Aquaculture 595 (2025) 741484

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Archetypes of aquaculture development across 150 countries

Stefan Partelow[a,b,*], Ben Nagel[a,c], Rebecca Gentry[d,e], Jessica Gephart[f], Juan Rocha[g]

[a] Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany
[b] Center for Life Ethics, University of Bonn, Germany
[c] Jacobs University, Germany
[d] Florida State University, USA
[e] The Nature Conservancy, New Zealand
[f] Department of Environmental Science, American University, Washington, DC, USA
[g] Stockholm Resilience Center, Sweden

ARTICLE INFO

Keywords:
Aquaculture
mariculture
sustainable development
fisheries
social-ecological systems

ABSTRACT

In this study we compile and integrate data on 42 indicators to examine the social, economic, governance and environmental conditions shaping aquaculture development across 150 countries, including the top 100 aquaculture producing countries. We apply cluster analysis to identify social-ecological archetypes of aquaculture development across these indicators. We also calculate the percentage of global aquaculture production within the quartile ranges of 15 indicators of singular relevance for development. This shows how much aquaculture production is taking place in countries performing low or high on key indices. For example, we show that 85% of global aquaculture production is taking place in countries with the highest or high climate risk, 74% in countries with the lowest or low environmental performance scores, and 90% in countries with the highest or high food supply variability. Our cluster analysis identifies four distinct archetypes driven by the 42 country-level indicators, which includes: climate risk, inland water area, coastal population, seafood consumption, trade balance, governance indices and environmental performance. We characterize the four archetypes as: Archetype 1 - Emerging aquaculture producers, Archetype 2 - Limited aquatic food engagement, Archetype 3 - Developing economy aquaculture producers, Archetype 4 - Wealthy economy aquaculture producers. We discuss this complexity of factors driving each archetype with country specific examples, as well as the utility of integrated social-ecological analysis for both continued aquaculture research and development practice.

1. Introduction

Understanding the diverse factors guiding current aquaculture development is essential for analyzing the sector's rising contributions to food and livelihoods. These factors include social, economic, environmental and governance dynamics. The sector is now a key contributor to global food security and nutrition (Garlock et al., 2022; Gephart and Golden, 2022) producing near equal amounts of seafood as capture fisheries (Garlock et al., 2020; Naylor et al., 2021). However, many questions remain regarding its sustainability. A main challenge is analyzing the drivers of development across the highly diverse sector with marine, brackish and freshwater geographies, each with unique culturing techniques and environmental dependencies. This is further complicated by the integration of aquaculture production systems into local ecosystems, cultures, markets and governance structures, many of which were established to serve the capture fishery and agriculture sectors (Blanchard et al., 2017; Manlosa et al., 2021b; Partelow et al., 2021).

At least 39 countries now produce more from aquaculture than from capture fisheries (Cottrell et al., 2021), 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 to >90% of total production (FAO, 2022). Furthermore, 80% of Asian aquaculture production volume is produced by small-scale enterprises (FAO, 2022). The recent FAO Illuminating Hidden Harvests report (WorldFish et al., 2023) estimates that Asian small-scale fisheries contribute 47% to Asian production (combining capture and aquaculture), and 64% to all small-scale fisheries production volume globally.

* Corresponding author at: Center for Life Ethics, University of Bonn, Bonn, Germany.
E-mail addresses: stefan.partelow@uni-bonn.de (S. Partelow), ben.nagel@leibniz-zmt.de (B. Nagel), rrgentry@fsu.edu (R. Gentry), jgephart@american.edu (J. Gephart), juan.rocha@su.se (J. Rocha).

https://doi.org/10.1016/j.aquaculture.2024.741484
Received 5 February 2024; Received in revised form 12 August 2024; Accepted 13 August 2024
Available online 14 August 2024

Such estimates depend on how small-scale aquaculture is defined (Smith and Basurto, 2019), as some studies suggest that aquaculture growth is driven by commercially oriented medium sized enterprises, for example in Bangladesh (Hernandez et al., 2018). Beyond Asia, aquaculture has vast development potential, particularly in Latin America and Africa, but it is unclear if aquaculture in those regions will follow similar development trajectories as Asian countries, or which factors will be most influential in shaping growth. The overarching question of this study is: what factors are driving aquaculture development across countries? And can we better understand current trends by combining diverse data and using archetype analysis methods to analyze them at the macro-level?

1.1. Factors influencing aquaculture development.

Macro-level conditions such as environmental, economic, and political factors shape aquaculture development trajectories. Identifying indicators to measure such factors at the country level is essential for understanding and comparing risks and opportunities for aquaculture expansion, intensification and diversification. For example, environmental conditions and restraints differ across production systems. Freshwater systems are by far the most globally dominant production mode, primarily in earthen ponds, which require water availability in high volumes from adjacent water bodies, which can face higher climate risk from droughts or flooding. Indicators of abundant freshwater resources can provide insights into a country's potential for aquaculture expansion, whereas countries with limited water resources may have growth constraints. Water distribution potential via canal and irrigation systems for pond and inland systems is also essential, making it a useful indicator of a country's potential for development expansion (Gephart et al., 2017; Partelow et al., 2018). In marine systems, the length of a country's coastline is an indicator of 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 (Gentry et al., 2017a) as well as competition for the rights to operate farms in coastal spaces which are often contested and/or multi-sector (Tecklin, 2016; Schlüter et al., 2020). 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 growth through economic opportunity (Ruff et al., 2020). Multiple macro-dimensions of governance will play a role, particularly the six dimensions provided by the World Governance Indicators (https://info.worldbank.org/governance/wgi/) (Davies et al., 2019), as well as the size of a country's overall agricultural sector and its proportional contributions to the economy.

Aquaculture product demands vary greatly across the sector (Naylor et al., 2021), representing an important economic context for development trajectories. Existing import and/or export markets for seafood products in a country can indicate 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 those from capture fisheries - which may be overexploited, or from more expensive agricultural products such as meat (Longo et al., 2019). Furthermore, current aquaculture and capture fisheries production are key factors reflecting demand, reflecting the blue transitions hypothesis that aquaculture emerges where capture fisheries are declining but where seafood value chains, livelihoods and culture still exist (Cottrell et al., 2021).

Drivers for aquaculture production may also be reflected in current outcomes of overall food security, reflecting the need to produce either more food or more stable food. Fish and seafood can provide dietary health benefits to, for example, rural or low-income communities with minimal access to other essential nutrient sources (Thilsted et al., 2016; Hicks et al., 2019), particularly in the 29 countries facing the triple burden of childhood stunting, anemia and obesity (DIPR, 2017). 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 (Béné et al., 2016a; Partelow et al., 2018; Manlosa et al., 2021a).

The above indicators exist in different combinations to create unique development conditions for each country. Novel methods are needed that can make sense of diverse data patterns across heterogenous contexts (in this case countries). It is likely that, despite this heterogeneity, patterns of development conditions, and perhaps trajectories, can be identified and understood as archetypes (Sietz et al., 2019; Eisenack et al., 2021). Understanding aquaculture archetypes can advance the field's understanding of development trends beyond species production data when more diverse data is collected and aggregated. Most high-level assessments on aquaculture development utilize the FAO species production data – which is the most comprehensive country-level data available. However, most studies do not couple this data with other known and available data shaping the sector (Costello et al., 2020; Cottrell et al., 2021; Gephart et al., 2021; Henriksson et al., 2021; Naylor et al., 2021). This study offers one of the first attempts to aggregate and analyze diverse data as a baseline for continued research. Using archetype analysis can help make sense of the complex system interactions by identifying broad patterns of similarity across the data. Archetype analysis has been shown to be useful in aquaculture contexts at smaller scales (Nagel et al., 2024) and for identifying quantitative patterns of social-ecological interaction in environmental governance (Partelow et al., 2024), but has yet to be applied to country-level comparative assessments. Quantitative archetype analysis can be used as a baseline for better understanding country-specific development trends, which can then be complimented with more nuanced data in each country.

1.2. Building on prior research.

This study builds on prior research to understand aquaculture development trajectories at the country-level. Most notably we use the study by Gephart et al. (2020) as a starting point for understanding aquaculture development narratives and scenarios, and their likely contributions to livelihoods and nutrition. There is a need, however, for existing conceptualizations and perspectives to be empirically tested, in a way that can support existing literature (Hernandez et al., 2018; Costello et al., 2020). A number of studies have made progress doing this at different levels, sub-sectors or on specific indicators. 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 (Davies et al., 2019; Gentry et al., 2019a). Furthermore, public perceptions of aquaculture have been shown to vary widely across type and location of development (Froehlich et al., 2017), showcasing the role of social context as a potential driver (or limiting force). Additional studies, such as Cottrell et al. (2021) and Golden et al. (2017) pull from a variety of 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 (Cottrell et al., 2021), but only benefits nutritionally at-risk communities in limited situations and locations (Golden et al., 2017). The value of using diverse and integrated data in aquaculture development research was confirmed by Ruff et al. (2020) in a study that compared models of mariculture production across the globe using social and economic data in addition to ecological data. Although these foundational studies have made needed progress, knowledge gaps still exist in regards to understanding macro-level development trends with more comprehensive data.

We compile and integrate 42 country-level indicators associated with aquaculture development, and analyze the emergent archetypes within those data across 150 countries. Our data provides, to the best of our knowledge, the most comprehensive compiled dataset and assessment of social, economic, governance and environmental factors shaping aquaculture trends. Archetypes represent distinct patterns of social-ecological system interactions leading to specific outcomes that are similar across cases (Sietz et al., 2019). 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 (Eisenack et al., 2021). Archetype analysis has been applied in different contexts and levels of granularity, such as in drought adaptation (Villamayor-Tomas et al., 2020), cognitive archetypes of farmer perceptions in the context off sustainable land use barriers (Piemontese et al., 2021) and poverty and food security archetypes across administrative districts (Rocha et al., 2019). However, archetype analysis has only been applied in a few select studies in aquaculture (Mathé and Rey-Valette, 2018; Troell et al., 2021; Asche et al., 2022; Nagel et al., 2024). Mathé and Rey-Valette (2018) examine archetypes of perceptions among stakeholders in pond fish farming systems in France and Brazil, showing how patterns of perceptions can be understood in relation to different policies and actions in the sector. Troell et al. (2021) show how identifying different combined features of aquaculture systems as archetypes can help understand their different contributions to the Sustainable Development Goals. Asche et al. (2022) showcase how the Chinese seafood market can be differentiated into a four-archetype matrix based on consumer destination (domestic; export) and production origin (foreign; domestic). Lastly, Nagel et al. (2024) use archetype analysis to understand the social-ecological similarities and differences (also with the SESF) among 85 community-based pond aquaculture farms in the Nusa Tenggara Barat province of Indonesia. In order to compare and contrast the findings in this study, we discuss our archetype findings with current literature, particularly in relation to the aquaculture development scenarios proposed by Gephart et al. (2020).

2. Methods

2.1. Conceptual framework

An important hypothesis in this study is to test if both social and ecological factors influence aquaculture development across countries. This would be confirmed if indicators from these different categories are those which are driving the most variation between cluster analysis groups, which is our method for identifying the archetypes. Furthermore, an important tool for conceptually organizing diverse data is a framework. Frameworks help scholars organize data to test hypotheses with empirical approaches, and in this study, we use the social-ecological systems framework (SESF) (Ostrom, 2009; McGinnis and Ostrom, 2014) to help us organize descriptive inquiry into diverse development indictors (Partelow, 2023). The SESF is arguably the most comprehensive social-ecological systems framework for guiding the identification of relevant variables in social-ecological systems (Binder et al., 2013; Partelow, 2018; Nagel and Partelow, 2022). The framework has been used for different purposes in the literature. The way it is used in this study is as an organizational conceptual framework to categorize diverse data into different meaningful thematic areas. We do not attribute our selection of indicators as those which best enable a diagnosis of collective action, or an assessment of the drivers shaping collective action to govern the commons, which is its typical use in other studies (Partelow, 2018). We used the framework as a starting point for searching for diverse secondary data that could be meaningful to include in the study to ensure a balance of diverse potential indicators. The framework has only been applied to analyze aquaculture systems in a few studies, all at smaller-scales (Partelow et al., 2018; Johnson et al., 2019; Paramita et al., 2023; Riany et al., 2023; Nagel et al., 2024), and never for a macro-level country comparison. However, the quantitative comparative approach we take, using the SESF as a conceptual data organizing tool, has been demonstrated as useful outside of aquaculture, including important analyses by Gutiérrez et al. (2011), MacNeil and Cinner (2013), Leslie et al. (2015), Rocha et al. (2019) and Fujitani et al. (2020).

Applications of the SESF need to be contextually tailored to the context where they are applied. We went through each second-tier variable of the SESF and considered if country-level data on aquaculture is available, using the framework as a check-list and guiding tool. In this study, a key challenge was data availability at the country-level with high coverage across at least the top 100 aquaculture producing countries. Data may exist on variables that we did not include in the study, such as more granular social data. For example, there is a lot more social data that could have been included – and which we are aware of as meaningful indicators of development (e.g., sector specific employment, markets, or prices) – but required exclusion from the study due to either the lack of coverage across at least the top 100 producers or availability. We needed to find a balance. For example, if we added a 43rd indicator, but it only had coverage over 110 countries, we would have to drop data from the other 42 indicators for 40 countries. This would be a big loss, and we therefore only included robust data sets with high coverage, even if this meant losing the breadth of more diverse indicators. The SESF was a useful guide in helping us consider and search for a wider range of variable indicators that other studies have not yet considered.

The SESF has 8 first-tier variables (Table 2), and we categorized each indicator into one of the first-tier variables. We did not assign specific indicators to second-tier variables of the SESF, although the second-tier variables acted as our guide or check-list for indicator selection. The purpose was not to have coverage across the second-tier variables, but to use the second-tier variables as a guide to improve coverage of data across the generic first-tier variables which are more conceptually meaningful to our macro-level context. The following six first-tier variables were assigned indicators: Actors; Governance; Resource systems; Resource units; Social, economic and political settings; External ecosystems. We did not select any indicators for the two first-tier variables 'Interactions' and 'Outcomes'. For our archetype analysis, defining a specific outcome was not the goal. One reason is that it would be too difficult to justify one specific outcome of interest over another, as there are clear interactive effects. We did not have the goal to provide an explanatory analysis of an outcome (e.g., drivers of total production). This may be a useful next step, but we aimed to first characterize different development pathways as archetypal patterns, seeking to empirically validate existing conceptual literature. The other excluded concept from the framework is the 'Interactions' variables, which refer to indicators about social interactions. We found no available data, and concluded that the use of six first-tier variables was sufficient for the purpose of this study.

2.2. Data collection

All data used in this study were collected from secondary sources (Table 2; Supplementary Material A). We searched for 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. The SESF was used as a guiding tool for searching for different types of data within the framework's broad first-tier categories and specific second-tier variables. 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 producers. The final data included 42 indicators with full coverage across 150 countries (Table 2). Justifications for all indicators are provided in relation to their relevance to aquaculture development (Supplementary Materials A).

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

2.3. *Data formatting*

All data were downloaded from 2019 or the most recent available year from the original sources (Supplementary Materials A). 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, although 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. All indicator data was normalized between 0 and 1 for cluster analysis. In the Supplementary Material B, there is a column indicating which indicator data were log transformed or not. Data formatting allowed us to exclude variables with high correlation values, to exclude variables with skew or transformation issues and/or exclude variables due to lack of coverage. Our final data contained full coverage of 42 indicators across 150 countries standardized by ISO 3166 code, including the top 100 aquaculture producers.

2.4. *Data analysis*

2.4.1. *Global production conditions*

Quartile calculations were generated with 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 added together to assess the amount of global production occurring within the four quartile ranges 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.

2.4.2. *Cluster analysis to identify archetypes*

Identifying typologies or archetypes of aquaculture development that consider a wide range of indicators is a clustering problem. This means that there is a need to consider the degrees of similarity of all indicator values across all observed countries in order to classify them into groups with similar or different value profiles. The 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; livelihood security; environmental sustainability) (Ostrom, 2009; Biggs et al., 2022). We used the SESF as a guide to balance indicator selection and structure the data analyze across these dimensions. To find an appropriate clustering solution to identify these archetypes in a transparent and reproducible way, we adapted the data-driven approach of Rocha et al. (2019) to identify an ideal clustering algorithm based on internal and stability validation using r package "clValid" (Brock et al., 2008), and an optimal number of clusters using r package "nbClust" (Charrad et al., 2014). To help interpret which indicators were driving clustering of the resulting archetypes, we ran an analysis of variance (ANOVA) followed by Tukey tests to identify all significant ($p < 0.05$) pairwise differences between clusters for each indicator (Fig. 3).

Our data-driven identification of clustering approaches (Rocha et al.,

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 first-tier	First-tier interpretation	Indicators used
Actors	Indicators specific to a country's population and relation to seafood.	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	Indicators on a country's governance performance.	Accountability; Political stability; Government effectiveness; Regulatory quality; Rule of law; Prevalence of Corruption; Doing Business score
Resource systems	Indicators specific to the conditions for aquaculture.	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	Indicators specific to the production of aquaculture.	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 & political settings	Indicators specific to broader social and economic trends.	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	Indicators influencing the aquaculture environment externally.	Climate change risk

2019) identified an ideal configuration of four clusters interpreted as development archetypes (Fig. 1), based on a majority rule from a comparison of 26 clustering 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. The "nbClust" package tests 9 different clustering algorithms, and the majority rule and stability measures help determine which clustering approach best fits the data. For our final clustering, we applied the hierarchical approach with a Manhattan distance measure and Ward agglomeration method to minimize within-cluster distance (Charrad et al., 2014). The outcome result is that countries are categorized into groups based on their similarities and differences in the data (Fig. 3; Fig. S1).

2.4.3. *Comparing archetypes to theory*

We compare our data-driven archetypes with the literature-based development scenarios proposed by Gephart et al. (2020), which have not yet been empirically examined or validated. Gephart et al. propose two axes determining four scenarios; the x-axis (− regionalized to globalized +), and the y-axis (− endless growth to doughnut economics +). The x-axis intends to represent how production is oriented for domestic consumption (regionalized) versus export (globalized). The y-axis intends to represent the degree of social and environmental protections, with endless growth representing few protections and doughnut economics representing more. The two axes create four plot quadrants: (1) Food Sovereignty (−,+), (2) Blue Internationalism (+,+), (3) Aquatic Chicken(+,-) and (3) Aqua-Nationalism(−,-) (Table 3). To test these, we selected 10 indicators from our data that most closely represent the two axes suggested by Gephart et al., using the quartile ranges of those indicators to assign a 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).

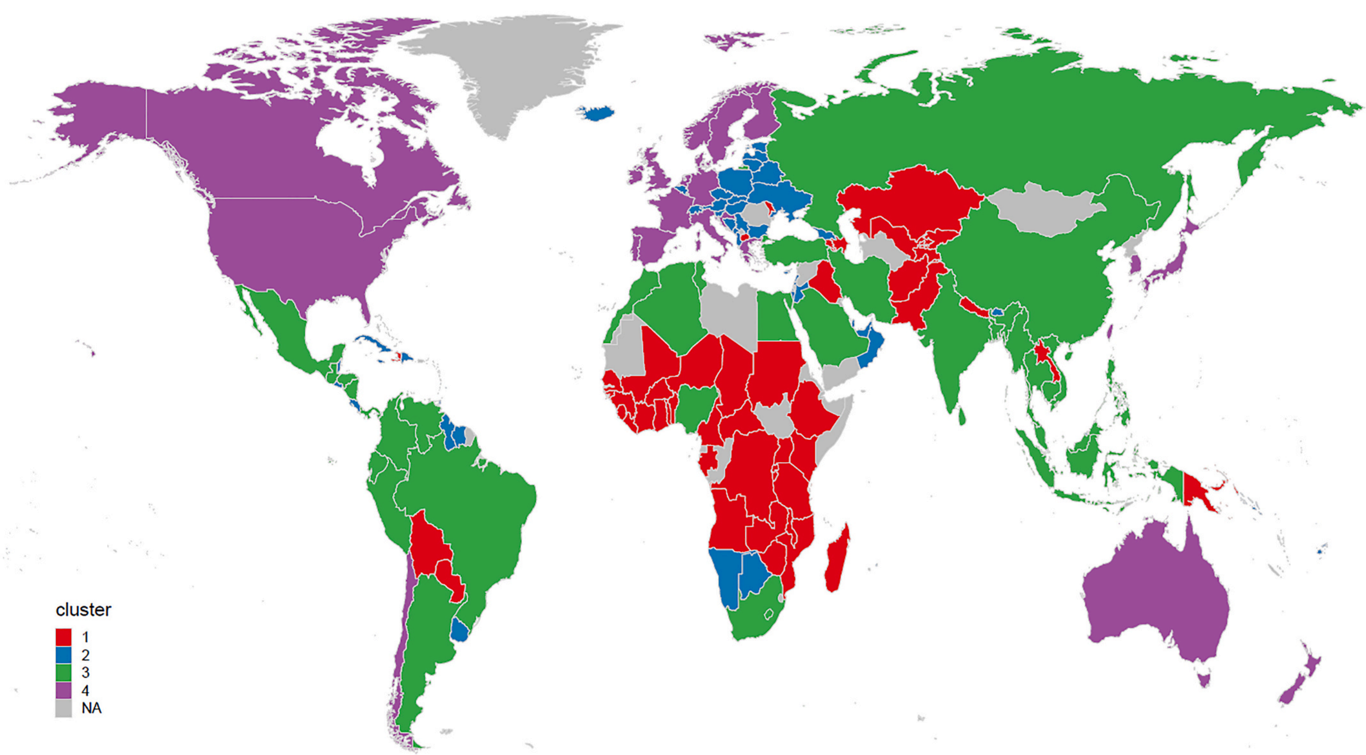

Fig. 1. Countries colored by the four cluster (archetype) groups.

Table 3
Four development scenarios proposed by Gephart and colleagues (33).

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

The sum of all indicator scores for a country on each axis were calculated to enable a simple coordinate plot that places each country into one of four quadrants in the coordinate field. This represents the null hypothesis of how individual countries are grouped, and provides a baseline to test the extent to which our data-driven archetypes align with the development scenarios. We directly compare the overlaps of country classifications between the Gephart et al., development scenarios (i.e., 10 indicators) and our full data cluster analysis groups (i.e., 42 indicators). A paired *t*-test can then be performed to assess whether the matched pair groupings are significantly different or not.

3. Results

3.1. Comparing production conditions and risks

The conditions under which aquaculture develops in a country are highly influential on its ability to produce food and contribute to sustainability, 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 categories (i.e., 1st and 2nd quartile ranges or 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. In regards to food security, 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, and also in countries with high fish consumption per capita and high capture fisheries production. In terms of tonnage produced, 90% of aquaculture is produced in countries ranking in the 1st or 2nd quartiles (i.e., lowest) of the per capita food availability index, which means that the availability of food is below the global median. Across numerous indicators, the distribution of global production across quartile ranges is rather even. This includes the prevalence of anemia among women of reproductive age, where fish can provide essential iron in the diet. Methodologically, we have excluded China's production numbers from these calculations because they skew the global picture. We nonetheless underline where China falls within each quartile for each indicator in Table 1.

3.2. Archetypes of aquaculture development

We identify four primary and broadly encompassing archetypes of aquaculture development. The four archetypes are: (1) Archetype 1 - Emerging aquaculture producers (Emerging), (2) Archetype 2 - Limited aquatic food engagement (Limited), (3) Archetype 3 - Developing economy aquaculture producers (Developing), (4) Archetype 4 - Wealthy economy aquaculture producers (Wealthy). Each country in our analysis is classified into only one of the archetypes by their similar or dissimilar indicator value profiles (Table 4). The archetype names have been attributed to give a simple narrative interpretation characterizing each, but do not fully reflect the complexity of factors shaping each archetype, which we unpack in the discussion. The one-word archetype names are used throughout the paper as a short-form reference.

Archetype 1 - Emerging aquaculture producers (Emerging).

Archetype 1 includes countries (Fig. 1; Table 4) characterized by low aquaculture production and the lowest total aquaculture species count of the four 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 (Fig. 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 has numerous west Asian countries, importantly the land-locked countries, with the lowest average GDP of all archetypes (Fig. 2; Fig. 3).

Archetype 2 - Limited aquatic food engagement (Limited).

Archetype 2 countries have both low total aquaculture production and the lowest overall capture fisheries production, an above average freshwater production ratio, but also the lowest inland water area and irrigation area, and above average environmental performance (Fig. 1; Fig. 2; Table 4). 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 4) with moderately above average GDP, lowest average total population, and the lowest average value added from agriculture, fisheries, and forestry (Fig. 2; Fig. 3).

Archetype 3 - Developing economy aquaculture producers (Developing).

Archetype 3 includes countries with high total aquaculture

Table 4
List of the number of countries and their names within each archetype.

Archetype	Number of total countries (#) and country names
1 - Emerging aquaculture producers	(48) 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	(48) 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, Suriname, Switzerland, Trinidad and Tobago, Ukraine, United Arab Emirates, Uruguay
3 - Developing economy producers	(32) 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	(22) 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

production, high aquaculture import and export values, high total species counts across all production types along with the highest average brackish species counts and brackish production ratio (Fig. 1; Fig. 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 (Fig. 2; Fig. 3). Archetype 3 includes most of southeast Asia including China and India, as well as Russia and most of Latin America (Fig. 1; Table 4).

Archetype 4 - Wealthy economy aquaculture producers (Wealthy).

Like Archetype 3 (Developing), 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 (Fig. 1; Fig. 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 (Fig. 2; Fig. 3). Archetype 4 encompasses primarily high GDP countries including most of western Europe as well as Japan, Australia, the United States, and Canada, with moderately high overall and coastal populations (Fig. 1; Table 4).

3.3. Indicator variation across archetypes

Each cluster group was paired to examine the significance of individual indicators between each archetype pairing (Fig. 3) to better understand what drives variation. Of the 42 indicators tested for significance between the archetype pairs, six indicators were significant between all pairs (Table 5) using an analysis of variance, followed by a Tukey test (significance = $p < 0.05$). These are, arguably, the most important indicators driving variation between the archetypes. Importantly, the six indicators cover five of the six framework tiers, indicating that both social (Actor, Gov., S.) and ecological (RS, RU) indicators are important for explaining variation across the aquaculture development data. This supports our hypothesis that data within different tiers of the social-ecological systems framework help explain the variation in aquaculture development archetypes, more than singular social or ecological data alone. While each archetype has a different configuration of the most explanatory variables across the six framework tiers, the six indicators that are significant across all the archetypes come from five different framework tiers (Table 4). This suggests that in all archetypes, there are factors related to the Actors, Governance, Resource Systems, Resource Units and Social, Economic and Political Settings that are meaningful for understanding development trends (Table 4).

The number of significant indicators between paired archetypes varied by count and percentage across the archetype pairings (Table S2). The number of indicators with significant value differences was highest between archetypes 4 (wealthy) and 2 (limited) ($n = 30$), suggesting they are the most different, and the lowest between archetypes 4 (wealthy) and 3 (developing) ($n = 18$). The other archetype pairs had similar counts: 2–1 (limited-emerging) ($n = 26$), 3–1 (developing-emerging) ($N = 29$), 4–1 (wealthy-emerging) ($n = 29$), 3–2 (developing-limited) ($n = 28$). We further calculated the percentage difference between pairings with each first-tier of the social-ecological systems framework (i.e., the number of significant indicators per framework tier/total indicators per framework tier) (Table S2). When averaging the percentage differences across the six framework tiers for each archetype pair, archetypes 3–1 (developing-emerging) (71%) and 3–2 (developing-limited) (70%) have the highest differences, and 4–3 (wealthy-developing) (41%) have the lowest.

3.4. Comparing archetypes to existing development scenarios

We compare our four data-driven archetypes to the four scenarios defined by Gephart et al., (2020). We represent the literature-based scenarios with a set of 10 indicators (5 for each axis) (Table S1) selected from our archetype analysis, picking those that best match the two-axis descriptions proposed by Gephart. Each of our four archetypes has a dominant alignment with a different literature-based scenario, covering all four (Fig. 4; Table 3). Archetype 1 (emerging) aligns mostly strongly with the Aquatic Chicken scenario, with 46% of the countries from our archetypes group falling into this quadrant, and 29% with Food Sovereignty. Archetype 2 (limited) aligns most strongly with Blue Internationalism (56%), but also with Food Sovereignty (33%), similar to Archetype 4 (wealthy), which is aligned with Food Sovereignty (56%) and Blue Internationalism (39%). Archetype 3 (developing) aligns the strongest with Aqua-Nationalism (67%). 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 on a paired *t*-test (*p*-value = 0.007), rejecting the hypothesis that the country-pairings across the two groups are the same. Nonetheless, there are substantial overlaps.

4. Discussion

4.1. How to focus governance on countries within each archetype

Archetype 1 - Emerging aquaculture producers.

Prioritizing aquaculture development initiatives that contribute to public health while ensuring that rapid growth doesn't compromise environmental integrity - despite weak national governance performance - will be important for meeting sustainability goals (Partelow et al., 2023a). Countries in Archetype 1 (emerging) likely lack the types of government investment into the sector (such as sector-specific

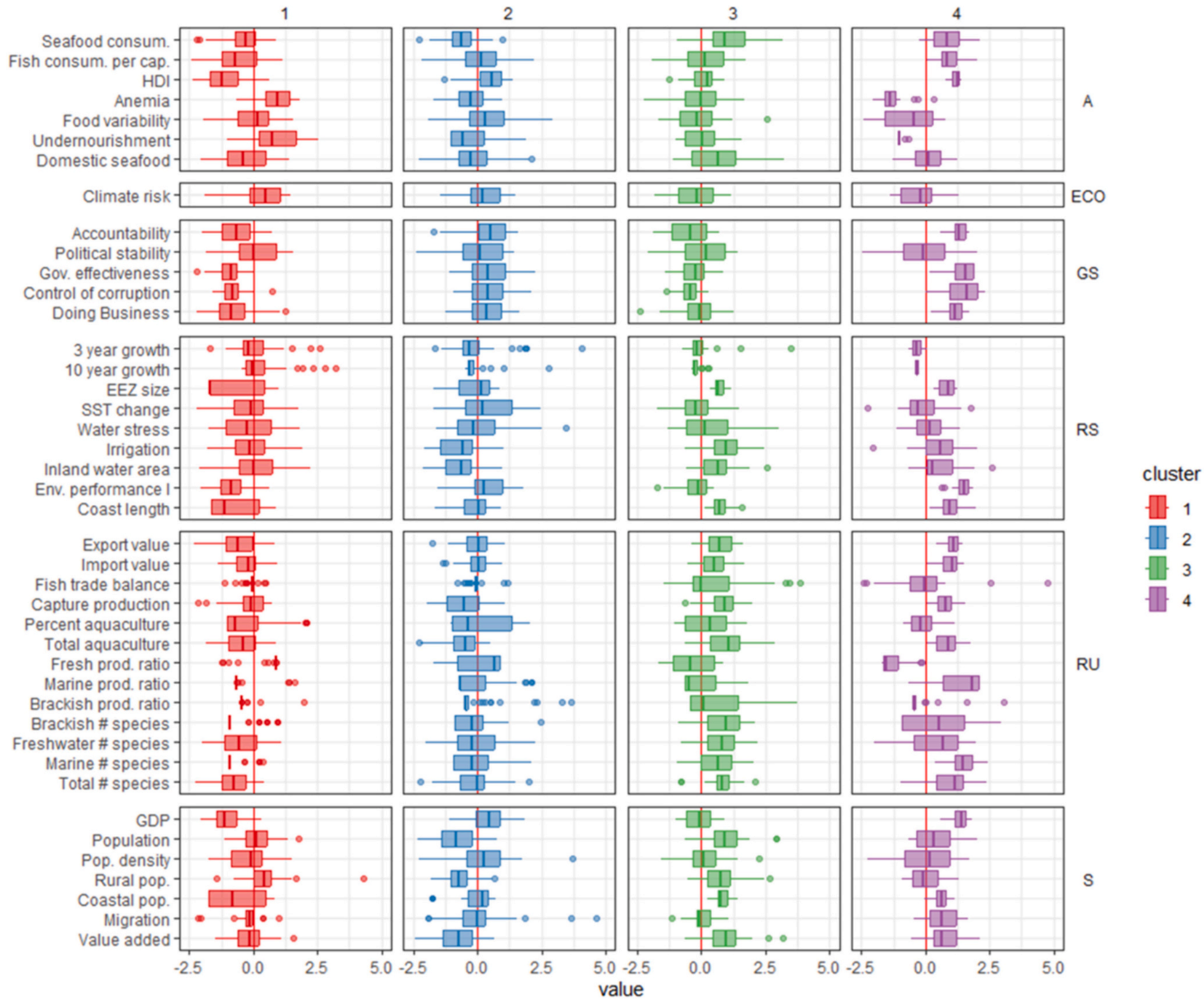

Fig. 2. Quartile distributions for each variable in each cluster (archetype). The global mean is indicated as a red line through each set. All variable distributions are centered to the global mean. Variables are organized into groups by their social-ecological system first-tier variable classification: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

agencies and extension officers) that other more established producers have, as only about half of the countries worldwide have specific legal frameworks established for aquaculture (FAO, 2021). It must also be noted that over 85% of all production is in countries facing the highest climate risks (Tigchelaar et al., 2021). Countries in Archetype 1 (emerging) face the highest climate risks and have the lowest environmental performance scores, 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 (Froehlich et al., 2018; Lebel et al., 2021; Tigchelaar et al., 2021). Shocks to existing production due to climate change can undermine food supply stability in the same countries which also rank in the most unstable quartiles of per capita food supply variability, undernourishment and rank low on the Global Food Security Index (Béné et al., 2016b; Thilsted et al., 2016; Garlock et al., 2020). Archetype 1 countries need to find a balance between identifying suitable environmental conditions for production that also considers the health of waterways to ensure that cultured food is safe for human consumption (Gentry et al., 2017b; Oyinlola et al., 2018). Strengthening and supporting existing community-based approaches may be most effective to ensure that prioritizing livelihood security is coupled with addressing nutrition issues for dispersed rural populations (FAO, 2022). Assessing inland water interdependencies with the agricultural sector needs to be a priority, as well as the impacts of effluent going into watersheds on coastal production sites. Securing property rights for smallholders to access and use water and land should be considered as a starting point for justice-based development (Tecklin, 2016; Fernández-González et al., 2020; Schlüter et al., 2020). 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 (Watson et al., 2018; Bush et al., 2019a). 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 interdependent policy choices that address food security and agriculture stability issues.

Archetype 2 - Limited aquatic food engagement.

Aquaculture is an established sector in Archetype 2 (limited) countries, but unlikely to be a main priority development area for food security and the economy, given the sector's low value added to the overall economy. Archetype 2 (limited) scores well on national governance and environmental performance, but likely faces issues related to intensification, investment into technology and cultural adoption

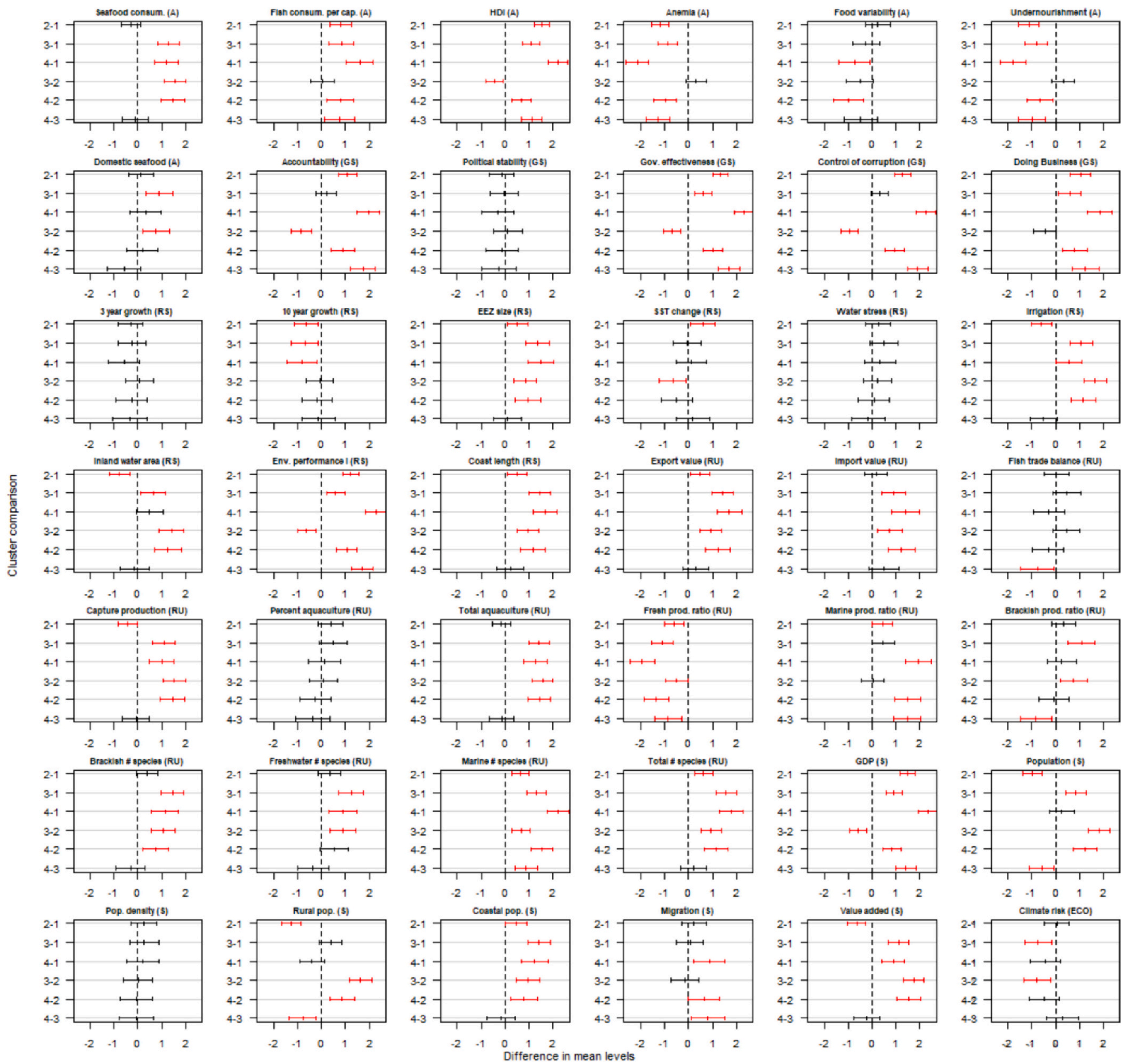

Fig. 3. Pairwise significant differences between clusters (i.e., archetypes) for each individual indicator using analysis of variance followed by Tukey test. The pairings of each cluster/archetype combination are labeled on the y-axis. For example 2–1 is comparing Archetype 1 and Archetype 2. Significant ($p < 0.05$) pairwise cluster differences are labeled in red.

Table 5
Indicators that are significant between all group pairings in Fig. 3. One indicator from each first-tier framework category is present, excluding External Ecosystems (ECO). This supports our hypothesis that the most significant variables for understanding aquaculture development are a mix of diverse social and ecological variables.

Significant indicators between all group pairings	Framework classification
Human Development Index (HDI)	Actors (A)
Government effectiveness	Governance (Gov)
Environmental performance	Resource system (RS)
Freshwater production ratio	Resource units (RU)
Number of marine species	Resource units (RU)
Gross Domestic Product (GDP)	Social, economic, political settings (S)

(Kreiss et al., 2020). Inland freshwater and irrigation availability score low, although freshwater production is the dominant production environment, suggesting that the use of technology intensive recirculating fed-aquaculture systems in densely populated fish ponds is common (Ahmed and Turchini, 2021). Considering how such production interacts with other sectors, there is likely a need to establish a more regulatory intensive governance landscape to avoid environmental harms and ensure benefits to people, both economically and for public health. Due to lower domestic demand for seafood compared to Archetypes 3 (developing) and 4 (wealthy), larger portions of production may be for export from larger companies rather than from rural small-scale producers, for example to other European Union markets (Gephart and Pace, 2015). Creating the right market incentives for sustainability and understanding changes in consumer demand may help inform effective strategies.

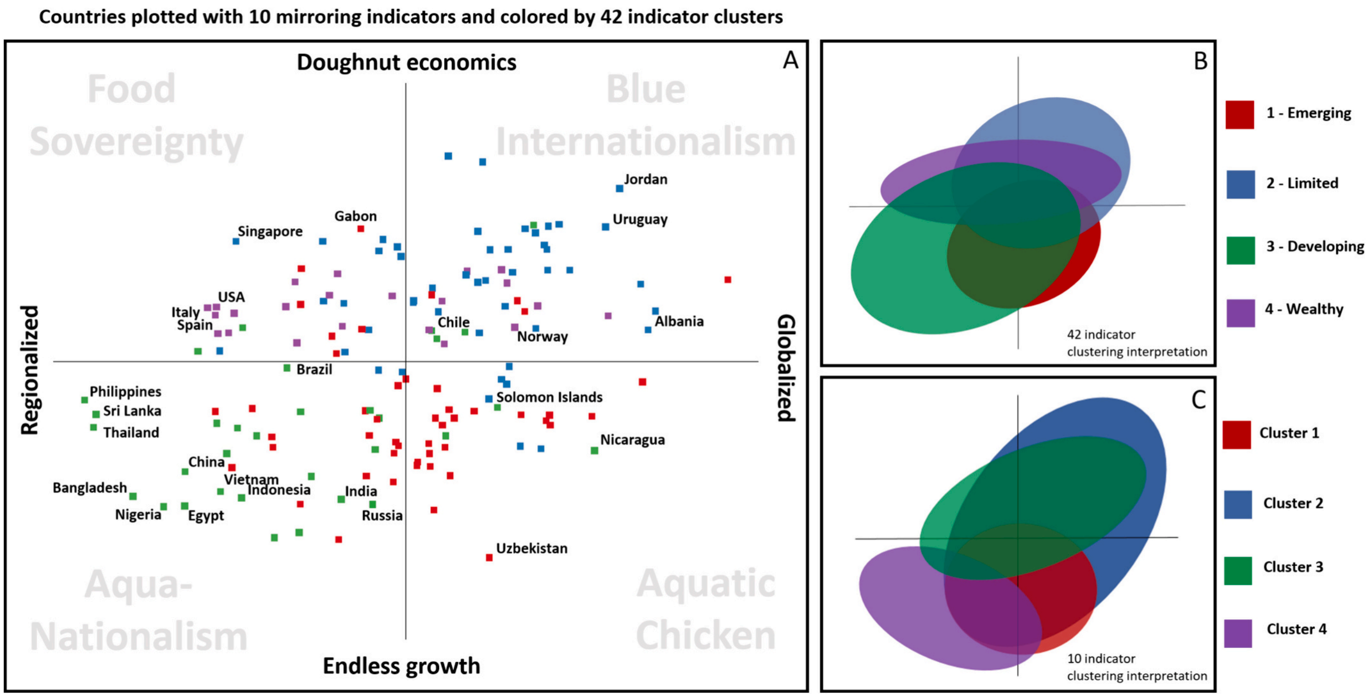

Fig. 4. (A) Countries plotted on two axes with a select set of indicators designed to match the variables proposed by Gephart et al. (2020). The cluster groups are plotted by the 10 indicator values, but colored by the archetype groups from the full 42 indicator data analysis classification to assess overlap. The plot assesses to what extent Gephart's conceptualization (Food Sovereignty, Blue Internationalism, Aquatic Chicken, Aqua-Nationalism) overlaps with our data driven approach. (B) An ellipse of the full 42 indicator cluster groups, mirroring the coloration in plot A. (C) An ellipse of the cluster group overlaps, when the cluster analysis is performed with only the selected 10 indicators, used to plot the countries in part A.

Archetype 3 - Developing economy aquaculture producers.

Countries in Archetype 3 (developing) require the most urgent governance attention given the role of seafood production within the agricultural economy and culture. Large rural production investments spawned by traditional practices in high seafood consuming societies has quickly put pressure on aquaculture to meet domestic needs that were historically met by capture fisheries that are now on the decline (Belton et al., 2018; Cottrell et al., 2021). Scaling from low intensity traditional pond aquaculture towards technology-driven fish production enterprises needs collective action among actors across the value chain – from inputs, production, packaging, transport and market - to minimize environmental impacts (Bush et al., 2019b; Belton et al., 2020b). Simultaneously, aquaculture needs to prioritize governance 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 (Partelow et al., 2023a). 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 (Partelow et al., 2018; Manlosa et al., 2023; Paramita et al., 2023), 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 (Partelow et al., 2023a). The push towards intensification will likely come with increased use of feed and medication due to increases in stocking density to achieve higher production (Cashion et al., 2017; Froehlich et al., 2018; Cottrell et al., 2020). Governance should consider feed sourcing, disease spread and water effluent where intensification is increasing (Partelow et al., 2023a). Seafood in Archetype 3 (developing) 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 (Gephart and Pace, 2015; Asche et al., 2022). 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 (Tecklin, 2016; Fernández-González et al., 2020; Schlüter et al., 2020).

Archetype 4 - Wealthy economy aquaculture producers.

Governing aquaculture in Archetype 4 (wealthy) – which is strongly characterized by countries dominating the marine mariculture subsector - will include enabling mechanisms for technology development (Gentry et al., 2019b), increasing public awareness and consumer uptake of farmed seafood products (Froehlich et al., 2017) and ensuring that feed supply chains don't export environmental impacts to the countries where they are produced (Froehlich et al., 2018; Cottrell et al., 2020). For example, debates over fish escapes, environmental impacts, feed input issues and public perceptions of sustainability - particularly in Norwegian and Chilean salmon farming – have been highly contested (Chu et al., 2010; Olaussen, 2018; Quiñones et al., 2019). Although the offshore sector is well-established in many countries, concerns over sustainability remain, particularly about the ability to replace capture fisheries production volume – and as a general means to provide high quality seafood at scale (Edwards et al., 2019; Belton et al., 2020a). The governance of aquaculture in Archetype 4 (wealthy) countries will need to fit into an already crowded institutional landscape because these countries also have well-established capture fisheries and other coastal economy sectors that have longer histories of governance and established administrative institutions (Partelow et al., 2023a). In this case, aquaculture expansion among wealthier producing nations may need to consider removing governance barriers to allow aquaculture growth and rights, if desired, or deliberate engagement with sectors who already have established rights and regulations (Gentry et al., 2019b).

4.2. Unpacking development scenarios

Although there is only weak statistical alignment between our data-driven archetype analysis and Gephart's development narratives, there are many qualitative overlaps and similarities useful for discussion. The most evident is the alignment of countries in Archetype 3 (developing) with the Aqua-Nationalism narrative characterized by intensive regional or domestic food production under high growth conditions with less regulatory protections. Many if not most of the largest aquaculture producers in Asia and Africa fit into this narrative of Aqua-Nationalism and Archetype 3 (developing), including India, Indonesia, China, the Philippines, Vietnam, Nigeria and Egypt. Importantly, the term we allocate to Archetype 3 as 'Developing economy aquaculture producers' reflects more the social-economic development status than the maturity of the aquaculture sector, which has been well-established for decades or longer as a livelihood and food source in most of these countries. Countries in Archetype 4 (wealthy) are split in our analysis between Gephart's Blue Internationalism narrative and regional Food Sovereignty. The countries in this archetype are ranked highly on social-economic development indicators, but seem to have different market orientations, seafood cultures and drivers of the sector's growth within the group. For example, Spain, Japan, France, Italy and the United States have a trade balance skewed towards more imports and perhaps production oriented at domestic markets, where as Chile and Norway are international trade-oriented. Chile is the only country in Archetype 4 (wealthy) from South America or Africa, likely driven by its high value-added from a nearly exclusive marine production sector. Japan is the only country from Asia in archetype 4. Other interesting observations are that Archetypes 2 (limited) and 4 (wealthy) have the highest number of indicators with significant value differences in the archetype analysis, whereas they were quite closely aligned in Gephart's scenario analysis. Many countries in both seem to be oriented towards freshwater production and export. The indicators with the largest value range differences are seafood consumption, marine production ratio and value added to the agriculture sector. Marine production ratio is relevant here because many archetype 2 (limited) countries are land-locked. Archetype 2 countries have the lowest value-added ranges among all archetype groups, suggesting the sector is less meaningful for the overall agricultural economy. Furthermore, 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 (emerging) and 3 (developing). This suggests that high seafood consumption is dependent on domestic production, which relies on local ecosystem health that may degrade if not cared for.

Our empirical archetypes can inform revised conceptual narratives for aquaculture development. Here it will be important to not only compare between archetypes, but also within the archetypes. Broad conceptual narratives are unlikely to fit all countries in the same archetype groups, but can be used as a starting point to further investigate how specific countries are similar or different. Comparing regional or continental sub-groups of countries can help better understand within archetype differences between, for example, European or Asian, producers (Kreiss et al., 2020). Within mariculture dominant countries (Archetype 4 - wealthy), temporal development narratives have been observed with high variations between countries (Gentry et al., 2019b). Similarly, within Archetype 3 (emerging), there are clear differences in governance strategy, scale, cultural context and domestic versus export drivers between countries such as China, Indonesia and the Philippines, although their macro-characteristics are similar enough to be considered in the same archetype at the global level (Manlosa et al., 2021a; Asche et al., 2022). Important to many contexts, is the consideration of whether aquaculture development is being driven by top-down policy and market measures (i.e., interventionist), or bottom-up self-emergent (i.e., immanent) local demands and cultural changes (Belton and Little, 2011). This is important for understanding how value chains and innovations emerge, and the motivations of stakeholders along value chains to find collective solutions that work locally and can be sustained through adaptive capacity (Belton and Little, 2011; Bush et al., 2019b; Belton et al., 2020b). This, for example, has been observed in many Asian producers in Archetype 3 (developing), and could inform development pathways in less established producers (e.g., archetype 1 – emerging). Governance will be essential across the entire sector, and the usefulness of better understanding development scenarios and archetype groups is to provide more nuanced insights so that governance and institutional changes can be guide at the appropriate levels and scales (Partelow et al., 2023a).

4.3. Why archetype analysis is useful and methodological considerations

Archetype analysis is useful for understanding aquaculture development for two major reasons. First, it offers a starting point for examining the relationships between meaningful indicators across different regions. It also provides an empirical foundation to develop hypotheses of development drivers and trajectories in specific countries. Our analysis has shown that data from five out of six categories of the social-ecological systems framework were the most relevant for explaining differences between archetype groups. This provides solid support for examining integrated and more nuanced data from a social-ecological perspective in individual countries. For example, in Indonesia it would be useful to examine the details of the country's classification into archetype 3 (developing), by looking at more nuanced data on how high seafood demand and large marine and freshwater capacity for aquaculture expansion interface with current governance policies to improve environmental performance and livelihoods (Henriksson et al., 2017; Paramita et al., 2023; Nagel et al., 2024). In order for governance practices to fit highly diverse aquaculture contexts across Indonesia, capacity for understanding social-ecological interactions will be key for successful institutional development and change (Paramita et al., 2023). 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. Scaling or amplifying effective policies may only be feasible in similar contexts. Archetype analysis identifies countries with these similarities to enable these comparisons, and can be expanded to provincial level comparisons within countries.

(Leslie et al., 2015; Rocha et al., 2019). 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 and goals.

To leverage the potential of archetype analysis for understanding development scenarios, aquaculture science needs to move beyond the singular use of production output data as the only meaningful indicator of a country's trajectory. Archetype analysis can show us which indicators are co-shaping and interacting in identifiable patterns. It is clear that aquaculture systems are embedded within environmental, economic, and social contexts that create complex interdependencies, but are often poorly understood at a more granular level. 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). Research informing policies that fails to recognize these linkages can therefore result in unanticipated trade-offs or missed opportunities for synergies (Blanchard et al., 2017). Other outcomes also need to be considered such as livelihoods, environmental performance and value chain resilience. However, numerous barriers remain such as establishing causality among identified variables and production. For example, we can assume that a relationship between land available for irrigation and freshwater production growth exists - or value added to the economy and livelihood security - but further country specific sub-national data would be needed for further testing. Using publicly available secondary data can add substantial value to current analyses given the clear relevance of many available indicators. 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. A clear data gap exists at the sub-national level, where discrepancies in reporting standards and coverage often exist. Another data gap is fixed time-scale data, where yearly intervals are standard but lack nuance by failing to recognize important seasonal changes in species farmed, value added, livelihoods or environmental impacts that, for example, are likely to shift between the wet and dry seasons in many tropical countries, or summer and winter towards the poles. Sub-national data is essential for understanding how governance can better fit to the multifaceted development trajectories of many producing countries. For example, in India, Indonesia or Brazil, data may be available, but not in a centralized location, and might not be standardized among the country's diverse districts which face internal language, financial and administrative access barriers. Furthermore, species production data, which most high-level studies are based on (Garlock et al., 2020; Naylor et al., 2021), 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 (Bush et al., 2019b). For example, how growth trends reflect land and water allocation rights (Gephart et al., 2017), or the associated risks of storm or drought impacts, or how conflicts emerge due to conflicting rights (Partelow et al., 2018). Many indicators on these factors may already exist or can be compiled or modeled from publicly available sources, yet few studies are engaging with such analyses.

Nonetheless, there are barriers and challenges when using and integrating diverse data for archetype analysis. Although a lot of data is standardized at the country-level, there is often a lack of specificity about that data for any one country. Many countries self-report data, such as the FAO production data, which is not all collected in a similar way. Furthermore, data from different sources often has different formats that require transformation in order to apply analytical tools. Transforming and normalizing data may skew the raw interpretation of the values. There is a tradeoff here between allowing comparable integration with other data and skewing specific meanings of individual countries. Optimizing the analysis in this study would be best done with sub-national statistics collected with standardized techniques. However, this type of data is not yet available across all countries of interest. Our analysis has been guided by prior archetype research by Rocha et al. (2019), who provide a detailed methodological process for making data use and transformation choices for cluster analysis with the data available.

A final issue is the need more for social data (Partelow et al., 2023b) that has high coverage, is sector specific and collected with standardized methods across countries. This would include valuing livelihood and social wellbeing data alongside production data when discussing the sector's sustainability. Data on property rights, markets, pricing and employment would be highly valuable. Data on these factors does exist in many countries, but not in many others, which is why these are not included in our study. Nonetheless, recognition for the human-centric contributions that the sector can make on issues of food security, livelihoods and public health is gaining traction (Golden et al., 2017; Garlock et al., 2024). Archetype and social-ecological analysis can help show the relationships that social data have with other production and environmental condition data. Adding social data can help test claims about the benefits or risks of aquaculture growth by examining their influence on social context, economic or institutional changes in governance. Here, cross-sector and cross-country learning will be important to parse out differences. Finally, aquaculture governance will struggle if it is not informed by systems thinking approaches that move beyond the farm level and consider broader social, economic and political contexts (Partelow et al., 2023a). Archetype analysis is particularly useful for including these factors, which can help ground our assumptions about the sector's contributions to food security and environmental impacts with more robust science (Belton et al., 2020a).

5. Conclusions

Our study demonstrates that integrating diverse types of macro-level data on social, economic, environmental and governance factors can inform a more nuanced understanding of aquaculture development trajectories at the country level. We have shown how 150 countries each have different development profiles, characterized by observed differences among the 42 indicator values in each country grouped into four distinct archetypes. Nonetheless, similar patterns of development can also be observed across countries with similar indicator values. Here, we have shown the value of using archetype analysis - premised on cluster analysis – for understanding how countries with similar development profiles can be identified and interpreted as having similar development narratives. By doing this, our analysis was able to empirically test prior conceptualizations in the literature on aquaculture development scenarios with our four archetypes of development. The four archetypes are: (1) Archetype 1 - Emerging aquaculture producers (Emerging), (2) Archetype 2 - Limited aquatic food engagement (Limited), (3) Archetype 3 - Developing economy aquaculture producers (Developing), (4) Archetype 4 - Wealthy economy aquaculture producers (Wealthy). Our analysis shows that 6 of the 42 indicators were statistically significant across all archetypes, when the archetypes were paired and individually tested against each other for variation. Importantly, the six indicators cover five different conceptual tiers of the social-ecological system framework, indicating that diverse data from social, economic, environmental and governance factors are needed to fully explain development differences across countries. We believe our study provides a necessary empirical basis to current speculations about the aquaculture sector's many potential development trajectories, and what is driving current trends. We further discuss the need for more accurate data on diverse aquaculture sector indicators, including social science indicators coupled with production data, to better understand sub-national trends and the effects of the sector on key outcomes of interest such as environmental sustainability, food security, livelihood opportunities, and public health.

Author contributions

SP and BN conceptualized and designed the study. SP, BN and RG selected the indicators. SP and BN collected the data. SP, BN and JR analyzed the data. All authors interpreted the results, wrote and edited the paper.

CRediT authorship contribution statement

Stefan Partelow: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ben Nagel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rebecca Gentry:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jessica Gephart:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Juan Rocha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis.

Declaration of competing interest

The authors declare no competing interests.

Data availability

All data associated with this study are present in the paper or the

Supporting information.

Acknowledgments

We acknowledge funding support from the German Federal Ministry of Education and Research, Grant/Award Number: 031B0785, within the frame of the COMPASS: Comparing Aquaculture System Sustainability project. We are grateful for general support from the Leibniz Centre for Tropical Marine Research (ZMT), and all co-authors acknowledge support from their respective organizations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2024.741484.

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