets of evolved rules, norms, social practices and environmental conditions shaping what they produce, how and how much. Yet little is known about the diversity of these pond aquaculture communities, or what factors—both social and ecological—shape production trends and sustainability outcomes. We designed a standardized survey to collect data on 26 indicators from 85 diverse community-based fish farmer groups across the province. Data included indicators on ownership, rules, history, production trends, demographics, government involvement, livelihood dependence, environmental characteristics and risks. Clustering analysis was applied to identify five unique archetypes of pond aquaculture communities, each distinguished by a different set of development challenges and opportunities. Our findings highlight the need to move beyond a 'one-size-fits-all' policy approach. We suggest moving towards a locally adapted capacity building strategy that can recognize contextual needs so that policy programs can better target and differentiate between farmer groups that face similar challenges. We further discuss how empowering collective action among the farmers can reduce risks associated with producing blue food for local consumption and regional markets.

1. Introduction

Governments face the challenge of developing coherent policy programs that are also locally adaptable to the diverse conditions where they are implemented. However, in some natural resource systems (RSs) such as land-based pond aquaculture—the most common form of fish production in the world [1, 2]—policy program designs are hampered by the little knowledge available about the social and ecological diversity of producing communities, the challenges and risks they face or the capacities they need to improve sustainability outcomes [3, 4]. For decades, social-ecological systems research has been examining methodologies for standardizing the data collection and analysis of diverse natural RSs at the community level to address this problem. However, aquaculture is a RS that has been almost entirely overlooked [5–7]. Despite some progress in countries where aquaculture plays a large role in shaping economic development and food security, there is still a need for policy strategies to find a middle pathway of generalizability that balances coherence with adaptability. One strategy is to pursue methods that can identify similar case studies so that policy programs can more effectively target management and capacity investments into systems with similar conditions and needs while avoiding inefficient generalizations or the burden of always needing to contextualize [8]. Researchers can help by exploring new methodological tools and combining existing ones to analyze diverse social-ecological systems (SES) data. Most SES research remains rooted in individual case studies covering small spatial extents [9], and while existing SES case libraries attempt to facilitate comparative research, meta-analyses are often limited by differences in methods, design, and transparency across studies [10].

Archetype analysis offers a state-of-the-art approach for analyzing and categorizing social-ecological complexity [11]. Archetype analysis in sustainability research refers to range of methodological approaches which are used to 'understand recurrent patterns of variables and processes that shape the sustainability of social-ecological systems in different locations … at an intermediate level of aggregation' [12]. Archetype analysis is a comparative approach to identify patterns in the diverse combinations of factors across individual cases (which could range from grid cells to communities to individuals), while also understanding that there is no single universal explanation for the phenomena of interest but rather multiple models, or archetypes [11]. Archetypes therefore inhabit a middle range between frameworks and theories, and between unique individual cases and one-size-fits-all panaceas. Archetype analysis has been applied to a diverse range of sustainability research contexts including archetypes of recurring spatial patterns and trajectories in land use and development [13, 14], as well archetypes of farm vulnerability determinants [15] and cognitive archetypes [16]. Archetypes approaches are valuable because they allow data to be analyzed together in a way that can identify multiple configurations or explanations of system complexity and produce narratives of each archetype's development trajectory. Archetypes can also support policy makers [12], e.g. a generic policy could be adapted into several different approaches within which individual cases are grouped by their common features. Local governments tasked with national policy implementation could use archetype analysis to efficiently adapt their approach to cluster of contexts with similar challenges and problem contexts. In the present study, we apply archetypes analysis to the diverse and rapidly growing sector of smallholder[5] pond aquaculture to identify social-ecological archetypes, or typologies, of fish farming communities that might face similar governance challenges.

1.1. Aquaculture governance challenges

Aquaculture is the fastest-growing food sector globally, and small-scale community-based pond aquaculture is the most common production strategy, particularly in rural developing contexts in Indonesia, China and India where livelihood and food security are often explicitly linked to the sector's potential to contribute to community-based sustainability [17–19]. At the same time, aquaculture development has also been linked to critical sustainability challenges, including social issues of inequity, privatization, and elite land grabbing [20–23] as well as ecological issues of eutrophication, disease outbreaks, and mangrove deforestation [24–27]. Community-based pond aquaculture is primarily (though not exclusively) a low tech rural agriculture sector, often found in communities with high poverty rates, low education and limited technical knowledge of production or impacts. This creates barriers for investing, organizing, and networking to improve production sustainability [28].

Pond aquaculture systems are dependent on a variety of common-pool resources and public goods, suggesting that collective action is needed to govern those commons sustainably [3]. Community-based coastal pond aquaculture has been described as a 'hybrid' commons [29], often consisting of large networks of private earthen ponds owned or managed by many different individual farmers, and connected to the sea or freshwater sources through a shared canal network. Governance problems rooted in social dilemmas emerge where there is a misalignment between individual self-interest and group goals that needs to be resolved with the development of rule and norm systems (i.e. institutions) that incentivize pro-social behavior to avoid undesired outcomes. In these pond systems, failure to coordinate canal maintenance (who contributes), water distribution (who gets how much and when) and outflow (when and where the pond waste goes) between farmers can lead to inequitable access, degradation of water conditions, disease cross-contamination and production collapse across the entire pond network [30]. This is

[5] Here it is worthwhile to note the ongoing discourse regarding the use of the terms 'small-scale' and 'smallholder' in fisheries and aquaculture research, particularly that these labels are often vague and ill-defined, and tend to overly homogenize or stereotype the diversity of characteristics and experiences of people in these sectors [74–76]. We find the terminology useful in distinguishing community-based aquaculture from the growing industrial fish farming sector in Indonesia, which widely consists of isolated and entirely privatized farm operations owned by an individual company or investor, and which thus do not face the commons dilemmas noted in this section. Still, we recognize these criticisms and avoid pursuing a single definition for 'small-scale' or 'community-based' aquaculture in favor of identifying and defining multiple typologies of aquaculture communities within our case region, based on a wide range of indicators.

often further complicated if water quality parameters degrade along the length of shared canal systems when maintenance is not properly provisioned [31].

Little is known, however, about the diversity of commons, SES conditions and governance institutions that exist among pond aquaculture communities. As a result, policy programs attempting to develop interventions to improve production, livelihoods and food security are often operating blindly in regards to what is actually needed in communities and what interventions will be most effective. This leads to the question of what types of research and analytical tools can provide effective insights for better guiding policy based on sufficient contextual knowledge? We argue that governments, for example in Indonesia, would benefit from being able to better categorize the types of problems aquaculture communities face so that those problems can be better matched with intervention programs that fit their needs. As a starting point, many of the knowledge blindspots are social (i.e. rules-in-use for managing commons, role of ownership rights), and the ecological factors need to move beyond simple production data in way that can better characterize the environmental conditions and risks (i.e. flood and disease risk, mangrove deforestation).

1.2. Indonesian aquaculture policy

The Indonesian government faces the challenge of wanting to rapidly expand domestic pond aquaculture production, but it wants to simultaneously do this across highly diverse social and environmental contexts. Current government programs encourage small-scale coastal pond farmers to self-organize into 'cluster-based[6]' farmer groups (Indonesian: POKDAKAN) of neighboring farmers to encourage grassroots collective action [32]. Cluster-based management schemes are being increasingly introduced by governments in many aquaculture-producing countries, including India, Vietnam, and Indonesia [33, 34], and involve the organization of neighboring farmers into voluntary cooperative groups to manage shared resource risks and challenges through collective action. By coordinating production activities, farmers can reduce costs and increase profits through economies of scale, and gain increased access to markets and certifications which might otherwise only be available to large industrial farms. In some cases, cluster-based schemes have become a self-propagating model, where collective benefits of self-organization are clear [33–35]. At the same time, cluster-based farming is not a universal prescription for sustainability, and requires contextualized and adaptive policy support and locally relevant incentives for self-organization [33, 36]. In Indonesia, the goal of the cluster-based POKDAKAN program is to enable communities to develop their own institutions for governing aquaculture and improving market access and opportunities, potentially leveraging existing customary deliberation and collective action cultural norms such as 'awig-awig' and 'gotong royong' which encourage community cooperation [32, 37, 38]. So far, farmer group formation is encouraged and supported primarily through external financial incentives, as pond farmers are required to register into groups in order to access subsidy programs.

A key policy question in this context is: to what extent are farmer groups successfully self-organizing? Initial studies have suggested that many groups have failed to meet development goals or their own livelihood needs because they face a diversity of challenges. Numerous reasons have been cited, the most important being the lack of technical training and knowledge to identify their own collective action problems, and need for capacity building programs which address this to reduce risk and help reframe the problem around social capacities rather than the need for technical solutions [29, 31, 39]. Existing policy evaluation tools have been criticized as not reflecting the actual social-political and environmental reality of local communities [40]. Failing to include community members in decision-making and the narrow focus on production indicators have been cited as key reasons why policy programs are missing their targets, because they overlook the importance of assessing the underlying social and environmental conditions driving performance [41–43]. The widely implemented PITAP program (Participatory Pond Irrigation Management), for example, offers direct payments to farmers who contribute to canal maintenance but largely overlooks investing into capacities (e.g. problem recognition, administration, leadership skills) that would enable farmers to work together on their own once the direct funding period ends, or understanding why farmers were not working together before, leading to mixed results and criticisms of the program's design [44, 45]. What is clear, however, is that pond aquaculture farmer groups and their communities are diverse. There are likely to be, nonetheless, common factors hindering or enabling success across certain communities. If these factors can be more clearly identified, they could be used to inform the adaptation of policy programs to address underlying issues that can improve community outcomes while meeting national growth targets in the sector.

1.3. Research objectives

The goal of this study is to collect and analyze new empirical data on the underlying factors influencing community-based pond aquaculture groups through a survey of 85 farmer groups in Nusa Tenggara Barat

[6] In an attempt to minimize confusion between our method of analysis (cluster analysis) and unit of analysis (fish farmer clusters), we homogenize our terminology as follows:
Cluster or clustering analysis: Data analysis method.
Cluster-based: Farmer organization management strategy. Also referred to as 'farmer groups'.

(NTB) province, Indonesia, so that we can understand if they can be classified into social-ecological archetypes of communities facing similar contextual challenges. Policy programs could then better tailor their design and implementations to meet the needs of those specific typologies. We use the SES framework to help us organize and identify the complexity of variables important for the analysis, and then apply cluster analysis methods to identify common patterns of development by grouping farmer communities into groups with similar indicator values that represent shared baseline characteristics and development needs.

2. Materials and methods

2.1. Study region: NTB province, Indonesia

NTB is the 5th largest aquaculture producing province in Indonesia, and also one of the poorest [46]. The expansion of aquaculture in NTB has been targeted as a key area for livelihood and economy development across the province (figure 1). Government authority over aquaculture in Indonesia is largely encompassed by the Ministry of Marine Affairs and Fisheries (MMAF/KKP) but heavily decentralized to the province and regency (provincial subdistricts, Indonesian: kabupaten) governments. NTB consists of eight rural regencies and two cities, each with a local Department of Marine Affairs and Fisheries (DKP) managing local aquaculture development programs and support. Coastal brackish pond aquaculture (Indonesian: tambak) was only widely introduced in NTB in the 1980s but is now the most economically important aquaculture production subsector in the province in terms of production yield and value [46]. While there are a growing number of industrial intensive shrimp farms in NTB, the sector is still dominated by smallholder production, making it a critical emerging sector for rural coastal livelihoods. In some NTB farmer groups, the lack of collective action amongst fish farmers has been attributed to a lack of knowledge and training capacity which has hindered problem recognition (such as the importance of canal maintenance for water quality), limiting incentives to work together [29]. Production collapse and pond abandonment remain widespread problems across the province.

2.2. Archetypes approach with clustering analysis

While there are many methods and no standardized criteria for archetype analysis, Eisenack *et al* 2019 provide a set of propositions for comprehensive archetype analysis [11], including that archetypes characterize components which re-occur across multiple cases, and that a comprehensive archetype analysis characterizes each archetype by a particular configuration of attributes and hypotheses or theoretical explanation regarding the role of the attributes, as well as a set of cases where the archetype holds. In the present study, we adapted a data-driven clustering analysis approach applied in recent sustainability literature [14, 16] to identify and characterize typology[7] archetypes of smallholder aquaculture farmer groups, based on 26 social and ecological farmer group-level indicators of coastal pond aquaculture development. Indicator data collection primarily consisted of a standardized questionnaire-based survey of community-based pond aquaculture farmer groups across NTB, supplemented by a small number of secondary data indicators (table 1). A survey approach was utilized as there is a shortage of consistent secondary aquaculture data availability and coverage in Indonesia. The unit of analysis was selected on the basis that farmer groups form arguably the primary unit of potential self-organization and governance for community-based pond aquaculture in Indonesia, and connects our research to the broader literature on cluster-based aquaculture management approaches.

2.3. Analytical framework

We used Elinor Ostrom's SES framework to guide and organize a selection of indicators relevant for collective action and sustainable governance in smallholder aquaculture [47]. The framework provides a common vocabulary of decomposable (1st- and 2nd-tier, etc) variables empirically linked to sustainability outcomes: within an SES, Actors (A) act and make decisions in connection to a RS populated by resource units (RUs), while governance systems (GS) consist of the formal and informal rules guiding Actor behavior. The SES is embedded in and connected to other external related ecosystems (ECO) and influenced by the wider social, economic, and political setting (S). SES outcomes (O) are the product of interactions (I) across all these dimensions and therefore vary with SES context. The SES framework was developed around the idea that while there are no panaceas, there are likely to be reoccurring patterns of variables and processes linked to successful (or unsuccessful) sustainability outcomes across diverse SES contexts [48, 49]. Identifying generalizable patterns across SES cases is needed to contribute to research synthesis and facilitate SES theory-building, as well as to create actionable knowledge to inform decision-makers operating in often information-scarce contexts. While the SES framework provides a checklist of variables to be applied to identify generalizable patterns across heterogeneous SES cases, archetype analysis refers to a suite of methodological approaches

[7] Archetypes can be conceptualized as 'typologies' (classification of each case into one archetype) or 'building blocks' (each archetype refers to a particular recurring process or attribute; each case is characterized by the presence of one or a combination of archetypes) [12].

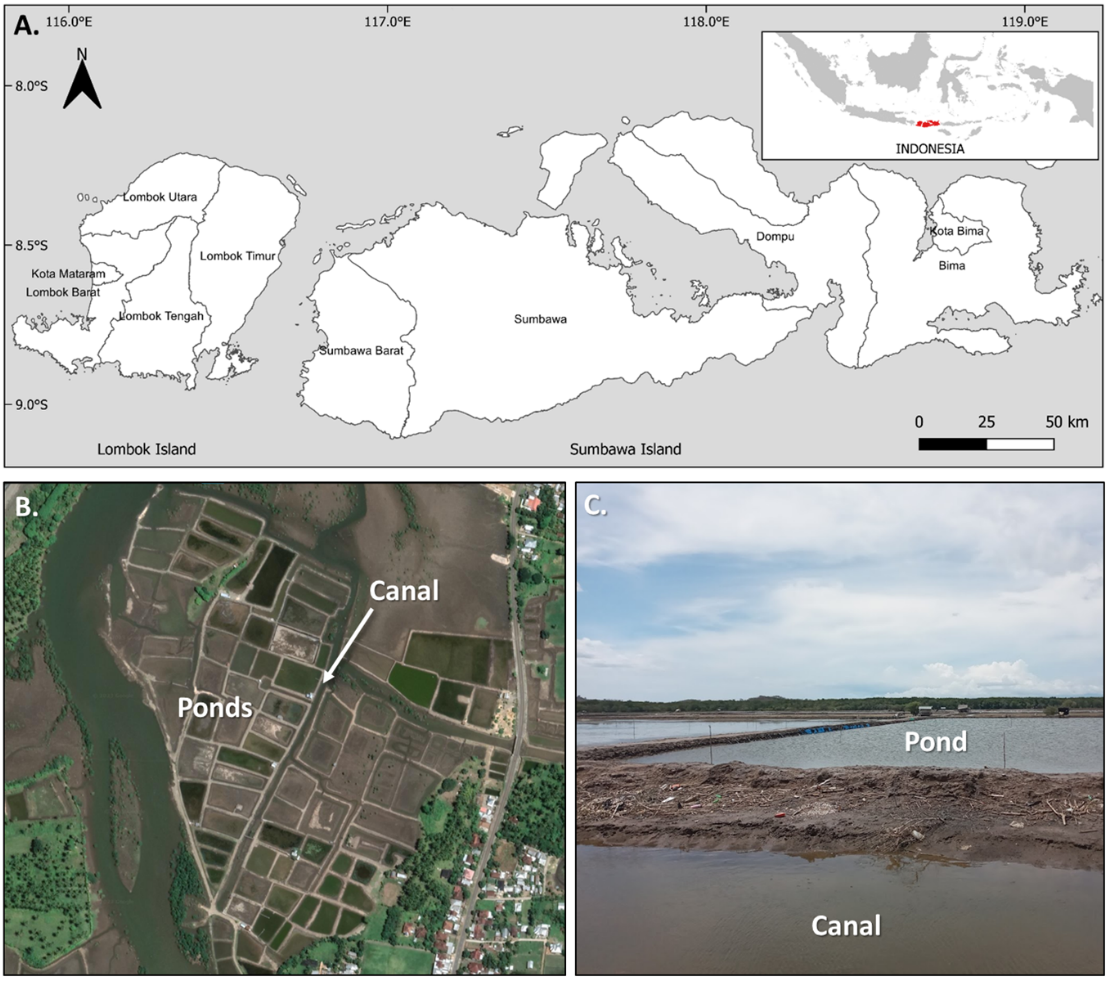

Figure 1. (A) Nusa Tenggara Barat province. Boundary lines and labels indicate the ten second-level administrative divisions of the province, including eight rural regencies and two cities. (B) Satellite image of a coastal pond aquaculture community in NTB. Imagery: 2022. Source: Google Earth. (C) Traditional extensive earthen ponds and canal in NTB. Photo taken by authors.

used to accomplish this. In our study, the SES framework provides a theoretically grounded and broadly comparable framework to guide a holistic selection of indicators across multiple dimensions of sustainability and compare governance challenges across the resulting archetypes.

2.4. Data selection and collection

Due to limited secondary data coverage and consistency, we conducted a survey of coastal pond aquaculture farmer group leaders across NTB to collect self-reported primary data for the majority of evaluated indicators. Numerous studies have provided guidelines for applying the SES framework empirically [7, 50–53]. There is no standardized approach for operationalizing the framework, however we followed existing methodological guides aimed at increasing SES framework study transparency [7]. Each indicator was selected based on strong theoretical and/or empirical inclusion criteria regarding their connection to potential for collective action and sustainability, including previous research applying the SES framework to pond aquaculture in NTB [29, 31] and preliminary results from a parallel participatory modeling study in review. Finally, a comprehensive review of potentially relevant indicators applied across other studies applying the framework [7] was used to identify any further potentially relevant variables for our case. The final list of indicators was coded to the 1st- and 2nd-tier variables of the framework (table 1). Several variables hypothesized as important to our case were dropped from analysis due to lack of available data (appendix 2, table S2).

The standardized questionnaire to collect self-reported indicator data from farmer groups was iterated and revised during a preliminary pretesting phase to maximize interpretability and consistency of responses, which typically involved considering trade-offs between data validity and accuracy. A small number of additional indicators based on secondary data were also included (table 1). From April–November 2022, a total of 85 complete farmer group surveys were completed. Supporting

Table 1. List of indicators and their alignment with the SES framework 1st and 2nd tier variables. See table S2 for additional considered indicators excluded from final analysis, and appendix 3 for inclusion criteria.

Indicator	Farmer group indicator	SES framework 1st- and 2nd-tier	Sustainability index 1st-tier dimension	Data structure	Source
1	Farmer group size	A1 Number of actors	Actor	Exact numeric estimate	Farmer group survey
2	Education	A2.1 Socioeconomic attributes	Actor	Proportion (10% estimate)	Farmer group survey
3	Women membership	A2.2 Socioeconomic attributes	Actor	Proportion (10% estimate)	Farmer group survey
4	Farmer group history	A3 History or past experiences	Actor	Exact numeric estimate	Farmer group survey
5	Aq. as primary livelihood	A8 Importance of resource	Actor	Proportion (10% estimate)	Farmer group survey
6	Ownership of aq. pond land	GS4 Property rights systems	Governance	Proportion (10% estimate)	Farmer group survey
7	Operational rules-in-use	GS5 Operational choice rules	Governance	Index/sum score of multiple binary indicators	Farmer group survey
8	Collective-choice rules-in-use	GS6 Collective choice rules	Governance	Index/sum score of multiple binary indicators	Farmer group survey
9	Monitoring and sanctioning rules	GS8 Monitoring and sanctioning	Governance	Index/sum score of multiple binary indicators	Farmer group survey
10	Size of farmer group production area	RS3.1 Size of resource system	Resource System	Exact numeric estimate (hectares)	Farmer group survey
11	Village aq. production area	RS3.2 Size of resource system	Resource System	Exact numeric calculation (hectares)	Secondary. Source: Indonesian Ministry of Environment and Forestry (MENLHK).
12	Growth in aq. production area	RS3.3 Size of resource system	Resource System	Exact numeric calculation (hectares)	Secondary. Source: Indonesian Ministry of Environment and Forestry (MENLHK).
13	Presence of shared infrastructure	RS4.4 Human constructed facilities	Resource System	Index/sum score of multiple binary indicators	Farmer group survey
14	Age of pond aq. network	RS6 Equilibrium properties	Resource System	Exact numeric estimate	Farmer group survey
15	Avg. 3 year flood impact	RS7.1 Predictability of system dynamics	Resource System	Proportion (20% estimate), averaged across 3 years	Farmer group survey
16	Avg. 3 year disease impact	RS7.2 Predictability of system dynamics	Resource System	Proportion (20% estimate), averaged across 3 years	Farmer group survey
17	Ratio of poly- (vs. mono-)culture ponds	RU Resource Units	Resource Units	Proportion (10% estimate)	Farmer group survey
18	Avg. 3 year profit consistency	RU4 Economic value	Resource Units	Proportion (20% estimate), averaged across 3 years	Farmer group survey

(Continued.)

Table 1. (Continued.)

19	Ratio of (semi)intensive ponds versus traditional	RU5.1 Number of units	Resource Units	Proportion (10% estimate)	Farmer group survey
20	3-year production trends	RU5.2 Number of units	Resource Units	Ordinal categorical (increased, stayed the same, decreased)	Farmer group survey
21	Number of harvests/year	I1 Harvesting	Actor[a]	Exact numeric estimate	Farmer group survey
22	Govt. training rate	I5.1 Investment activities	Investments[b]	Proportion (10% estimate)	Farmer group survey
23	Govt. CBIB certification rate	I5.2 Investment activities	Investments[b]	Proportion (10% estimate)	Farmer group survey
24	Govt. subsidy rate	I5.3 Investment activities	Investments[b]	Index/sum score of multiple binary indicators	Farmer group survey
25	Total village mangrove area	ECO3.1 Flows into/out of SES	(Related) ecosystem	Exact numeric calculation (hectares)	Secondary. Source: Global Mangrove Watch [56]
26	Change in village mangrove area	ECO3.2 Flows into/out of SES	(Related) ecosystem	Exact numeric calculation (hectares)	Secondary. Source: Global Mangrove Watch [56]

[a] As government investments (I5) were our primary interaction of interest, harvesting rate (I1) was included in the 'Actor' dimension of our sustainable governance index (see section 2.3).

[b] Corresponds to the 'Interactions' 1st-tier dimension of the framework, modified here as government investment activities (I5) were the primary interactions of interest.

information regarding questionnaire design and data collection, as well as full descriptions and inclusion criteria for each indicator, can be found in appendices 2 and 3.

2.5. Clustering analysis

All 26 quantitative indicators included in the final clustering analysis were scaled to zero mean and unit variance. Selecting an appropriate clustering algorithm and number of clusters to best partition and describe a dataset is to some degree a subjective process, so to aid the transparency of our approach we applied a standardized approach proposed by Rocha *et al* [14] combining r packages 'NbClust' [54] to identify an optimum number of clusters (archetypes), and 'clValid' [55] to select an optimum clustering technique based on several measures of internal and stability validation. For additional details regarding the clustering approach, see appendix 2.

2.6. Assessing sustainability barriers and opportunities across 1st-tier SES dimensions

To aid in the interpretation of our archetypes, we additionally applied the SES framework to evaluate potential for sustainable governance across each 1st-tier SES dimension for each archetype, based on theoretical and empirical criteria linking each indicator to the potential for emergence of collective action and sustainable governance in our case province (table 2). The exact contribution of each SES variable to system outcomes depends on its interaction with other variables and is likely to vary with case and normative contexts, and challenges in a particular SES dimension can be overcome with appropriate institutions. Each score should therefore be interpreted as the potential, or likelihood, for each dimension to

Table 2. Example of index indicator score calculation by quantile distribution. SES framework 2nd-tier variable: RS6 Equilibrium properties. Based on empirical criteria that older pond and canal systems are more prone to degradation of water conditions if coordination of maintenance activities is not effectively governed.

Percentile rank	Indicator RS6: age of village pond network (years)	Indicator index score rubric
0%	1	1.00
10%	4	0.90
25%	5	0.75
50%	10	0.50
75%	25	0.25
90%	41.6	0.10
100%	42	0.00

be an opportunity for (1), or barrier to (0), sustainable governance in each archetype. Adapting a previous approach [50], for each farmer group, a single 0:1 normalized index score was calculated for each 1st-tier framework dimension based on an equally-weighted composite of all indicators in that tier. We used ANOVA and Tukey tests to compare significant differences in average 1st-tier scores between the archetypes. Supporting information regarding the index calculation and ranking scores for each indicator can be found in appendices 2 and 3.

3. Results

Our clustering analysis approach using the 'clValid' and 'nbClust' R packages to identify an optimum partitioning identified hierarchical clustering as the best-performing algorithm for our data, and an optimal number of five clusters, or archetypes, to describe the heterogeneity in coastal smallholder pond aquaculture farmer groups in NTB (figure 2). We ran the hierarchical clustering using a Manhattan distance measure and Ward's agglomeration method to minimize within-cluster variance [54]. Each farmer group archetype is defined by a distinct configuration of SES characteristics. Figure 3 plots the distribution of all indicator values for each archetype in relation to the total population average. Pairwise significant differences between archetypes for each indicator can be found in figure S1. Certain indicators are more significantly different between clusters than others (figure S1), and we have referred to these findings to descriptively characterize each archetype based on indicators with meaningful differences.

3.1. Archetype 1: emerging semi-intensive (n = 32 farmer groups)

This archetype consists of relatively new farmer groups with small group size, composed of farmers with high education rates, moderately high rates of government good aquaculture methods certification (CBIB), and a moderately high dependence on aquaculture as a primarily livelihood, with minimal farmer group rules-in-use and few types of shared infrastructure between farmers. Farmer groups in this archetype have at least partially adopted semi-intensive to intensive monoculture shrimp cultivation practices, with small total pond area. Pond networks in this archetype often consist of a mix of less profitable but lower cost and maintenance traditional ponds, with more costly and resource intensive but more profitable semi-intensive and densely stocked shrimp ponds. While most farmer groups in this archetype reported relatively high net profit consistency over the past three years, the majority also reported a decreasing trend in production. This archetype is primarily located in southeast Lombok and West Sumbawa regencies, with a small number of cases in Bima regency.

3.2. Archetype 2: self-governed polyculture (n = 13 farmer groups)

Many archetype 2 communities have a relatively long history of aquaculture, but many of the farmers have only recently formally registered as groups. Farmers in these groups have relatively low education rates, and lower dependence on aquaculture as a primary livelihood. Farms in this group have low rates of pond land ownership, often renting pond area. These farms receive few government subsidies, little access to CBIB certification, and the lowest rates of government aquaculture training, but at the same time are defined by some of the highest prevalance of operational, collective choice, and monitoring and sanctioning categories of farmer group rules-in use, suggesting a high degree of self-governance within these farmer groups. The pond RS in this archetype consists of established, older pond networks with entirely traditional and entirely extensive production practices and the highest rates of polyculture production of any archetype, integrating milkfish, shrimp, and other species in the same ponds with moderate profit consistency. Three-year production trends in this archetype are mixed, however this is the only archetype where a majority of farmer groups reported increasing production trends. This archetype also has amongst the highest mangrove deforestation rates. This archetype is dispersed across the province but has the highest prevalence in West Lombok and Sumbawa regencies.

3.3. Archetype 3: expansive traditional (n = 26 farmer groups)

This archetype is characterized by farmer groups with high group size, education rates, dependence on aquaculture, and pond land ownership, with few farmer group rules-in-use present. Farmer group membership is mostly men but with a marginally higher rate of women membership than other groups. These farms consist entirely of traditional extensive, low stocking rate and low input cultivation practices using very large ponds of primarily monocultured shrimp or milkfish, with the highest farmer group and village district pond area of any archetype. Pond networks in this archetype have a moderate average age, and have had relatively high profit consistency in the past three years, but also some of the highest rates of flooding and disease impacts. Farms in this archetype are in regions with historically high mangrove coverage, but also some of the highest mangrove deforestation rates. Spatially, this archetype is located in Bima and Dompu regencies of Sumbawa island.

3.4. Archetype 4: small urban flood-impacted (n = 9 farmer groups)

This archetype has similar actor and governance conditions to Archetype 3 farms, but with smaller farmer group membership and no women membership, as well as some of the longest farmer group history in

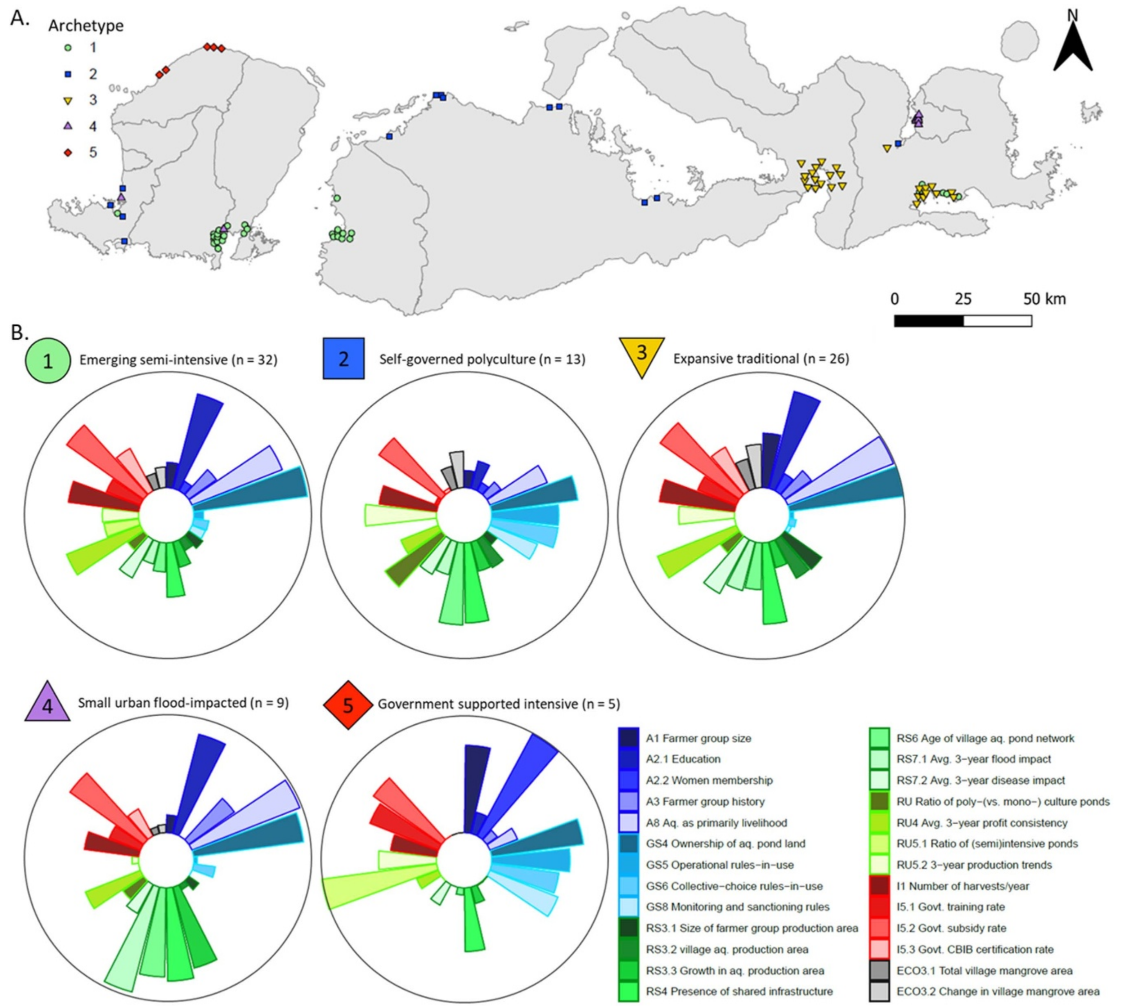

Figure 2. (A) Spatial distribution of farmer group archetypes across NTB province based on clustering analysis results. Farmer group locations are accurate to the nearest village district boundaries. (B) Flower diagrams for each archetype representing the average 0:1 normalized values of all indicators 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.

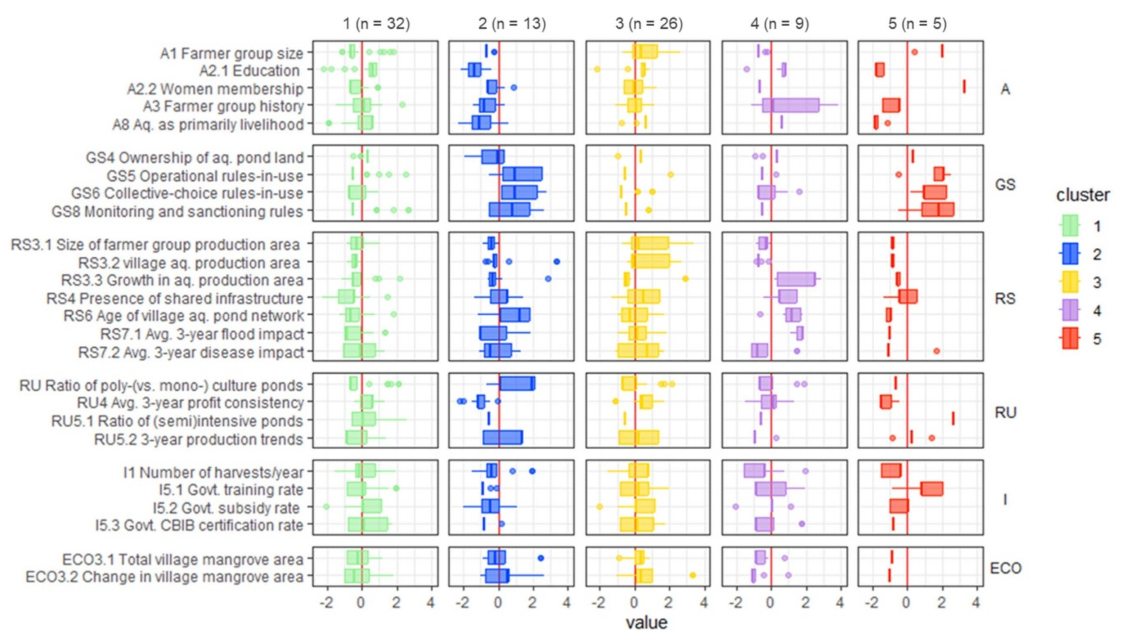

Figure 3. Indicator score distributions for each archetype, normalized to zero mean and unit variance across the population. Zero values (red line) represent the average value for that indicator across all surveyed aquaculture farms in Nusa Tenggara Barat.

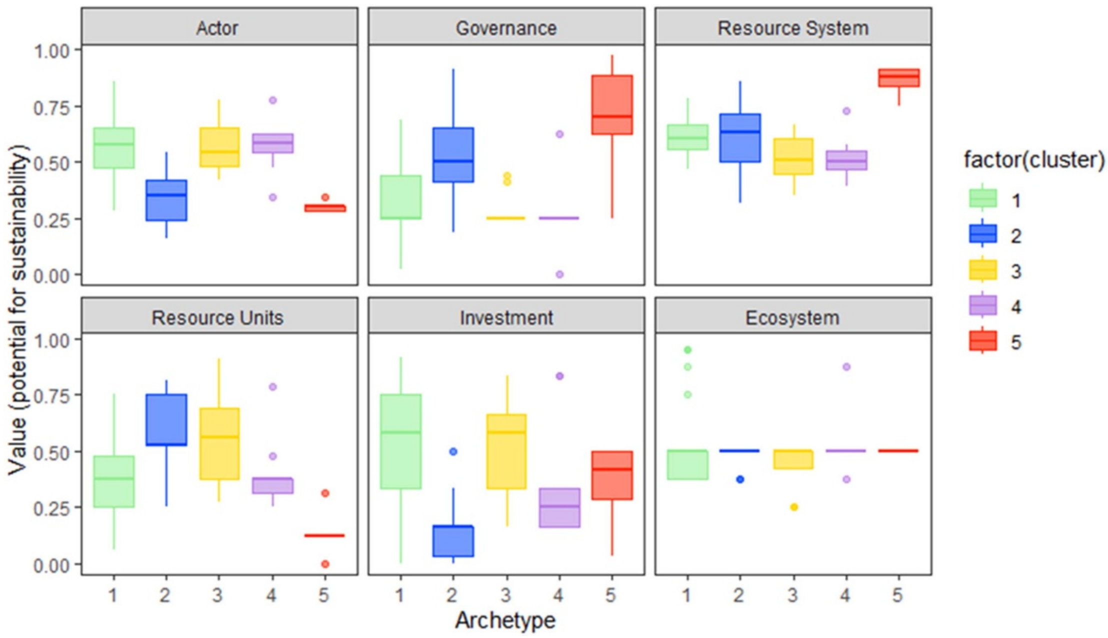

Figure 4. Box plots showing distributions of potential for sustainable governance scores for each archetype across the 1st-tier dimensions of the SES framework. High values (1) indicate increased potential for sustainable governance in that SES dimension relative to other groups, low scores (0) reduced potential for sustainable governance relative to other groups. The 'Investment' category aligns with the 'Interactions' dimension of the SES framework, here modified as government investments (2nd-tier variable I5—investment activities) were the primary interactions of interest. Pairwise significant differences between archetypes for each SES index dimension can be found in figure S3.

the province. A distinguishing feature of this archetype is that cases are predominantly amongst some of the oldest pond networks, located in small, primary urban village districts which have seen a high relative growth in cultivation area in the last five years, but with overall very small pond production area, and little to no surrounding mangrove area. Production is entirely traditional with moderate rates of polyculture production methods and typically old ponds although there has also been a rapid recent expansion in new pond construction. Farms in this archetype have had lower profit consistency compared to small, intensifying farms and traditional large and extensive farms, as well as the highest reported flooding impacts of any archetype, with nearly all farmers in each farmer group being economically impacted by flooding in each of the past three years. All groups in this archetype reporting a decreasing production trend over the past three years. This archetype is primarily located in Bima City on Sumbawa island, with two isolated cases in West Lombok and Central Lombok regencies.

3.5. Archetype 5: government supported intensive (n = 5 farmer groups)

This archetype consists of five farmer groups which are all a part of a recent North Lombok regency government program aiming to develop aquaculture as a livelihood for women. As this program was initiated in the last few years, this archetype has the most recent history of aquaculture, with very large (50+) group membership size consisting completely of women. The government has partnered with local commercial aquaculture farms to provide both technical and management training to the women's groups, which thereby have the highest training rate and, alongside archetype 2, the highest prevalence of farmer group rules-in-use across all three categories. Compared to the other archetypes which consist of privately-owned earthen coastal brackish ponds, in this archetype the government subsidized the construction of 40–50 recirculating biofloc system (BT) tanks for each farmer group, connected via pumps to water reservoirs and the sea. As a result, this archetype has the smallest cultivation area of any archetype and production consists entirely of highly intensive (shrimp) monoculture. The elevated location of the ponds have made flooding impacts negligible. Cases in this archetype have so far had minimal impacts from disease, but also the lowest profit consistency of all archetypes. This archetype is situated entirely along the coast of North Lombok regency, a region with historically minimal mangrove coverage.

3.6. Comparing sustainability barriers and opportunities across archetypes

Composite index score results indicate significant relative differences in the potential for sustainable governance between the farmer group archetypes and across 1st-tier dimensions (figure 4), with each archetype having a unique configuration of barriers and opportunities. For example, archetypes 2 and 5 had the lowest average Actor scores but highest average GS scores. Archetypes 1 and 3 had high average actor and investment scores, but archetype 1 had amongst the lowest RUs scores and archetype 3 the lowest RS scores, and both had low GS scores. Archetype 4 had high average actor scores but some of the lowest scores in all other dimensions. Archetype 5 had high average governance and RS scores, but some of the lowest actor and RUs scores. Across all cases, high scores in one SES dimension were not consistently related to high scores in others. Only RS and GS, and investment and actor, respectively, were significantly positively related with each other (figure S2).

4. Discussion

Pond aquaculture farmer groups in Indonesia are highly heterogeneous both socially and ecologically. At the same time, we can identify five distinct archetypes. Each archetype indicates different sustainability challenges and tradeoffs. Below we discuss how policy programs can be adaptive to archetype specific needs so that national policy strategies and self-organized farmer groups can meet in the middle and develop joint pathways towards sustainability. We further discuss how the study helps inform the development of mid-range theories of governance based on cluster groups.

4.1. How policy can improve by adapting to archetypes

Our findings suggest that most farmer communities lack the self-organizational capacity to address many of the problems they face, whether social or environmental. This suggests that policy programs can play a key role in driving improvements. The question is how? While cluster-based approaches aim to support grassroots level collective action amongst small-scale fish farmers, the development and adoption of these approaches is in many cases being driven by governments, rather than spontaneous self-organization amongst farmers to address commonly understood problems. This creates problems when top-down government support and incentives for encouraging group formation are not aligned with needs of the communities themselves, leading to a failure of collective action due to lack of clear incentives for farmers to work together [57]. In NTB, cluster-based schemes have been encouraged but are not working for many groups, but perhaps these schemes (at least how policy programs engage with them) can be re-organized based on data-driven understandings of problems and conditions rather than spatial proximity. The archetypes identified in our study demonstrate that governance challenges across pond farmer groups are highly variable across SES dimensions. This suggests a clear need to move beyond universal programs to develop bounded best management practice recommendations for cases with similar configurations of social-ecological traits, such as the five archetypes we have identified, which face distinct and varying governance challenges.

Policy programs that can design effective incentives for groups to self-govern but avoid creating dependencies are key. First, we recommend that capacity building efforts (i.e. training, knowledge sharing) may prove to be more beneficial than simply offering material resources (i.e. equipment, money) and are likely to be more effective when adapted to the needs of farmer groups [29, 45]. From our findings we have suggested a set of capacities for each archetype that may be most likely to offer benefits based on their social-ecological conditions and challenges (table 3).

Second, for translating our findings into practice, we recommend the MMAF to expand support for viable grassroots approaches which better integrate local social-ecological context. This includes the need to characterize aquaculture communities, and expand sectoral performance indicators into a wider range of indicators, notably social and governance which are lacking and which influence collective action and long-term sustainability of individual communities. Our archetypes and capacities needed for each (table 3) can be a valuable starting point, however from a policy perspective these categories should not be considered definitive. The selection of appropriate indicators is likely to evolve over time based on local context, and a meaningful level of aggregation for farmer group policy (e.g. number of typologies) will likely be further refined based on both community needs and feasibility. A challenge is the lack of existing aquaculture development data to support more contextually tailored policy. This likely necessitates increasing capacities for MMAF extension officers and programs which aim to support communities at the grassroots level but are currently stretched thin. A baseline social-ecological survey could help triangulate patterns in the particular diverse governance challenges across local aquaculture communities. Typologies such as those identified in this study can further identify a more feasibly actionable middle ground between one-size-fits-all policy panaceas and developing grassroots development and extension programs across hundreds of individual communities. Identifying group typologies does not necessitate a direct adaptation of the clustering algorithms applied in this study, but could also be achieved to a reasonable degree through exploratory descriptive metrics, or expert and stakeholder assessments [58] which might be more practical tools for practitioners.

Third, with input from community members, existing programs like CBIB and POKDAKAN could be then used only as a starting template to create local best management practices adapted to community

Table 3. How policy can be adapted to each archetype.

Archetype	Capacities needed	Examples from the literature	Barriers	Opportunities
1: Emerging semi-intensive	Building leadership and coordination capacity, training to develop institutions for coordinating disease cross-contamination mitigation. Developing value chain connections to access healthier shrimp seed.	In some regions, including NW Sri Lanka, programs have supported shrimp farmer groups to successfully implement zonal calendar systems which coordinate production to minimize disease contamination [30]	SES framework 1st-tier: Resource Units, Governance System High disease risk from increasing intensification of shrimp monoculture production Limited group-level governance to mitigate disease risk	SES framework 1st-tier: Interactions (govt. investments), Actors High existing government investments in the form of subsidies and CBIB best aquaculture practice certification Trained, educated farmers with high dependence on aquaculture
2: Self-governed polyculture	Increase funding support and ecological knowledge. Connect with NGOs and researchers to leverage existing collective action norms to develop pilot silvofishery (mangrove-aquaculture) or IMTA (integrated multi-trophic aquaculture) programs to diversify economic opportunities while supporting resource system health.	Silvofishery and IMTA programs have already been implemented across Indonesia and can contribute to multidimensional sustainable development, but are more likely to be successful with strong governance and community participation [59–61].	SES framework 1st-tier: Actors, Interactions (govt. investments) Limited education, formal training Only moderate dependence on aquaculture Negligible government investment Increasing mangrove deforestation may impact resource system	SES framework 1st-tier: Resource Units, Governance System Strong self-governance norms emerging independent of govt. intervention High rates of polyculture, increasing resilience to environmental and market shocks
3: Expansive traditional	Workshops to develop capacities for organizing and provisioning canal maintenance, administrative training to support coordination of large groups and pond networks. Training regarding economic incentives for canal maintenance and mangrove health (coastal stabilization, flood mitigation, and water quality) to increase buy-in to canal provisioning and reforestation programs.	Organizing farmer groups around a particular shared risk perception such as water quality impacts can improve engagement and interaction of farmers within a group [34], and in NTB a lack of problem recognition regarding aquaculture commons dilemmas has been identified as a central challenge for some farmer groups [29].	SES framework 1st-tier: Resource System, Governance System Large, expansive ponds and canal networks create coordination challenges for maintaining water conditions Exacerbated by highest rates of mangrove deforestation No indications of group-level governance and coordination	SES framework 1st-tier: Actors, Interactions (govt. investments) High existing government investments in the form of subsidies and CBIB best aquaculture practice certification Trained, educated farmers with high dependence on aquaculture

(Continued.)

Table 3. (Continued.)

4: Small urban flood-impacted	Investments into tools and technologies to mitigate flooding impacts. Training programs and NGO partnerships to develop cooperative insurance models to manage financial risk of flood events. Workshops to increase horizontal coordination to improve access to urban market actors.	Cooperative insurance schemes have a long history in smallholder agriculture, whereby farmers collectively contribute to a mutual fund which members distribute in the event of losses. These schemes have more recently been explored as a risk-management tool for smallholder aquaculture [62].	SES framework 1st-tier: Resource System, Resource Units, Governance System, Interactions (govt. investments) Dramatically high flood impacts degrading resource system predictability, infrastructure, production and profitability No indications of group-level governance and coordination	SES framework 1st-tier: Actors Trained, educated farmers with long history of aquaculture production Urban proximity may facilitate increased access to markets/market actors
5: Government supported intensive	Investing in identifying financing opportunities to support cost of inputs after government program ends. Strong collective action norms combined with intensive production of high-value shrimp commodities should be leveraged to increase vertical coordination. Business and marketing training may help support value chain access, including securing contracts and certifications to increase financial stability.	By strengthening collective action, cluster-based organization of intensive shrimp farmers in Ca Mua, Vietnam facilitated increased access to contracts with processors, hatcheries, and feed producers [57].	SES framework 1st-tier: Resource Units, Actors Intensive shrimp monoculture highly profitable but high risk, high maintenance and monitoring requirements High costs of production inputs Low household dependence on aquaculture, limited capital	SES framework 1st-tier: Resource Units, Governance System Strong government training investments to increase technical training and establish strong self-governance norms and group rules-in-use Key livelihood opportunity for women with otherwise marginal access to education, training, and economic opportunities Small recirculating tank systems more predictable and controlled conditions

aquaculture goals, problem contexts, and relevant motivations for collective action. MMAF extension services will be key to developing, implementing, and evaluating these locally adaptive practices. This locally adaptive strategy has in some regions improved collective action outcomes to the point where cluster-based organization has become a self-propagating model [33], however widespread adoption in Indonesia is a challenge given the limited capacities of local aquaculture departments and extension services. Indeed, many of the most rapidly emerging aquaculture countries also have amongst the weakest governance capacities [3].

In Indonesia, while aspects of governance are to a degree largely decentralized, local aquaculture and fisheries departments often have limited resources and training to develop their own contextualized programs and best practice protocols to support aquaculture communities. This can be a barrier for translating our archetypes into practice, as even if the contextual SES challenges of each typology are understood by local managers who have the autonomy to act, lack of knowledge and capacity means that support is often limited to financial aid rather than developing locally adaptive management practices with communities. Our own interviews indicated little communication between regency-level government aquaculture departments (and communities) across the province. In essence, while decentralized, there is a lack of vertical and horizontal coordination and interaction for effective polycentric environmental governance to emerge. Our final recommendation is, therefore, for the development of local-to-regional (e.g. province-level) knowledge sharing hubs to help surmount this challenge. This can be accomplished by providing a platform or forum for government managers to communicate similarities and differences in aquaculture communities between regencies and share solutions and insights regarding what strategies and interventions work or do not work. The province-level DKP already acts to collate fisheries and aquaculture data from each regency to bridge central and local governments, potentially situated to serve as a key bridging organization to organize these forums between local DKP offices. Identifying additional collaborative opportunities with local NGOs and universities may also be critical to improve this bridging capacity.

4.2. Using archetype analysis to inform governance theory

Archetype analysis is particularly suited to making key contributions towards SES governance theory development, (1) by explaining cases in terms of diverse configurations of interconnected SES processes rather than single isolated variables, and (2) by identifying multiple models or variable configurations that explain some cases but not in others [12, 63]. In doing so, archetypes approaches contribute to middle-range SES theory building and testing, by establishing bounded ranges of conditions by which particular explanations are valid. In our approach, we have mostly explored patterns of co-occurrence regarding our indicators between the different archetypes. As a next step, research might continue to test theoretical explanations regarding the emergence of collective action in aquaculture communities (or SESs more broadly) by more explicitly modeling the specific social-ecological processes which explain collective action outcomes within a range of similar cases, such as each of the coastal aquaculture archetypes we identified [64, 65]. Applying a 'building blocks' archetype approach could be used to identify recurring sets of causal mechanisms and processes explaining governance outcomes in each typology or across multiple studies [11, 66], and further refine our single variable hypotheses (appendix 3) into hypotheses regarding how key interactions between certain variables influence outcomes. Finally, more explicitly modeling temporal dynamics of governance, such as path-tracing of the development of community-level aquaculture institutions over time, might also help unpack why self-governance is emerging in some SESs but not others [67].

Our archetypes approach contributes an important starting point for explaining the underlying SES interactions influencing collective action and sustainability in smallholder pond aquaculture. There are no standardized procedures for validating archetypes analyses, however Piemontese *et al* 2022 [68] propose six dimensions for assessing archetypes validity and found that external and application validity tend to be the weakest across archetypes studies. Regarding application validity, we presented and discussed our results to audiences of government managers, local researchers, and pond farmers in June 2023, which provided an important, albeit not systematic, step in validating our interpretation of the social-ecological patterns and governance challenges in each archetype, which are currently being used to draft formal policy recommendations. Regarding external validity, while the generalizability of our archetypes outside of our case province is uncertain, we hope our work can influence additional similar case studies into pond farming communities which dominate the aquaculture sector in many regions globally but remain understudied from an environmental governance lens [3]. A full self-reflection on these validity criteria in our study can be found in table S1.

4.3. Study limitations and opportunities for future research

A complete understanding of aquaculture transformations on coastal smallholder communities in Indonesia requires more research the growing industrial shrimp farming sector, given the many potential interlinkages, interactions and overlaps (e.g. markets, suppliers, regulations, infrastructure) connecting the small- and large-scale branches of the sector. As government production targets continue to drive expansion of the sector, smallholder aquaculture livelihoods should not be left behind. Our decision to focus only on community-based pond aquaculture POKDAKAN groups largely stemmed from COVID-19 restrictions and the high sensitivity of recent social conflicts between large private commercial farms and surrounding communities, which limited our access to informants from these groups. Another limitation is that our study focused entirely on farm-level production, but potential for collective action and sustainability is additionally influenced by a wide range of actors along the value chain, from processors to retailers, hatcheries and government and non-government organizations [57, 69, 70]. Informing sustainable development of the sector requires additional research which expands to other such actors along the value chain [71]. Our survey-based tool to collect self-reported farmer group data allowed some flexibility in indicator selection, but also had limitations in creating precise comparable quantitative estimates for certain indicators, such as revenue and production yields or biophysical RS data such as water parameters (table S2). Additionally, while we substantiate a hypothesis regarding the link of each indicator to farm group sustainability (appendix 3), in reality there are likely to be many nonlinear effects and variable interactions which influence the overall contribution of each indicator to farmer group outcomes. Finally, while our survey-based design included a self-evaluation tool to assess confidence of reported data, future studies could expand on this approach through more comprehensive methods for testing data validity, such as inter-rater agreement indices [72, 73].

5. Conclusion

Community-based smallholder pond aquaculture relies on different types of commons which can lead to social dilemmas and require collective action to jointly manage. Many countries are promoting cluster-based farm organization as a strategy for fostering collective action and improving outcomes in these communities but outcomes are mixed. Drawing from the archetypes approach, our analysis identified five social-ecological archetypes of cluster-based coastal brackish pond aquaculture groups in NTB province, Indonesia. These findings inform several key conclusions aimed at improving smallholder aquaculture policy. First is that regional aquaculture policy could be more effective if it targeted specific farmer groups facing particular problems and needs. Second is that collection of regular basic data on social and environmental indicators of aquaculture development is required to improve the capacity for policy to be tailored to these specific group needs and identify which groups have similar problems and needs. This is demonstrated by our archetypes results which highlight distinct differences in sustainability opportunities and barriers in different types of farmer groups. Third is that the advantages of a cluster-based approach are in facilitating collective action. Aquaculture policies that aim specifically at building capacity for collective action and cooperation within and between farmer groups are likely to benefit investments in collective action across all groups. We believe our study demonstrates a promising approach for identifying social-ecological patterns which can inform context-sensitive policy at an actionable middle range of generalizability, and we encourage future research to further explore and expand on our application of the archetypes approach.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.6084/m9.figshare.23846982.

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Author contributions

Author 1 conceived the study idea, led data collection in collaboration with Author 2, analyzed the data, and wrote the manuscript. Author 2 contributed to data collection and survey design. Author 3 contributed to the development of the study framing, and core supporting arguments, and supervised the development of the manuscript. All authors contributed to ongoing discussions of the results which contributed to the final manuscript. All authors contributed to manuscript revisions.

Ethical statement

A prior informed consent statement was shared and discussed with respondents before beginning the survey, which included the conditions that the data will be used for scientific purposes and individually identifying information would be kept confidential. Informed consent was obtained from all participants prior to the survey interview. Prior informed consent was obtained orally due to variability in respondent literacy, and a reliance on over-the-phone survey interviews to reach many respondents. 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) and in accordance with the principles of the Declaration of Helsinki.

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