Archetypes of aquaculture development across 150 countries

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Abstract

Aquaculture is expanding and intensifying globally, with implications for environmental, livelihood, food security and nutrition impacts. However, the way that aquaculture impacts people and the environment varies significantly across the globe, making it important to understand what factors shape different trajectories. Here we compile and integrate 45 country-level indicators to examine the social, economic, governance and environmental conditions shaping aquaculture development across 150 countries. We apply cluster analysis to identify social-ecological archetypes of aquaculture development. We empirically identify four archetypes driven by both social and ecological factors including: climate risk, inland water area, coastal population, seafood consumption, trade balance, governance indices and environmental performance. We name the four identified archetypes of aquaculture as: Archetype 1 - Emerging aquaculture producers, Archetype 2 - Limited aquatic food engagement, Archetype 3 - Developing economy producers, Archetype 4 - Wealthy economy producers. Each archetype is defined by its distinct range of values across the 45 indicators from the countries within the archetype. We discuss the utility of identifying country-level archetypes for both continued research and development practice as well as compare our archetypes with current literature on aquaculture development scenarios.

Introduction

Understanding the social, economic, environmental and governance factors guiding current aquaculture development is essential for analyzing the sector's rising contributions to food and livelihood security. The sector is now a key contributor to global food security and nutrition (1, 2) producing near equal amounts of seafood as capture fisheries (3, 4). However, many questions remain regarding its sustainability. A main challenge is analyzing the underlying drivers of a highly diverse sector with marine, brackish and freshwater geographies, each with unique culturing techniques and environmental dependencies. Aquaculture production systems are not isolated but embedded within local ecosystems, cultures, markets and governance structures, many of which were established to serve the capture fishery and agriculture sectors (5–7). At least 39 countries now produce more from aquaculture than they do from capture fisheries (8), but the global distribution of production is highly skewed towards Asia. China alone produces 62.7% of global aquaculture by weight as of 2022, with Asia as a whole contributing more than 90% of total production (9). Furthermore, 80% of Asian aquaculture production volume is produced by small-scale enterprises (9). Much of the rest of the world has remaining development potential, particularly in Latin America and Africa, but it is unclear if they will follow similar development trajectories as the Asian countries or which factors will be most influential in shaping continued growth.

Unique macro-level environmental, economic, and political conditions and restraints shape aquaculture development trajectories in different countries. Identifying indicators to measure such factors is essential for understanding and comparing risks and opportunities for aquaculture expansion, intensification and diversification. Environmental conditions shaping aquaculture development differ across production systems. For example, freshwater systems are by far the most dominant, primarily in earthen ponds, which require water availability in high volumes from adjacent water bodies which can have high climate risk from droughts or flooding. Abundant freshwater resources can provide countries with suitable room for expansion, whereas countries with limited water resources may be constrained to alternate aquaculture expansion paths. Water distribution is at least as important for inland aquaculture as it is for agriculture given high water needs, making existing water distribution capacity (e.g., irrigation canals) an indication of development potential (10, 11). In marine systems, the length of a country's coastline provides geographical opportunities for mariculture expansion. However, expansion also depends on environmental conditions such as sea surface temperature which affects the suitability of culturing certain species (12) as well as competition for the rights to operate farms in coastal spaces which are often contested and/or multi-sector (13, 14).

Aquaculture product demands vary greatly across the sector (3), representing an important economic context for development trajectories. Existing import and/or export markets for seafood products in a country may be a driver of aquaculture expansion to meet local economic and food needs. Similarly, the size of rural and coastal populations can shape demand for aquaculture if seafood cultures and consumption already exist, or if aquaculture products serve as substitutes or supplements for existing products - such as from capture fisheries - which may be overexploited, or from more expensive agricultural products such as meat (15). Indicators of human health and undernourishment can provide insights into where the dietary health benefits of seafood products may be most effective (16, 17), particularly in the 29 countries facing the triple burden of childhood stunting, anemia and obesity (18). Nonetheless, the ability of aquaculture to contribute positively to these issues will depend on context. For example, investments into rural small-scale pond aquaculture may foster local livelihood transitions or food security in underdeveloped areas (10, 19, 20). Furthermore, macro-economic factors such as Gross Domestic Product, Human Development Index, and the regulatory ease of starting a business (i.e., Doing Business score) likely influence sector growth (21). Multiple dimensions of governance will play a role, particularly the six dimensions provided by the World Governance Indicators (https://info.worldbank.org/governance/wgi/) (22), as well as the size of a country's overall agricultural sector and its proportional contributions to the economy.

The above factors, among others, exist in different combinations to create unique development conditions for each country. Nonetheless, many countries face similar combinations of conditions, and perhaps trajectories, which can be grouped and understood as archetypes (23, 24). Understanding aquaculture archetypes based on diverse social and ecological data sources will help scholars and practitioners move beyond limited species production data when evaluating development trends, allowing analysts to include a more comprehensive range of known factors that contribute to social wellbeing and environmental sustainability in the sector. Most high level assessments in the sector are based on species production data from the FAO, the most comprehensive country-level data available, yet most studies do not couple this data with other known and available data shaping the sector (3, 8, 25–27). Integrating more comprehensive data to inform archetype analysis can further differentiate the risks and opportunities across localities to better inform policymakers and governance practitioners in finding context appropriate solutions.

The need for comprehensive and integrated data to understand and characterize aquaculture development has been gaining increasing attention over recent years (e.g., 11, 27). In response, a number of studies have demonstrated the utility of multi-disciplinary analysis and use of broader data sets in aquaculture research. For example, the use of global governance and economic data has been used to explain aquaculture development trajectories and potential across countries, confirming connections between local governance and sustainable development (22, 29). Furthermore, public perceptions of aquaculture vary widely across type and location of development (30) highlighting the potential for social context to be a potential driver (or limiting force) for aquaculture development. Additional studies, such as Cottrell (8) and Golden (31) pull from wide data sources in examining the role aquaculture plays in shifting seafood economies and food security, finding that new aquaculture development is generally associated with market expansion (8), but only benefits nutritionally at-risk communities in limited situations and locations (31). The value of using diverse and integrated data in aquaculture development research was confirmed by Ruff and colleagues (21) in a study that compared models of mariculture production across the globe using social and economic data in addition to ecological data alone. The above studies have provided substantial insight into using integrated data analysis on sustainability issues in the sector. There are nonetheless many remaining gaps because current literature has either only focused on specific questions or indicators, or has been limited to specific geographies or production types, which spotlights the use-value and need for a comprehensive global overview of the sector's interlinked sustainability issues.

We compile and integrate 45 country-level indicators associated with macro-level aquaculture development and analyze archetypes across 150 countries. Our data provides, to the best of our knowledge, the most comprehensive compiled data set and assessment of social, economic, political and environmental factors shaping aquaculture trends. Archetypes represent distinct patterns of social-ecological system interactions leading to specific outcomes that are similar across cases (23). The value of archetype analysis is that researchers, practitioners and policymakers are better equipped for understanding the types of complicated system interactions that shape development outcomes to inform governance (24). Archetype analysis has been applied in different contexts and levels of granularity, such as in drought adaptation (32), cognitive archetypes of farmer perceptions of sustainable land use barriers (33) and poverty and food security archetypes across administrative districts (34). However, archetype analysis has not yet been applied at scale to analyze aquaculture development. Therefore, in order to compare and contrast our findings, we discuss our archetype results with prior literature review research on aquaculture development scenarios by Gephart and colleagues (35).

Methods

Conceptual framework

An important hypothesis in this analysis is to test if both social and ecological factors influence aquaculture development across countries. To conceptually organize our data to examine this hypothesis, we use the social-ecological systems framework (SESF) (36, 37), arguably the most comprehensive social-ecological framework for guiding the identification of relevant variables in social-ecological systems (34, 38, 39). The SESF has 8 first-tier variables (Table 2), and we categorized each indicator into one of the first-tier variables. The following six first-tier variables were assigned indicators: Actors; Governance; Resource systems; Resource units; Social, economic and political settings; External ecosystems.

Data collection

All data used in this study were collected from secondary sources (Table 2; Supplementary Material A). We searched publicly available data at the country level that either (1) represents the macro-conditions under which aquaculture is produced, or (2) is a specific indicator of aquaculture sector development. When selecting data there is a tradeoff between coverage (i.e., the number of countries that can be included) and depth (i.e., the number of indicators). Many data sets have detailed indicators of relevance for aquaculture, but have limited coverage. Our goal was to include at least the top 100 aquaculture producing nations. The final data included 45 indicators with full coverage in 150 countries (Table 2). Justifications for all indicators are provided in relation to their relevance to aquaculture development (Supplementary Materials A).

Data formatting

All data were downloaded from 2019 or the most recent available year from the original sources. The coverage of some data was not comprehensive in 2019 for all years, but data often existed for prior years. In order to increase coverage, if a country did not have data for 2019, the most recent available year was taken, not older than 2015. Raw correlation tables were made against all indicators, allowing us to drop highly correlated indicators. Tests of normal data distribution for each indicator were done to assess the need for data transformation and/or normalization of individual indicators. Data formatting allowed us to exclude variables with high correction values, exclude variables with skewing or transformation issues and/or exclude variables due to lack of coverage. Our final data contained full coverage of 45 indicators across 150 countries standardized by ISO 3166 code, including the top 100 aquaculture producing countries.

Table 2. Data used as indicators for aquaculture development at the country level, organized by the SES framework (SESF). The justification for aquaculture relevance, sources of the data, descriptions and any transformations made to the original data for the analysis are provide in the Supplementary Materials A.

SESF	Indicators used
Actors	Total seafood consumption; Fish consumption per capita; Human Development Index (HDI); Prevalence of anemia; Per capita food supply variability; Prevalence of undernourishment; Domestic seafood supply
Governance	Accountability; Political stability; Government effectiveness; Regulatory quality; Rule of law; Prevalence of Corruption; Doing Business score
Resource systems	3-year aquaculture production growth rate; 10-year aquaculture production growth rate; Exclusive Economic Zone (EEZ) size; Sea surface temperature (SST) change; Water stress index; Irrigation capacity; Inland water area; Environmental performance; Coastline length
Resource units	Export value seafood products; Import value of seafood products; Fish trade balance; Capture fisheries production; Percent aquaculture of all seafood production; Total aquaculture production; Fresh production ratio; Marine production ratio; Brackish production ratio; Number of brackish species produced; Number of freshwater species produced; Number of marine species produced; Total number of species; Freshwater production total; Marine production total; Brackish production total
Social, economic and political settings	Gross Domestic Product (GDP); Total population; Population density; Rural population; Coastal population; Rates of migration; Value added to economy from agriculture, fisheries and forestry
External ecosystems	Climate change risk

Data analysis

Global production conditions

Quartile calculations were produced on the raw data ranges in order to assign each country to a quartile range for each indicator. The total aquaculture production from all countries assigned to each quartile range was summed to assess the amount of global production occurring under the conditions from each indicator. China was excluded from this analysis, given its large production volume (57.5%), which skews results. However, the quartile ranges that China falls into for each indicator is indicated for reference.

Cluster analysis to identify archetypes

Identifying typologies or archetypes of aquaculture development that consider a wide range of indicators is a clustering problem that considers the degrees of similarity of all indicator values across all observed countries in order to classify them into groups. Social-ecological systems literature suggests that a mix of social, economic, governance and environmental variables likely contribute to determining natural resource outcomes (i.e., production) and therefore classification. To find an appropriate clustering solution to identify these archetypes in a transparent and reproducible way, we adapted the data-driven approach of Rocha and colleagues (34) to identify an ideal clustering algorithm based on internal and stability validation using r package "clValid" (40), and an optimal number of clusters using r package "nbClust" (41). To help interpret which indicators were driving clustering of the resulting archetypes, we ran analysis of variance (ANOVA) followed by Tukey tests to identify all significant ($p < 0.05$) pairwise differences between clusters for each indicator (Figure 3).

Our data-driven identification of clustering approaches identified an ideal configuration of four clusters, or development archetypes (Figure 1), based on majority rule from a comparison of 26 indices using r package "nbClust". A stability evaluation test with r package "clValid" identified hierarchical clustering as the optimal clustering approach based on 4 of 7 stability measures. For our final clustering, we applied the hierarchical approach with a Manhattan distance measure and Ward agglomeration method to minimize within-cluster distance (42). The cluster analysis categorizes countries into groups based on their similarities and differences in the data (Figure 3; Figure S1).

Comparing archetypes to theory

We compare our data-driven archetypes with the literature-based development scenarios proposed by Gephart and colleagues (35), which have not yet been empirically examined. Gephart and colleagues propose two axes determining four scenarios; the x-axis (- regionalized to globalized +), and the y-axis (- endless growth to doughnut economics +). The two axes create four plot quadrants: (1) Food Sovereignty (-,+), (2) Blue Internationalism (+,+), (3) Aquatic Chicken(+,-) and (3) Aqua-Nationalism(-,-) (Table 3). To do this we selected indicators from our data that most closely represent the two axes suggested by Gephart and colleagues, using the quartile ranges of those indicators to assign value (+ or -) along the axes (Table S1). The quartile range scores were assigned as the following: -2 (1st quartile), -1 (2nd quartile), +1 (3rd quartile), +2 (4th quartile). The sum of all indicator scores for a country on each axis were calculated to enable a simple coordinate plot that places each country in one of four coordinate quadrants. This then represents the null hypothesis of how individual countries are grouped, to test the extent to which our data-driven archetypes align with the development scenarios. Gephart and colleagues label each of the quadrants based on literature support as likely corresponding to the following development trajectories: Food sovereignty (+,-), Blue Internationalism (+,+), Aquatic Nationalism (-,-) and Aquatic Chicken (-,+). We directly compare the overlap of country classification between the Gephart development scenarios and our cluster analysis groups. A paired t-test can then be performed to assess whether the match pair groupings are significantly different or not.

Table 3. Four development scenarios proposed by Gephart and colleagues (35).

Scenario	**Axis classifications**	**Narrative**
Food Sovereignty	Doughnut economics Regional	● Sustainable local rural production by small-holders ● Production fits local cultural needs and environment limits ● Diverse species, but higher urban prices ● Limited trade creates risk, but nutritional needs are met
Blue Internationalism	Doughnut economics Global	● Sustainability goals with global trade and strong governance ● Technology transfer leads to high production efficiency ● Moderate diversity, trade lowers prices, eases urban access ● Disease risks mitigated through global cooperation ● Fiscal incentivizes align production with nutrition goals
Aquatic Chicken	Endless growth Regional	● Globalization encourages boundless economic growth ● Intensified production with limited environmental regulation ● Reducing cost is prioritized over other risks. ● Global trade sources feed in low cost competitive markets ● Mass production of few species at different price categories ● Businesses with knowledge and capital trump small-holders ● Disease risk is high and nutrition contributions are lower
Aqua Nationalism	Endless growth Global	● Domestic focus drives growth for local demand ● Limited knowledge transfers and low trade makes production inefficient ● Growth over regulation leaves higher environmental impacts ● Production and price volatility leads to nutrition insecurities ● Moderate cultural adoption but lower awareness of benefits

Results

Comparing production conditions and risks

The conditions under which aquaculture is produced in a country are highly influential on its development trajectory, and can explain historical trends and future scenarios. We find that 86% of aquaculture is produced in countries that score in the most at-risk 1st and 2nd quartile ranges (bottom half) of the Climate Risk Index, which ranks countries based on the extent which they have been affected by the impacts of weather-related loss events (storms, floods, heat waves etc.) (Table 1). Similarly, 74.44% of aquaculture is produced in countries that rank in the worst performing 1st and 2nd quartile ranges of the Environmental Performance Index, which provides a data-driven summary of the state of sustainability around the world. 62.9% of aquaculture is produced in countries with moderate food security concerns, and 68.95% in countries ranking in the 2nd quartile of the Human Development Index. A large majority of aquaculture is produced in countries with high coastal and rural populations, also countries with high fish consumption per capita and high capture fisheries production. 90% of aquaculture tonnage is produced in countries ranking in 1st or 2nd quartile of the per capita food availability index, where availability of food stability is below the global median. Across numerous indicators, such as the prevalence of anemia among women of reproductive age, where fish can provide essential iron in the diet, the distribution of global production across quartile ranges is rather even. Including China further skews the indicator percentages in either direction depending on where China is classified (i.e., underlined in Table 'conditions')

Table 1. The percent of global aquaculture produced within each quartile range of each index. Each country has a ranking for each index, and therefore falls into one of four quartile ranges. The total amount of aquaculture produced by all countries that fall within each quartile range for each indicator is summed and shown as a percentage of the total global aquaculture so that total production equals 100% across the four quartiles for each index or indicator. The quartiles with the highest production (dark gray) and second highest (light gray) are highlighted for interpretation. The total production data excludes China, which accounts for ~58% of total global production, skewing the data. Where China falls within each quartile is underlined.

Country level index	SESF	Percentage of total global aquaculture production within each quartile (excluding China)			
		1st (lowest)	2nd	3rd	4th (highest)
Climate Risk Index (ECO)	ECO	43.31	42.69	6.62	7.37
Per capita food supply variability (A)	A	37.90	52.11	7.34	2.65
Environmental Performance Index (RS)	RS	33.15	41.29	10.41	15.15
Global Food Security Index (A)	A	7.52	62.90	17.22	12.37
Human Development Index (HDI)	SEP	4.52	68.95	8.58	17.94
Gross Domestic Product (GDP)	SEP	9.06	65.41	10.42	15.11
World Governance Index	GS	13.94	19.16	49.68	17.22
Doing Business score	GS	9.24	12.91	60.28	17.57
Water Stress Index	RS	5.71	15.04	50.10	29.15
Prevalence of undernourishment	A	17.18	9.01	56.53	17.28
Anemia in women of reproductive age	A	20.38	17.67	36.71	25.24
Fish consumption per capita	A	16.16	5.57	15.25	63.01
Capture fisheries total production	RU	0.58	1.35	6.11	91.96
Coastal population	A	1.06	7.22	2.15	89.56
Rural population	A	3.42	4.02	13.29	79.27

Archetypes of aquaculture development

Archetype 1 - Emerging aquaculture producers

Archetype 1 includes countries (Figure 1; Table S2) characterized by low aquaculture production and the lowest total aquaculture species count of any archetypes, while also having the highest ratio of freshwater production and highest average 10-year growth rate, as well as lowest average environmental performance (EPI) and EEZ size (Figure 2). Archetype 1 countries have the lowest seafood consumption per capita and HDI scores, and highest rates of undernourishment and anemia, as well as the lowest average scores for governance indicators including governance effectiveness, control of corruption, and doing business. This archetype covers much of central Africa and as numerous west Asian countries with the lowest average GDP of all archetypes (Figure 2; Figure 3). The geographical distribution of Archetype 1 includes a majority of sub-Saharan African countries and the land-locked countries in Asia and South America.

Archetype 2 - Limited aquatic food engagement

Archetypes 2 countries have both low total aquaculture production and the lowest overall capture fisheries production, above average freshwater production ratio, but also the lowest inland water area and irrigation area, and above average environmental performance (Figure 1; Figure 2; Table S2). These countries have the lowest overall seafood consumption but relatively average per capita consumption, with moderately high HDI and governance indicators. Archetype 2 consists of primarily eastern European countries along with a small number of African, South American, and Asian countries (Table S2) with moderately above average GDP, lowest average total population, and the lowest average value added from agriculture, fisheries, and forestry (Figure 2; Figure 3).

Archetype 3 - Developing economy producers

Archetype 3 includes countries with high total aquaculture production, high aquaculture import and export value, high total species counts across all production types, including the highest average brackish species counts and brackish production ratio (Figure 1; Figure 2). Archetype 3 countries have high land equipped for irrigation, inland water area, coast length, and EEZ size, but below average environmental performance. These countries have high overall seafood consumption and the highest average domestic seafood supply, and moderately low governance indicators. Archetype 3 countries have the highest average overall and rural population, as well as high coastal populations, with typically average to below average GDP (Figure 2; Figure 3). Archetype 3 includes most of southeast Asia including China and India, as well as Russia and most of Latin America (Figure 1; Table S2).

Archetype 4 - Wealthy economy producers

Like Archetype 3, Archetype 4 countries have high total aquaculture production, high aquaculture import and export value, and high total species counts across all production types, however Archetype 4 is characterized by the highest overall marine production ratio and marine species counts and lowest freshwater production ratio (Figure 1; Figure 2). Archetype 4 countries have the highest overall EPI performance score, as well as high coast length, EEZ size and land equipped for irrigation. Archetype 4 has the highest per capita seafood consumption, highest HDI score, and lowest rates of anemia and undernourishment, as well as the highest scores for most governance indicators (Figure 2; Figure 3). Archetype 4 encompasses primarily high-GDP countries including most of western Europe as well as Japan, Australia, US, and Canada, with moderately high overall and coastal populations (Figure 1; Table S2).

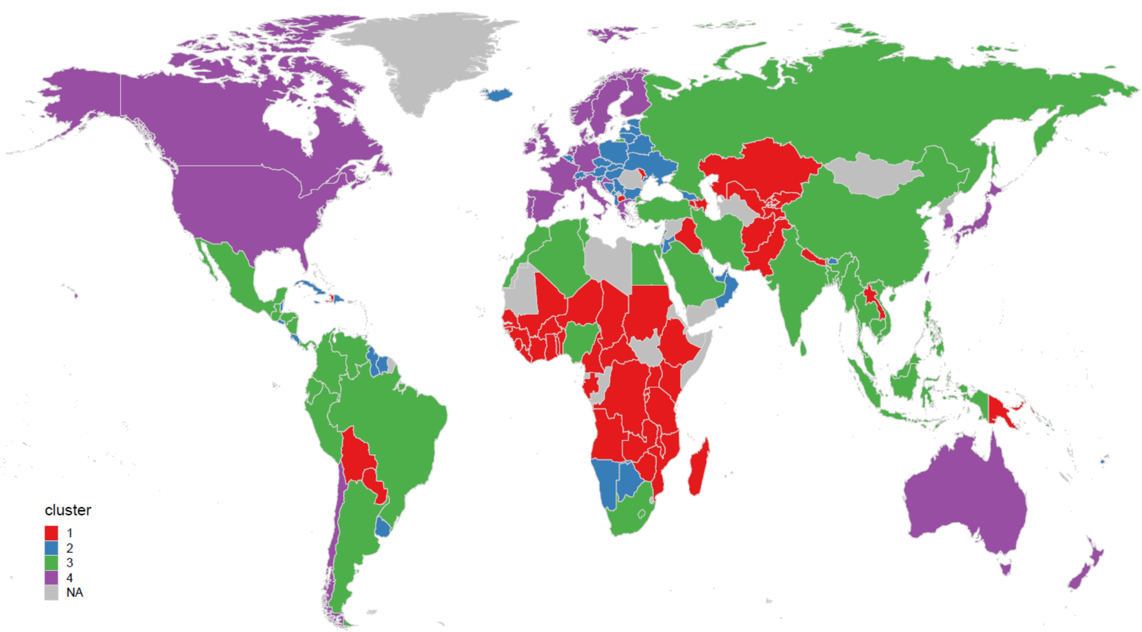

Figure 1. Countries colored by the four cluster (archetype) groups.

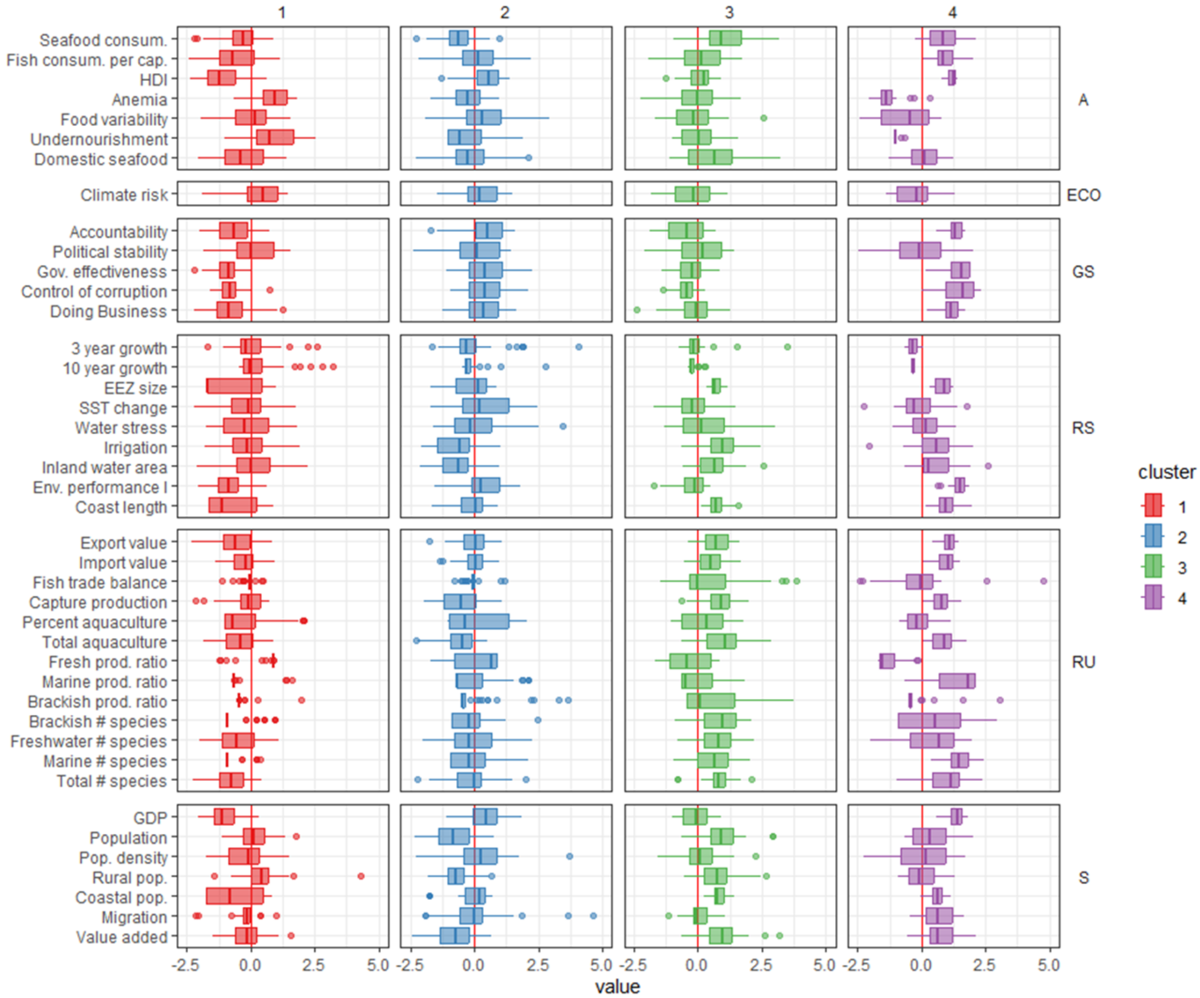

Figure 2. Quartile distributions for each variable in each cluster (archetype). The global mean is indicated as a red line through each set. All variable distributions are centered to the global mean. Variables are organized into groups by their social-ecological system first-tier variable classification: Actors (A), External ecosystems (ECO), Governance systems (GS), Resource systems (RS), Resource units (RU) and Social, economic and political settings (S).

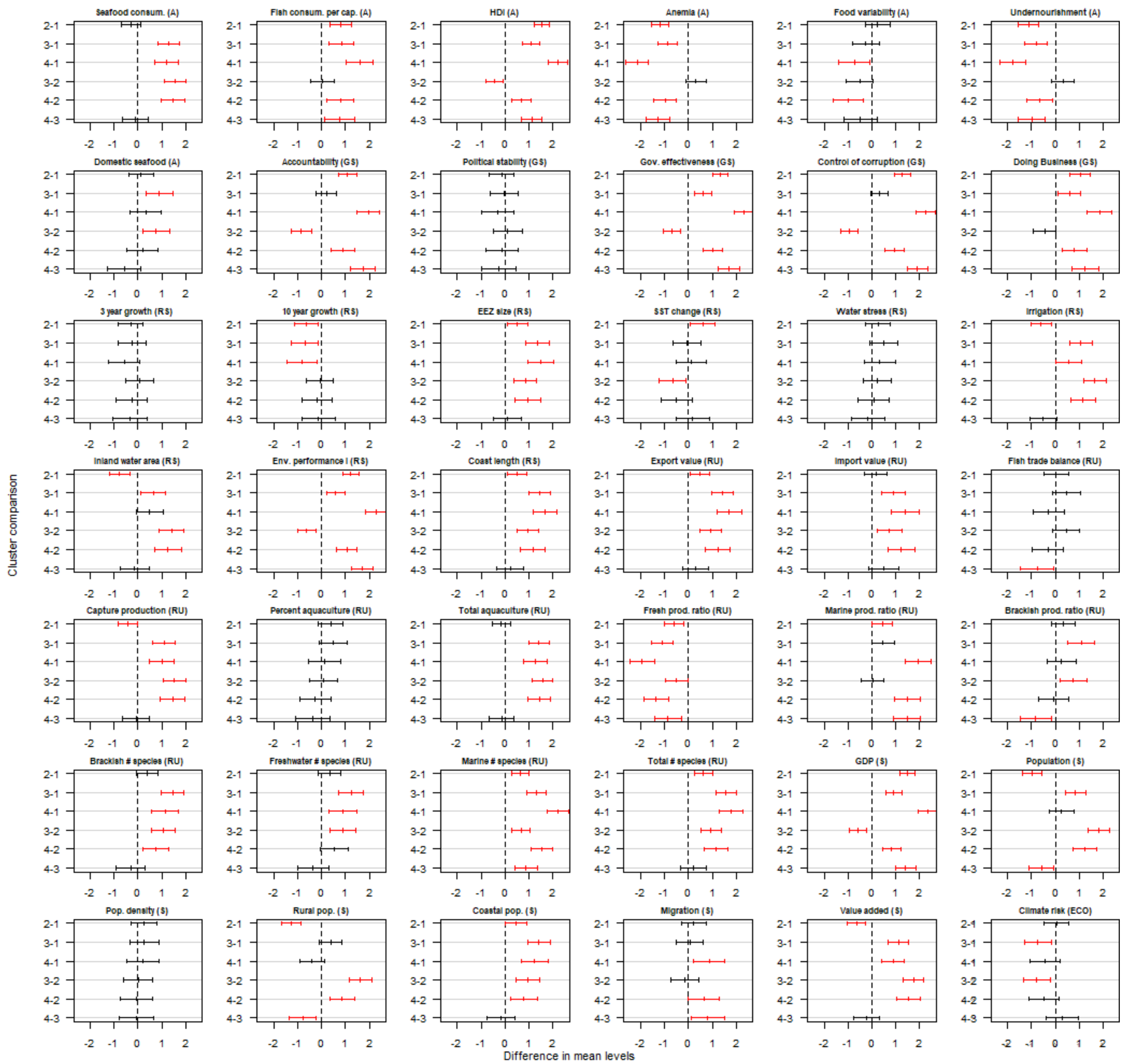

Figure 3. Pairwise significant differences between clusters for each individual indicator using analysis of variance followed by Tukey test. Cluster comparisons are labeled on the y-axis, which includes all possible pairwise combinations. Significant ($p < 0.05$) pairwise cluster differences are labeled in red.

Comparing archetypes to existing development scenarios

We compare our four data-driven archetypes to the four scenarios defined by Gephart and colleagues (35). The literature-based scenarios are represented by a select set of 10 indicators (5 for each axis) (Table S1) that best match the two-axis descriptions proposed by Gephart and colleagues. Each of our four archetypes has a dominant alignment with a different literature-based scenario, covering all four (Figure 4; Table 3). Archetype 1 aligns mostly strongly with the Aquatic Chicken scenario, with 46% of the countries from our archetypes group falling into this quadrant and with Food Sovereignty (29%). Archetype 2 aligns most strongly with Blue Internationalism (56%), but also with Food Sovereignty (33%), similar to Archetype 4 which is aligned with Food Sovereignty (56%) and Blue Internationalism (39%). Archetype 3 aligns the strongest at 67% with Aqua-Nationalism. Overall, the four scenarios and the four archetypes do have identifiable overlaps, however, not completely. The matched pairings of the two groups are significantly different from a paired t-test (p-value = 0.007537), rejecting the hypothesis that the country-pairings across the two groups are the same. Nonetheless, there are substantial overlaps.

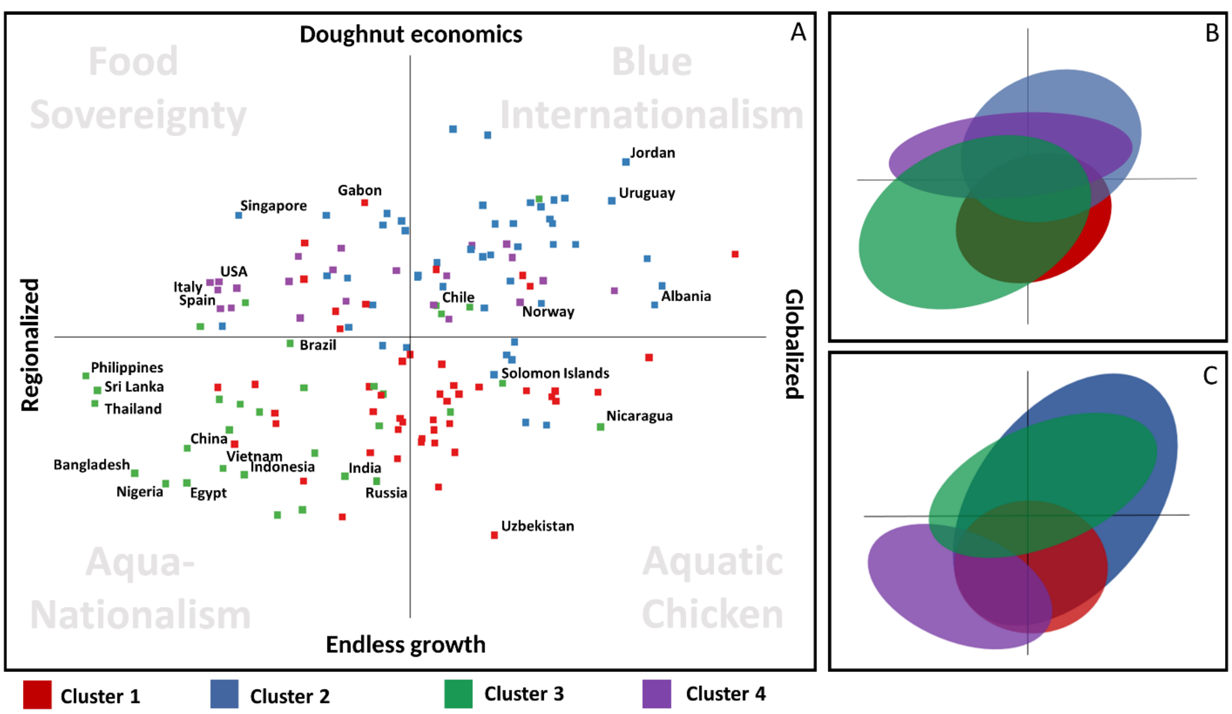

Figure 4. (A) Countries plotted on two axes with a select set of indicators designed to match the variables proposed by Gephart and colleagues (2020). The cluster groups are colored from the full indicator data that are shown to assess overlap. The plot assesses to what extent Gephart and colleague's theory driven archetypes (Food Sovereignty, Blue Internationalism, Aquatic Chicken, Aqua-Nationalism) overlap with our

data driven approach. (B) An ellipse of the cluster groups from the full 45 indicator analysis. (C) An ellipse of the cluster group overlaps, when the cluster analysis is performed with only the selected 10 indicators from Gephart and colleagues used to plot the countries in part A.

Although there is only weak statistical alignment of our data-driven archetypes analysis with the theory-driven development scenarios provided by Gephart (35), there are many overlaps and similarities useful for discussion. Both analyses propose 4 groups, but have different analytical goals useful to the field. The archetypes approach examines current data, where the sector has arrived, but not strategic intent and envisioned goals going forward. In contrast, the scenario analysis examines potential future states. For example, a plausible future scenario can exist without it currently existing, such that development organizations could be putting money toward something that looks like the Aquatic Chicken scenario. However, if that is only just beginning, then one would not expect to see it in the data yet. Furthermore, plausible scenarios can exist without them ever becoming a reality or recognized at scale.

Discussion

How to focus governance on countries within each archetype

Archetype 1 - Emerging aquaculture producers

Prioritizing development initiatives that target how aquaculture can contribute to public health while ensuring that rapid growth doesn't compromise environmental integrity despite weak national governance performance will be key. Countries in Archetype 1 likely lack the types of government investment into the sector as other more established producers such as sector specific agencies and extension officers. Strengthening and supporting existing community-based approaches may be most effective to ensure that prioritizing livelihood security is coupled with addressing nutrition issues for larger dispersed rural populations within countries in Archetype 1. Assessing inland water interdependencies with the agricultural sector needs to be a priority, as well as the impacts from watersheds on coastal production sites. Securing property rights for smallholders to at least access and use water and land should be considered as a starting point for justice-based development. Rural participation in governance in order to address local needs based on recognition of social differentiation will be important for social uptake and long-term value chain establishment driven by smallholders. Learning from similar countries in the region offers fruitful opportunities for collaboration, for example in sub-Saharan Africa, where aquaculture will need to fit into a complex web of policy choices that address food security and agriculture stability issues.

Archetype 2 - Limited aquatic food engagement

Aquaculture is an established sector in Archetype 2 countries, but unlikely to be a main priority development area for a country's food security and economy, given its low value added to the overall economy. Archetype 2 scores well on national governance and environmental performance, but likely faces issues related to intensification and technology. Inland freshwater and irrigation availability score low although freshwater production is the dominant production environment, suggesting intensified production that leverages technology to produce fed-aquaculture in more densely populated fish ponds. Considering how such production interacts with other sectors likely needs consideration within a more regulatory intensive governance landscape. Due to lower domestic demand for seafood, larger portions of production may be for export from larger companies rather than rural small-scale producers, for example to other European Union markets. Creating the right market incentives for sustainability and understanding changes in consumer demand may help inform effective strategies.

Archetype 3 - Developing economy producers

Countries in Archetype 3 require the most urgent governance attention given the role of seafood production within the agricultural economy and cultures. Large rural production investments spawned by traditional practices in high seafood consuming societies has likely very quickly put pressure on aquaculture to meet domestic needs historically met by declining capture fisheries yields. Scaling from low intensity traditional pond aquaculture towards technology driven fish production enterprises needs oversight from national governments to minimize environmental impacts. Simultaneously, aquaculture needs priority governance focus across scales, from national to local, to help tailor development ambitions to local needs and assist small-scale producers in increasing efficiency in production while securing stable market opportunities and innovation along the value chain. Investments into capacity building at the community level will help ensure that development financing and policies fit local contexts across sub-national contexts with very diverse production technologies, environmental and seafood cultures, for example in countries like India, Indonesia, the Philippines, China and Brazil. Due to multi-environment production expansion, understanding where aquaculture fits in agricultural development across sectors will require coordination and bureaucratic integration to avoid conflicts while addressing resource co-dependencies such as land and water rights. The push towards intensification will likely come with increased use of feed and medication to increase stocking densities for higher production needs to be a consideration for governance initiatives in relation to feed sourcing, disease spread and water effluent. Seafood in Archetype 3 countries is likely also being produced for export, particularly high-value species, which can be more cheaply produced where labor, taxes and environmental regulations are lower than in the wealthier countries consuming them. Such production externalities need to be considered in seafood pricing and policy, but are often not. Property rights issues in coastal spaces may be contested, for both mariculture and coastal earthen ponds, given the high coastal population densities using the coast for many other economic activities, larger aquaculture expansion may have to compete with tourism, port development and real estate interests.

Archetype 4 - Wealthy economy producers

Governing aquaculture in Archetype 4 will include finding enabling mechanisms for technology development, increasing public awareness and consumer uptake of farmed seafood products and ensuring the supply chains for feed don't export the environmental impacts of feed sourcing, whether capture fisheries and grain products, to the countries where they are produced. Aquaculture expansion among wealthier producing nations may need consideration of removing governance barriers to allow aquaculture growth if desired, or deliberate engagement with sectors who already have established rights and regulations for resource use historically.

Why archetype analysis is useful

Archetype analysis adds value for two major reasons. First, it gives scholars a head start into examining the relationships between the most meaningful indicators for aquaculture development in different regions, providing an empirical foundation for hypotheses examining development trends in specific countries. For example, Indonesia falls into 'Archetype 3 - Developing economy producers', which informs us that the country has high demand for seafood and large marine and freshwater capacity for aquaculture expansion, but faces governance and environmental performance challenges which could be key barriers for aquaculture development and require further Indonesia context-specific research to unravel. This approach encourages continued analyses to move beyond production data as a single monolithic indicator of development, and towards considering social-ecological factors such as environmental and economic limitations or political conditions. As such, our archetype analysis shows which indicators co-define a development trajectory, however, establishing causality among identified variables still needs to be examined. For example, we can assume a relationship between land available for irrigation and freshwater production growth, but further country specific sub-national data would be a next step for further testing. Second, there is a lot to be learned in development scholarship and practice by comparing policy and economic strategies between countries with similar social-ecological conditions. Archetype analysis identifies countries with these similarities. Making broad statements (e.g., developing theory or policy practices) regarding potential development trajectories will be more accurate when refined to specific groups of countries facing similar conditions.

In order to make global aquaculture assessments more contextually useful, there is a need to move beyond reliance on select species production data and towards more diverse sets of integrated macro-level social-ecological data. Publicly available secondary data can add substantial value to current analyses given the clear relevance of many available indicators on aquaculture development. For example, a substantial amount of data is readily available from the United Nations or World Bank. However, there are also limitations in current data that cap global comparative analyses at the national level, such as the lack of sub-national data, discrepancies in reporting standards and coverage among countries and fixed time-scale data (i.e., one year intervals). Furthermore, species production data, which most high-level studies are based on (3, 4), are in part a result of political and economic choices or emergent value chain dynamics. These social processes need to be more comprehensively considered and examined in the field. For example, how growth trends in productions reflect land and water allocation (11), or the associated risks of storm or drought impacts in those regions along with potential conflicts with other uses of those resources (10). On the other hand, choosing to intensify the sector likely needs consideration of existing environmental limits (43), potential for knowledge transfer (44), technology use, shifting towards fed-culture with efficient feed conversion ratios (45, 46) and dealing with concentrated effluent (47). Sector diversification may require consideration of many additional factors such as market options, trade partners and exploring diverse production mediums and culturing techniques to make use of environmental diversity. Many indicators on these factors already exist or can be compiled or modeled from publicly available sources, yet few studies are engaging with such analyses.

Risks facing the current production of aquaculture

A large majority of total global aquaculture production faces a high degree of risks from multiple social, economic and environmental factors. Over 85% of all production is in countries facing the highest climate risks (48), in a sector that is highly dependent on stable coastal ecosystems and/or the predictable availability of inland freshwater quantity and quality to provide food (45, 48, 49). Shocks to production due to climate change can undermine food supply stability in the same countries which already rank in the most unstable quartiles of per capita food supply variability and rank low on the Global Food Security Index (4, 16, 19). Furthermore, the majority of aquaculture is produced in countries where environmental performance is lowest, making ecosystems more fragile to climate related impacts determining production and food stability. Identifying suitable environmental conditions for production also needs to consider the health of waterways to ensure that cultured food is safe for human consumption (50, 51).

A substantial amount of aquaculture production occurs in countries with high seafood consumption per capita and high capture fisheries production, supporting the importance of analyzing social drivers of demand across multiple species and geographic scales (3). Aquaculture is also skewed strongly towards being produced in countries that rank low on the Human Development Index. This suggests that high seafood consumption is likely more heavily reliant on domestic production coupled to local ecosystem health. Furthermore, it is interesting to consider how economic integration through seafood trade connections may influence the ability to compensate for food system shocks locally, but also create vulnerabilities from being dependent on non-local market fluctuations that undermine food access stability. We can see that stronger dependence on local production also occurs in countries where governance and environmental performance are lower, such as in Archetypes 1 and 3. Strengthening local social-ecological system health is an encouraged approach to sectoral sustainability. Further strengthening seafood contributions to social wellbeing can include campaigns to raise awareness about the nutritional benefits of fish, especially for pregnant women and young children, to help reduce nutrient deficiencies and avoid related disease such as anemia (17, 52, 53). Targeting such approaches within countries in Archetype 1 may be particularly valuable since this group is characterized by high public health anemia and undernourishment risks. However, policy implementation must include further dimensions of social differentiation to be effective within target countries. High rural and coastal populations are such potential drivers of production for rural economies and local food (54), and thus development strategies should carefully consider the adoption or impacts of policy programs that may differ across those groups due to cultural or economic factors such as market or technology access, or cultural uptake of new seafood products.

Furthermore, aquaculture systems are embedded within environmental, economic, and social contexts that create complex interdependencies that are often poorly understood. For example, there are often strong interdependencies among aquaculture, capture fisheries and agriculture systems, both environmentally (e.g., via watershed connectivity) and politically (e.g., shared administrative agencies and financial resource allocations). Policies that fail to recognize these linkages can therefore result in unanticipated trade-offs or miss opportunities for synergies (7). Aquaculture development will face more roadblocks if governance is attempted in isolation from its known interrelated sectors (5). Sustainability research on aquaculture is lacking on key social and governance issues, particularly regarding governance options that may be facilitated by cross-sector and cross-country learning, where archetype analysis provides a useful starting point for identifying similar cross-country conditions and cross-sector co-dependencies. It could be argued that there is a need to reset current understandings of aquaculture development potential in order to re-frame our assumptions based on integrated social-ecological data (55), for example resulting from archetype analyses. This would include putting livelihood and social wellbeing data at eye-level with production data when discussing the sector’s sustainability. Nonetheless, the human-centric contributions that the sector can make on issues of food security, livelihoods and public health are gaining traction. Archetype analysis can bring social data hand-in-hand with more typically used production and environmental condition data. Adding social data can help ground and test claims about the potential benefits or risks or aquaculture growth often made by only analyzing production without knowledge of social context, economic or governance realities.

Methodological considerations

A large amount of existing data is standardized at the country level. However, consistency in country classification and territorial recognition is always a challenge. Using the FAO classifications, we selected country-level data due to its wide ranging availability across data sets from different sources, which required integration. Although many countries were dropped due to a lack of data coverage, we were still able to include the top 100 aquaculture producing countries by tonnage. Nonetheless with standardization at the country level, there is often a lack of specificity about the data for any one country. Much of the available country level data is self-reported by the countries themselves, such as the FAO fisheries production data, which is not all collected in a similar way. Furthermore, data from different sources has different formats that require transformation in order to apply analytical tools to them. Transforming and normalizing data may skew the raw interpretation of the values, at the tradeoff benefit of allowing integration with other data and comparison. Every study using such data faces the issues that the data reliability for any given country may be in question. Optimizing the analysis in this article would be best done with sub-national statistics collected with standardized techniques, however, this type of data is not available. Regarding the archetype analysis used and methodological choices associated with cluster analysis techniques, Rocha and colleagues (34) provide a detailed methodological assessment about how to make choices given the available analytical tools for cluster analysis and the given data. Our approach mirrored that analytical approach used. The methodological exercise of attempting to match our data with Gephart and colleagues (35) proposed scenarios is a useful exercise for discussion to approaches that arrive at similar results in the field, yet a full testing of the scenarios would benefit from starting the original data collection process with the goal of aligning a broader set of representative indicators.

Conclusions

Aquaculture development is shaped by a wide range of macro-level conditions including social, economic, environmental and governance factors. We identify four social-ecological archetypes globally, which are differentiated by their distributions across more than 40 indicators. Each archetype provides a unique fingerprint of the potential drivers, limitations and opportunities present across the countries within them, and allows comparison with countries in the other archetypes to better understand the likelihood of future development trajectories and how governance choices can help meet national-level goals and reduce risks. This analysis shows the value of integrated data analysis, and demonstrates the need for moving beyond isolated species production data as the cornerstone of understanding the sector's development. We advocate for future analyses to consider more pluralistic data integration - particularly social, economic and governance data - when assessing growth and the potential contributions of the sector to food and livelihood security. Coupling global and country-level assessments such as this with case study analyses of specific countries will assist in confirming or modifying knowledge about performance of the sector and its development in any specific country. We encourage such assessments and critique of this study to improve knowledge within the sector.

References

1. Garlock T, et al. (2022) Aquaculture: The missing contributor in the food security agenda. *Glob Food Sec* 32(February):100620.
2. Gephart JA, Golden CD (2022) Environmental and nutritional double bottom lines in aquaculture. *One Earth* 5(4):324–328.
3. Naylor RL, et al. (2021) A 20-year retrospective review of global aquaculture. *Nature* 591(March).
4. Garlock T, et al. (2020) A Global Blue Revolution: Aquaculture Growth Across Regions, Species, and Countries. *Rev Fish Sci Aquac* 28(1):107–116.
5. Partelow S, Schlüter A, Manlosa AO, Nagel B, Paramita AO (2021) Governing aquaculture commons. *Rev Aquac*.
6. Manlosa AO, Hornidge A-K, Schlüter A (2021) Aquaculture-capture fisheries nexus under Covid-19: impacts, diversity, and social-ecological resilience. *Marit Stud* (2014). doi:https://doi.org/10.1007/s40152-021-00213-6.
7. Blanchard JL, et al. (2017) Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nat Ecol Evol* 1(9):1240–1249.
8. Cottrell RS, Ferraro DM, Blasco GD, Halpern BS, Froehlich HE (2021) The search for blue transitions in aquaculture-dominant countries. *Fish Fish* (April):1–18.
9. FAO (2022) *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation.* (FAO, Rome) doi:10.4060/cc0463en.
10. Partelow S, Senff P, Buhari N, Schlüter A (2018) Operationalizing the social-ecological systems framework in pond aquaculture. *Int J Commons* 12(1):485–518.
11. Gephart JA, et al. (2017) The ‘seafood gap’ in the food-water nexus literature—issues surrounding freshwater use in seafood production chains. *Adv Water Resour* 110:505–514.
12. Gentry RR, et al. (2017) Mapping the global potential for marine aquaculture. *Nat Ecol Evol*:1–8.
13. Schlüter A, et al. (2020) Broadening the perspective on ocean privatizations: an interdisciplinary social. *Ecol Soc* 25(3):20.
14. Tecklin D (2016) Sensing the limits of fixed marine property rights in changing coastal

ecosystems: Salmon aquaculture concessions, crises, and governance challenges in Southern Chile. *J Int Wildl Law Policy* 19(4):284–300.

15. Longo SB, Clark B, York R, Jorgenson AK (2019) Aquaculture and the displacement of fisheries captures. *Conserv Biol* 33(4):832–841.
16. Thilsted SH, et al. (2016) Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* 61:126–131.
17. Hicks CC, et al. (2019) Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* 574(7776):95–98.
18. DIPR (2017) *Global Nutrition Report 2017: Nourishing the SDGs* doi:10.1891/1058-1243.21.1.9.
19. Béné C, et al. (2016) Contribution of Fisheries and Aquaculture to Food Security and Poverty Reduction: Assessing the Current Evidence. *World Dev* 79:177–196.
20. Manlosa AO, Hornidge AK, Schlüter A (2021) Institutions and institutional changes: aquatic food production in Central Luzon, Philippines. *Reg Environ Chang* 21(4). doi:10.1007/s10113-021-01853-4.
21. Ruff EO, Gentry RR, Lester SE (2020) Understanding the role of socioeconomic and governance conditions in country-level marine aquaculture production. *Environ Res Lett* 15(10). doi:10.1088/1748-9326/abb908.
22. Davies I, et al. (2019) Governance of marine aquaculture: pitfalls, potential and pathways forward. *Mar Policy* 104(February):29–36.
23. Sietz D, et al. (2019) Archetype analysis in sustainability research: Methodological portfolio and analytical frontiers. *Ecol Soc* 24(3). doi:10.5751/ES-11103-240334.
24. Eisenack K, Oberlack C, Sietz D (2021) Avenues of archetype analysis: Roots, achievements, and next steps in sustainability research. *Ecol Soc* 26(2). doi:10.5751/ES-12484-260231.
25. Costello C, et al. (2020) The future of food from the sea. *Nature* 588(7836):95–100.
26. Henriksson PJG, et al. (2021) Interventions for improving the productivity and environmental performance of global aquaculture for future food security. *One Earth* 4(9):1220–1232.
27. Gephart JA, et al. (2021) Environmental performance of blue foods. *Nature* In review(September). doi:10.1038/s41586-021-03889-2.
28. Gephart JA, Pace ML (2015) Structure and evolution of the global seafood trade network. *Environ Res Lett* 10(12):125014.
29. Gentry RR, et al. (2019) Exploring the potential for marine aquaculture to contribute to

ecosystem services. *Rev Aquac*:499–512.
30. Froehlich HE, Gentry RR, Rust MB, Grimm D, Halpern BS (2017) Public perceptions of aquaculture: Evaluating spatiotemporal patterns of sentiment around the world. *PLoS One* 12(1):1–18.
31. Golden CD, et al. (2017) Does aquaculture support the needs of nutritionally vulnerable nations? *Front Mar Sci* 4(MAY):1–7.
32. Villamayor-Tomas S, Iniesta-Arandia I, Roggero M (2020) Are generic and specific adaptation institutions always relevant? An archetype analysis of drought adaptation in Spanish irrigation systems. *Ecol Soc* 25(1). doi:10.5751/ES-11329-250132.
33. Piemontese L, et al. (2021) Barriers to scaling sustainable land and water management in Uganda: a cross-scale archetype approach. *Ecol Soc* 26(3). doi:10.5751/es-12531-260306.
34. Rocha JC, Malmborg K, Gordon LJ, Brauman KA, Declerck F (2019) Mapping social-ecological systems archetypes. *Environ Res Lett* 15(3):34017.
35. Gephart JA, et al. (2020) Scenarios for Global Aquaculture and Its Role in Human Nutrition. *Rev Fish Sci Aquac* 0(0):1–17.
36. Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. *Science* 325(5939):419–22.
37. McGinnis MD, Ostrom E (2014) Social-ecological system framework: Initial changes and continuing challenges. *Ecol Soc* 19(2):30.
38. Partelow S (2018) A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecol Soc* 23((4):36). doi:10.5751/ES-10594-230436.
39. Nagel B, Partelow S (2022) A methodological guide for applying the SES framework: a review of quantitative approaches. *Ecol Soc*.
40. Brock G, Datta S, Pihur V, Datta S (2008) clValid: An R Package for Cluster Validation. *JournalofStatisticalSoftware* 25(4):1–22.
41. Charrad M, Ghazzali N, Boiteau V, Niknafs A (2014) NbClust : An R Package for Determining the. *J Stat Softw* 61(6):1–36.
42. Charrad M, Ghazzali N, Boiteau V, Niknafs V (2014) NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set. *J Stat Softw* 61(6):1–36.
43. Edwards P (2015) Aquaculture environment interactions: Past, present and likely future trends. *Aquaculture* 447:2–14.
44. Gentry RR, Ruff EO, Lester SE (2019) Temporal patterns of adoption of mariculture

innovation globally. *Nat Sustain* 2(10):949–956.
45. Froehlich HE, Runge CA, Gentry RR, Gaines SD, Halpern BS (2018) Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc Natl Acad Sci U S A* 115(20):5295–5300.
46. Fry JP, et al. (2016) Environmental health impacts of feeding crops to farmed fish. *Environ Int* 91:201–214.
47. Henares MNP, Medeiros M V., Camargo AFM (2020) Overview of strategies that contribute to the environmental sustainability of pond aquaculture: rearing systems , residue treatment, and environmental assessment tools. *Rev Aquac* 12:453–470.
48. Tigchelaar M, et al. (2021) Compound climate risks threaten aquatic food system benefits. *Nat Food*. doi:10.1038/s43016-021-00368-9.
49. Lebel L, et al. (2021) Climate risk management practices of fish and shrimp farmers in the Mekong Region. *Aquac Econ Manag* 25(4):388–410.
50. Gentry RR, et al. (2017) Offshore aquaculture: Spatial planning principles for sustainable development. *Ecol Evol* 7(2):733–743.
51. Oyinlola MA, Reygondeau G, Wabnitz CCC, Troell M, Cheung WWL (2018) Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS One* 13(1):1–19.
52. Thilsted SH (2012) The potential of nutrient-rich small fish species in aquaculture to improve human nutrition and health. *Farming Waters People Food Proc Glob Conf Aquac 2010*:57–73.
53. Koehn JZ, et al. (2021) Fishing for health: Do the world’s national policies for fisheries and aquaculture align with those for nutrition? *Fish Fish* (July):1–18.
54. Filipski M, Belton B (2018) Give a Man a Fishpond: Modeling the Impacts of Aquaculture in the Rural Economy. *World Dev* 110:205–223.
55. Belton B, et al. (2020) Farming fish in the sea will not nourish the world. *Nat Commun* In press:1–28.

Supplementary material B

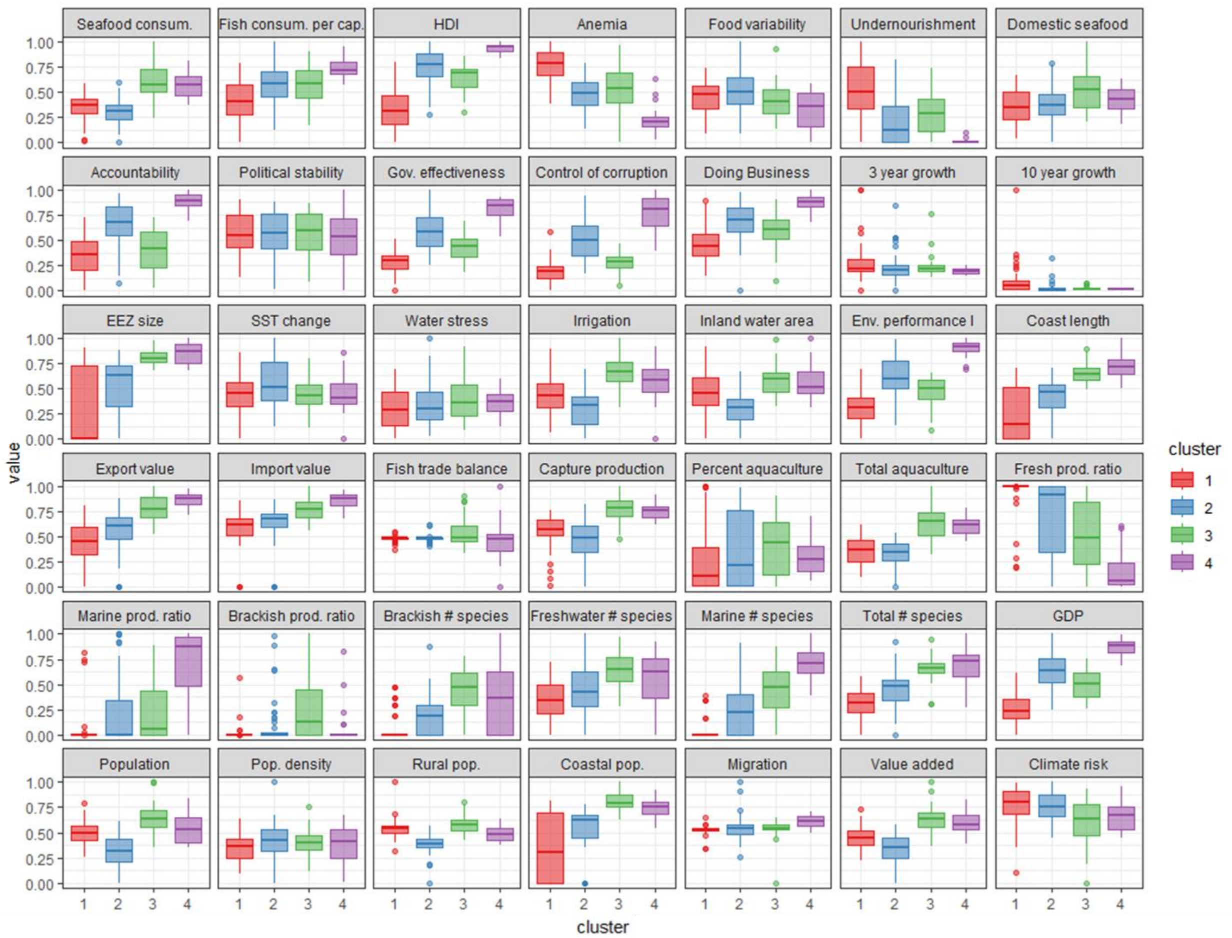

Figure S1. Quartile distributions of each variable within each archetype for range comparison.

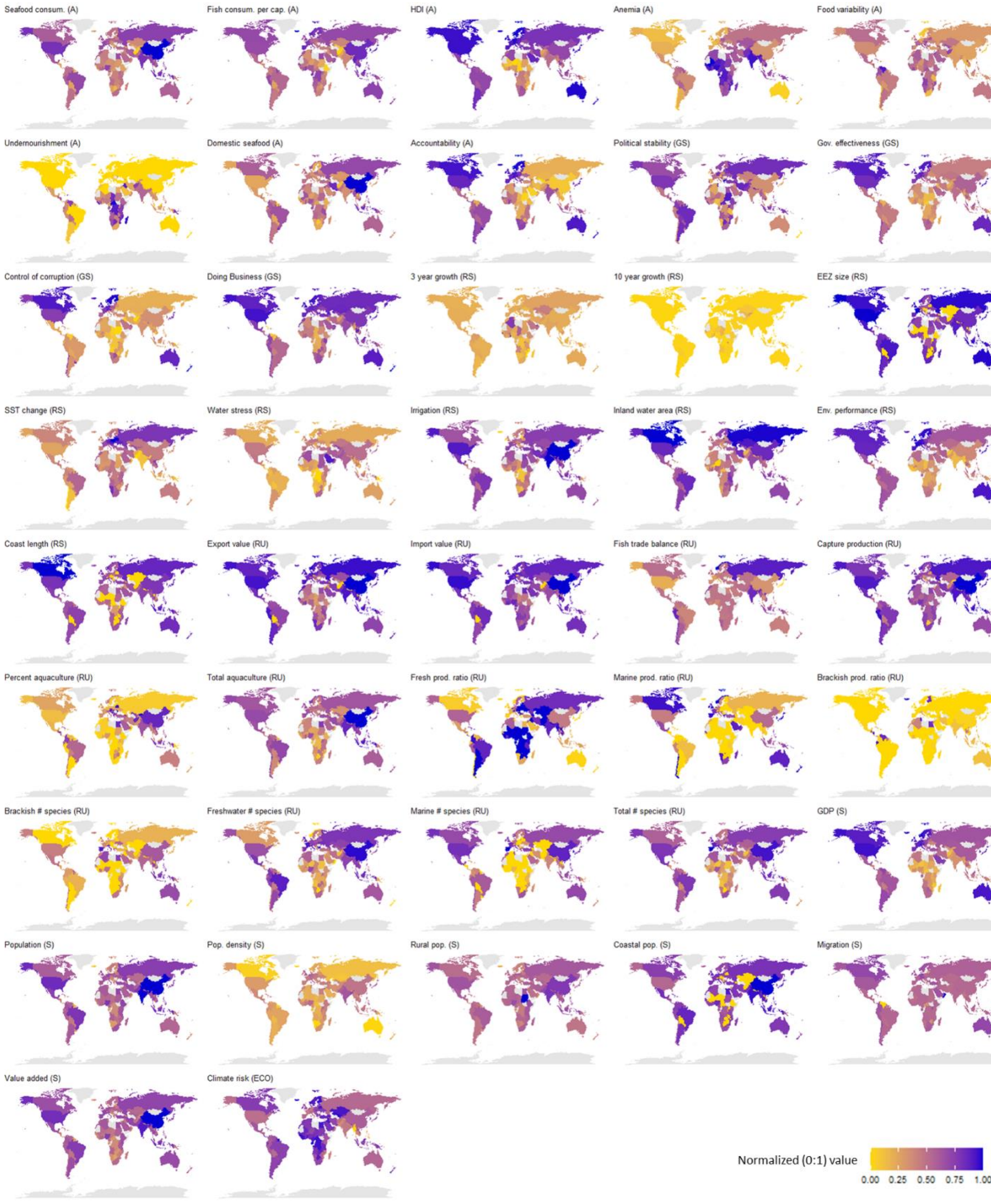

Figure S2. Global distribution of values for each indicator.

Table S1. Axis score indicator calibration table.

Axis 1: Endless growth (-) to doughnut economics (+)	**1st (low)**	**2nd**	**3rd**	**4th (high)**
Production	2	1	-1	-2
EPI	-2	-1	1	2
Growth 10yr	2	1	-1	-2
Governance	-2	-1	1	2
Doing business	2	1	-1	-2
Axis 2: Regional (-) to global (+)				
Trade balance	-2	-1	1	2
Rural population	2	1	-1	-2
Domestic seafood consumption	2	1	-1	-2
Species diversity	2	1	-1	-2
Undernourishment	2	1	-1	-2

Table S2. List of countries within each archetype.

Archetype	**Countries**
1 - Emerging aquaculture producers	Afghanistan, Angola, Armenia, Azerbaijan, Benin, Bolivia, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Congo, Ivory Coast, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Haiti, Iraq, Kazakhstan, Kenya, Kyrgyzstan, Lao, Liberia, Madagascar, Malawi, Mali, Moldova, Mozambique, Nepal, Niger, North Macedonia, Pakistan, Papua New Guinea, Paraguay, Rwanda, Senegal, Sierra Leone, Sudan, Tajikistan, Tanzania, Togo, Uganda, Uzbekistan, Zambia, Zimbabwe
2 - Limited aquatic food engagement	Albania, Austria, Barbados, Belarus, Belgium, Belize, Bhutan, Bosnia and Herzegovina, Botswana, Brunei Darussalam, Bulgaria, Costa Rica, Cuba, Cyprus, Czech Republic, Dominican Republic, El Salvador, Estonia, Fiji, Georgia, Guyana, Hungary, Iceland, Israel, Jamaica, Jordan, Latvia, Lebanon, Lesotho, Lithuania, Mauritius, Montenegro, Namibia, Oman, Poland, Qatar, Saint Lucia, Serbia, Singapore, Slovakia, Slovenia, Solomon Islands, Switzerland, Trinidad and Tobago, Ukraine, United Arab Emirates, Uruguay
3 - Developing economy producers	Algeria, Argentina, Bangladesh, Brazil, Cambodia, China, Colombia, Ecuador, Egypt, Guatemala, Honduras, India, Indonesia, Iran, Malaysia, Mexico, Morocco, Myanmar, Nicaragua, Nigeria, Panama, Peru, Philippines, Russian Federation, Saudi Arabia, South Africa, Sri Lanka, Thailand, Tunisia, Turkey, Venezuela, Vietnam
4 - Wealthy economy producers	Australia, Canada, Chile, Croatia, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, South Korea, Spain, Sweden, Taiwan, United Kingdom, USA