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Aquaculture production and diversification: What causes what?

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ABSTRACT

Aquaculture, an important source of food supply, is expected to be the main sector to satisfy growing seafood demand in the future. Being the most diversified food product in the world, aquaculture diversification can add resilience to global food security, satisfy consumer preferences, and promote price stability. Understanding the relationships between aquaculture production and diversification and their causations is crucial for developing effective strategies to support long-term sustainability and resilience of aquaculture development. This study investigates the direction of causal relationships between aquaculture production and diversification using a panel vector autoregression (PVAR) model with three decades of aquaculture production data and the Effective Number of Species (ENS) values by country. Diversification is measured in terms of within-group diversity (ENS_α) and between-group diversity (ENS_β); this approach provides deeper insights into diversification strategies. The model results show that between-group diversification is more conducive to production expansion globally, especially in the Americas and Asia, and the positive effects are long lasting. Within-group diversification also induces more production in Europe and, to a lesser extent, in Asia. Therefore, policies and market incentives that promote diversification across different species groups in the Americas and Asia, and diversification within the same species group in Europe and Asia, are potential strategies to expand aquaculture production. Other findings include production leading within-group diversification in Asia and Europe, but not in the Americas and Africa. A possible explanation is that production expansion would accumulate experience, develop scope economies and emerging technologies, and build up capacities. These factors generate spillover effects that facilitate species diversification, considering that Asia and Europe have a longer history of aquaculture development compared to the Americas and Africa. However, no significant relationship is found indicating production leading between-group diversification.

1. Introduction

Aquaculture production and its level of species diversification could be influenced by various factors such as resource endowments (Gyalog et al., 2022; Jayanthi et al., 2020; Metian et al., 2019; Rahman et al., 2019; Zhu et al., 2022), farming systems (Anderson, 2002; Bohnes et al., 2019; Bosma et al., 2016; Chary et al., 2022; Kaleem and Sabi, 2021), technologies (Asche, 2008; Asche and Smith, 2018; Bostock et al., 2016; Delgado et al., 2003; Sun and Ji, 2022; Yue and Shen, 2022), market demand (Cai et al., 2022; Harvey et al., 2017; Yue et al., 2023), consumer preferences (Harvey et al., 2017; Newton et al., 2021), climate change (Ficke et al., 2007; Handisyde et al., 2017; Harvey et al., 2017; Hermansen and Heen, 2012), environmental issues (Bostock et al., 2016; Delgado et al., 2003; Gephart et al., 2017; Harvey et al., 2017; Klinger and Naylor, 2012), trade/foreign competition (Cai et al., 2022; Guy et al., 2014), and political issues (Aarset and Jakobsen, 2009; Hall, 2004; Knapp and Rubino, 2016; Nobile et al., 2020). Different countries face different constraints and external factors that influence their aquaculture production levels and their ability to diversify. For example, some countries like those in Sub-Saharan Africa have the resources (e.g., inexpensive labor, favorable climate) for aquaculture production but lack the necessary technology to diversify (Machena and Moehl, 2001; Shaalan et al., 2018). Conversely, countries like Singapore have the technological capability to diversify but lack the natural resources and market capacity to upscale production via species diversification (Bohnes et al., 2020; Shen et al., 2021). Consequently, aquaculture

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production and diversification vary across countries and their patterns evolve over time (Cai et al., 2023). Whether and how production affects diversification, or the other way around, have important policy implications, especially since aquaculture is expected to be the main solution to satisfy the growing seafood demand in the future (Costello et al., 2020; Diana, 2009; Kobayashi et al., 2015). Higher aquaculture production could promote food security, particularly for low and middle-income consumers (Belton et al., 2018). A global study (Garlock et al., 2022) found that higher aquaculture production was associated with higher aquatic food consumption and further supports the significance of aquaculture development in regions that are vulnerable to food security. Diversification also promotes food security, especially in small-scale aquaculture systems (Wang et al., 2023), and improves resilience to the global food system (Troell et al., 2014). Understanding the relationships between aquaculture production and diversification and their causations is crucial for developing effective strategies to support long-term sustainability and resilience of aquaculture development globally and nationally. However, the relationships between aquaculture diversification and production have not been extensively studied.

The relationship between aquaculture diversity and production is akin to the intricate relationship between export diversity and economic growth. While there is an extensive literature in investigating that relationship, only Cai et al. (2022) and Garlock et al. (2023) have examined the relationship between species diversity and aquaculture industry development. A recent literature review (Sarin et al., 2022) shows that most studies indicate a positive relationship between export diversity and economic growth, although the direction of the causal relationship is still largely unresolved (Gözgör and Can, 2017). Cai et al. (2022) also found that there is a positive relationship between species diversity and aquaculture production, but their model could not determine the causalities between the two variables. Using one year of data, Garlock et al. (2023) could not find any relationship between aquaculture production and species diversification. The present study investigates the direction of those causal relationships and thus enhances the policy debate regarding aquaculture species diversity as a strategy for aquaculture development.

Conceptually, the relationship between aquaculture production and species diversity could be interactive. On one hand, aquaculture production expansion could build capacities through research and development and knowledge spillover (Kumar et al., 2018), accumulated experiences (Yue et al., 2023), and value chain synergy (Fernández Sánchez et al., 2023; Hu et al., 2019). The enhanced capacities would facilitate species diversification. Higher aquaculture production, however, could also lead to lower diversification if countries adopt technology for more cost effective species and abandon their native species (Foucart and De Pirro, 2022). On the other hand, diversification could be a way to expand aquaculture production by utilizing natural resources for more suitable species (e.g., polyculture practices, integrated multitrophic farming) (Milstein et al., 2006; Oboh, 2022; Ridler et al., 2007; Stenton-Dozey et al., 2021; Thomas et al., 2021), embracing technology progress and innovation (Jena et al., 2017; Sicuro, 2021), and upgrading value chains (Kaminski et al., 2018). Diversification driven by consumer preferences often leads to increased production as preferences change with rising incomes (Newton et al., 2021). Furthermore, diversification can create new consumer markets, as exemplified by the successful development of the crayfish market in China (Yue et al., 2023).

There are different ways to measure diversification in the literature. More common is to use Shannon diversity index to measure aquaculture diversity (Metian et al., 2019; Sicuro, 2021), agricultural diversity (Waha et al., 2022), and biodiversity (Supriatna, 2018). This study measures aquaculture diversity by the Effective Number of Species (ENS), a diversity measure essentially equivalent to the Shannon index (Cai et al., 2023; Cai et al., 2022). The ENS provides a more intuitive measure of diversity (Jost, 2006), with the scale ranges from 1 (the lower bound) to the total number of species (the upper bound). Following Cai et al. (2023), this study splits species diversity into two components: within-group diversity (ENS_α) and between-group diversity (ENS_β). The between-group diversification measures the distribution of production among five species groups: finfish, crustaceans, molluscs, aquatic plants (algae), and miscellaneous aquatic animals and animal products (MAA); whereas the within-group diversity measures the average species diversity within these groups. To uncover the causal relationships between aquaculture production and species diversity, a panel vector autoregression (PVAR) model is employed using three decades (1990–2020) of aquaculture production data and the ENS values by country. With the two different classifications of diversification, we reveal the inter-relationships among aquaculture production, diversification within the same species group, and diversification between different species groups. This study not only examines global experiences but also explores regional experiences since countries with similar production and diversification patterns tend to cluster geographically (Cai et al., 2023). The model results provide evidence-based policy implications for future aquaculture development.

2. Methods and data

2.1. Methods

The metrics for within-group diversity (ENS_α) and between-group diversity (ENS_β) are derived from the effective number of species (Hill, 1973), which is an established diversity measure. The general expression for this measure is given by:

$$D_q = \left(\sum_{i=1}^{n} s_i^q\right)^{1/1-q} \tag{1}$$

where n is the total number of species; s_i represents the share of species i in the production of all species; and q is the diversity order. When $q = 0$, the effective number of species is equal to the total number of species (i.e., $D_0 = n$), reflecting only richness without considering evenness. As q increases, the measure increasingly accounts for evenness.

This study adopts the Effective Number of Species (ENS) at the order $q = 1$ as the diversity measure:

$$ENS \equiv D_1 = e^{-\sum_{i=1}^{n} s_i ln(s_i)}. \tag{2}$$

The term within the exponent is the well-known Shannon index (H):

$$H \equiv -\sum_{i=1}^{n} s_i ln(s_i) = ln(ENS). \tag{3}$$

ENS in Eq. (2) can be decomposed into two components:

$$ENS = ENS_\alpha \times ENS_\beta. \tag{4}$$

As a measure of within-group diversity, ENS_α is equal to a weighted geometric mean of ENS within species groups (denoted as ENS_j), with the weight being the share of each species group in total production (denoted as s_j):

$$ENS_\alpha = \prod_j \left(ENS_j\right)^{s_j}. \tag{5}$$

ENS_β denotes the effective number of species groups, i.e.,

$$ENS_\beta = e^{\sum_j -s_j ln(s_j)} \tag{6}$$

which measures the richness and evenness of production distribution among the species groups (i.e., between-group diversity).

The PVAR model is used to examine the dynamics of aquaculture production and diversification. It alleviates the difficulty in uncovering the endogeneity of species diversity and aquaculture production using traditional econometric modeling with very limited data. The PVAR model comprises a system of equations consisting of three endogenous variables, namely aquaculture production (q), within-group diversity

(ENS_{α}), and between-group diversity (ENS_{β}). The PVAR model is specified as:

$$Y_{c,t} = \alpha_c + \Phi\, Y_{c,t-1} + \varepsilon_{c,t} \quad (7)$$

where $Y_{c,t}$ is a 3×1 vector consisting of the three endogenous variables (q, ENS_{α}, ENS_{β}), Φ is the matrix of autoregressive coefficients for the three endogenous variables, α_c is a vector of country fixed effects that controls for individual country's heterogeneity, and $\varepsilon_{c,t}$ is the white noise error term. Subscript c denotes country and t denotes time (year). The time index t ranges from 1990 to 2020. Aquaculture production (q) is in log form. The conceptual model in Fig. 1 shows the relationships that the PVAR model estimates.

To estimate PVAR model with fixed effects, it is common to apply forward orthogonal deviation to remove fixed effects (Khan et al., 2020; Love and Zicchino, 2006; Usman et al., 2022), otherwise, estimates would be biased (Nickell, 1981). Forward orthogonal deviation removes the mean of all future observations from each observation so that fixed effects are eliminated (Sigmund and Ferstl, 2021) and the transformed variables and lagged variables remain orthogonal (Love and Zicchino, 2006). Since our model has country fixed effects, we use forward orthogonal deviation to transform the data. Specifically, we use the R package "panelvar" to run the PVAR model by Generalized Method of Moments (GMM) technique and forward orthogonal deviation transformation (Sigmund and Ferstl, 2021). To assess the stability of the PVAR model, specifically whether the autoregressive process in the model is stable (i.e., the model's coefficients remain stable over time), we conduct a unit root test. If the eigenvalues of the model are within the unit circle, it indicates stationarity of the variables in the model. To examine the causality direction between aquaculture production and diversification, we conduct a panel Granger causality test. If the panel Granger causality test is significant, it indicates that the lagged values of one variable can predict (Granger cause) another variable. However, if countries do not have any diversification over time, which is a phenomenon discovered in Cai et al. (2023) that nearly half of national aquaculture has no within-group or between-group diversity, Granger causality test is unable to identify causation between production and diversification. To address this issue, we exclude countries with no diversification throughout the entire time series when conducting the Granger causality test. Granger causality test, therefore, cannot account for factors that hinder diversification development, such as regulations prohibiting the farming of non-native species. It is important to note that the estimation of the PVAR model includes all countries with aquaculture production, regardless of whether a country diversifies.

The estimated coefficients from the PVAR model are not very informative as they only show the relationships between the dependent variable and the lag variables. Therefore, we generate the orthogonalized impulse response functions (OIRFs) after we run the PVAR model to examine the effect of changing one variable on the dynamic responses of the dependent variable, holding other variables constant. The results of the orthogonalized impulse response functions, together with the 95% confidence interval bands, are shown in graphical forms. In addition, we use forecast error variance decomposition to show the percent of the variation in one variable that can be explained by the change to other variables, accumulated over 10 years.

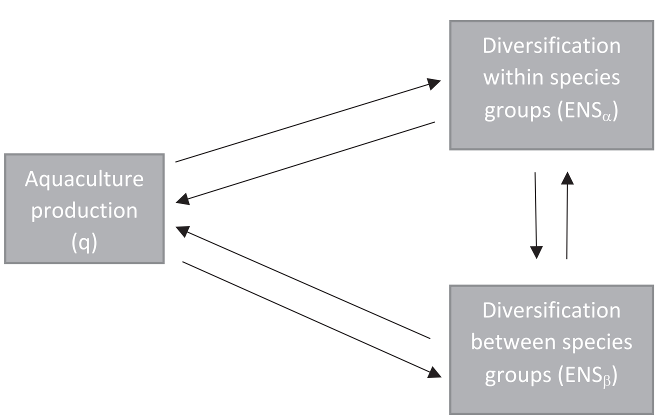

Fig. 1. Conceptual model of aquaculture production and diversification.

2.2. Data

Annual aquaculture production data by species and country come from the Food and Agriculture Organization of the United Nations (FAO) Global Aquaculture Production Statistics 1990–2020 (FAO (Food and Agriculture Organization of the United Nations), 2022). All of the Aquatic Sciences and Fisheries Information System (ASFIS) species items recorded in the database are included. According to the International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP), ASFIS species items can be grouped into eight divisions: 1) marine fishes, 2) freshwater fishes, 3) diadromous fishes, 4) molluscs, 5) crustaceans, 6) aquatic plants, 7) miscellaneous aquatic animals, and 8) miscellaneous aquatic animal products. For the calculation of ENS_{α} and ENS_{β}, we aggregated the first three divisions into "finfish" and the last two into aquatic animals and animal products to come up with five species groups. The five species groups used in this study include: 1) finfish, 2) molluscs, 3) crustaceans, 4) aquatic plants, and 5) miscellaneous aquatic animals and animal products (MAA). These five species groups are usually used in the aquaculture literature (Metian et al., 2019; Sicuro, 2021). For regional models, classification of regions is based on the United Nations' classification of countries or areas/geographical regions M49 standards (https://unstats.un.org/unsd/methodology/m49/). Countries are grouped into five regions: Asia, Europe, the Americas, Africa, and Oceania. A total of 208 countries are included in the analysis, comprising 53 in Africa, 47 in the Americas, 48 in Asia, 41 in Europe, and 19 in Oceania. As countries started aquaculture production in different years, years with no aquaculture production are excluded from the analysis. The total number of observations is 5649, including 1407 for Africa, 1194 for the Americas, 1386 for Asia, 1201 for Europe, and 461 for Oceania.

3. Results

3.1. Aquaculture production and diversification trends

The world aquaculture production was in a steadily increasing trend from 1990 to 2020, from under 20 million tonnes to over 122 million tonnes. Asia contributed about 90% of total production, followed by Europe before mid-21st century. The Americas superseded Europe as the second highest production region after mid-21st century. Africa ranked the fourth in production, and Oceania was ranked last (Fig. 2).

Diversification within species group varies by region. Asia and Europe were consistently more diversified within species group whereas the Americas and Oceania were less diversified in the same species group (Fig. 3).

The Americas and Asia were more diversified across species group and Europe and Africa were less diversified (Fig. 4). Comparing Figs. 3 and 4, ENS_{α} was higher than ENS_{β} for most regions, indicating aquaculture diversification was more driven by within-group diversification.

3.2. Model results

The model results for eq. (1) are shown in Appendix A. The unit root tests of the models show that all eigenvalues are within the unit circle, representing stationarity of the variables in the models. Note that because of the small sample size in Oceania ($n = 19$ countries), the model results are unstable and therefore not shown here.

The first-order lag in the PVAR specification was chosen based on Hansen's test for over-identifying restrictions (Akaike information

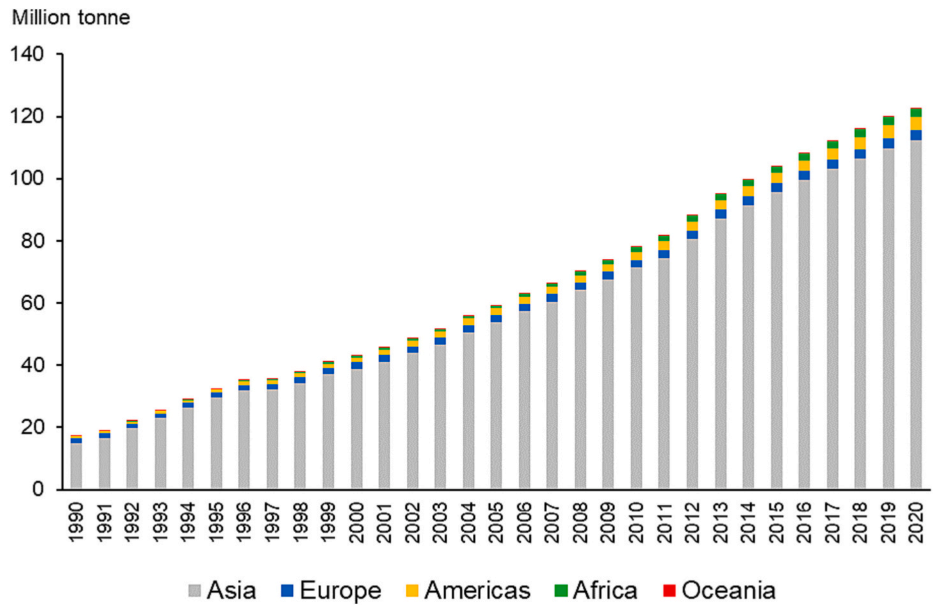

Fig. 2. Aquaculture production by region.

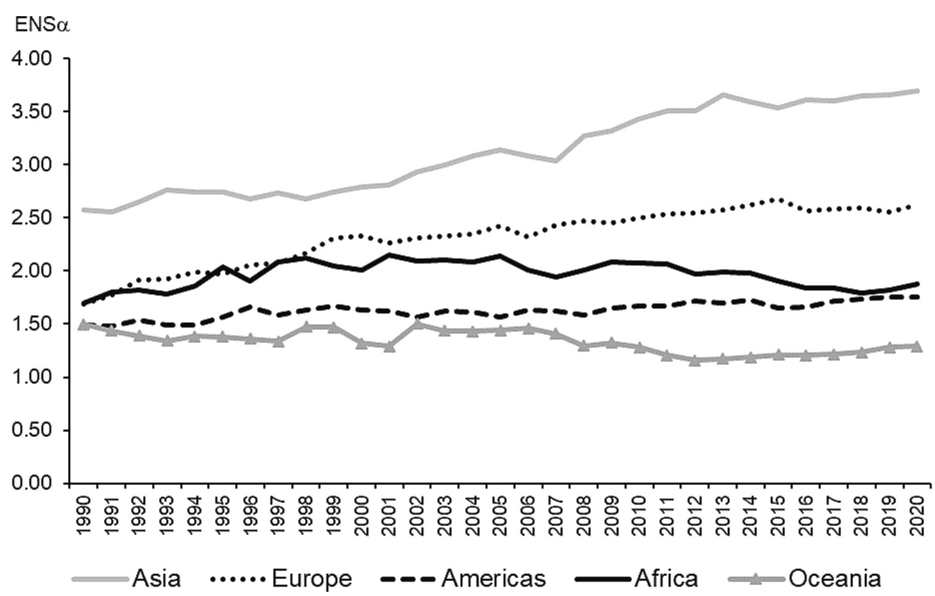

Fig. 3. Within-group diversity (ENS_α) by region (average across countries' ENS_α in the region).

criteria, the Bayesian information criteria, and the Hannan-Quinn information criteria). The panel Granger causality tests show that both production causes diversification and diversification causes production. Test results are shown in Appendix B. Table 1 summarizes the OIRFs results for the world and regional models. Detailed results in figures are shown in Appendix C.

OIRFs results can answer two important questions. The first is, "does production affect diversification?" The results show that higher production has positive and significant effects on diversification within species group for the world, Asia, and Europe, and the positive effects are rather long-lasting — 10 years in Asia and between 2 and 7 years in Europe. But the positive effect is insignificant in the Americas, and no relationship was found in Africa. Another finding is that a country's aquaculture production, regardless of its production volume, has no impacts on species diversification between species groups in any region. In other words, higher/lower aquaculture production level does not induce more diversification between species groups. This could be because diversification between species groups requires additional start-up resources that are either unavailable or have limited availability and different technologies that are unfamiliar.

The second question is, "does diversification affect production? If so, is it from within-group or between-group diversification?" The results show that diversification within species group has positive effects on production in Asia and Europe, but not in the Americas or Africa. The positive effects remain significant for 7 years in Asia and 9 years in Europe. This is coincident with the two regions having the highest within-group diversification (Fig. 3), suggesting that diversification within species group could be a promising strategy to expand the aquaculture sector in Asia and Europe. On the other hand, between-group diversity is more conducive to production expansion in the world, and also in the Americas and Asia, but not in Europe and Africa. The positive effects remain significant for 10 years in Asia and 6 years in the Americas. This indicates that success in diversifying into new species groups in Americas and Asia, where the highest between-group

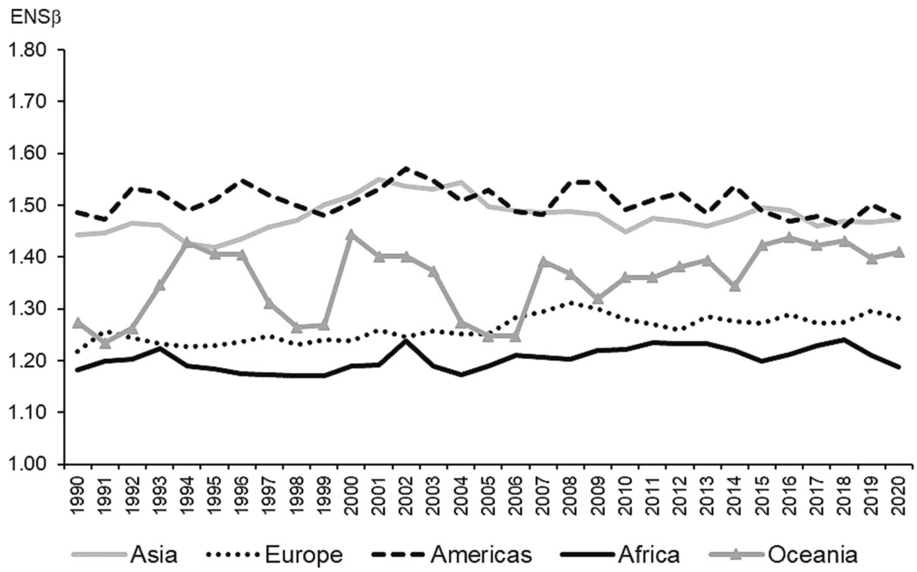

Fig. 4. Between-group diversity (ENS_β) by region (average across countries' ENS_β in the region).

Table 1
Summary of OIRFs results for world and regions.

	World	Asia	Europe	The Americas	Africa
Production leads ENS_α	+* (1−10)	+* (1–10)	+* (2–7)	+	X
Production leads ENS_β	X	X	X	–	X
ENS_α leads production	X	+* (1–7)	+* (1–9)	X	–
ENS_β leads production	+* (1–10)	+* (1–10)	X	+* (1–6)	X
ENS_α leads ENS_β	X	X	X	X	X
ENS_β leads ENS_α	+	+* (1–10)	+	–	X
Production leads Production	+* (1–10)	+* (1–10)	+* (1–10)	+* (1–10)	+* (1–10)
ENS_α leads ENS_α	+* (1–10)	+* (1–10)	+* (1–6)	+* (1–10)	+* (1–10)
ENS_β leads ENS_β	+* (1–8)	+* (1–8)	+* (1–5)	+* (1–8)	+* (1–6)

Notes: ENS_α represents within-group diversity and ENS_β represents between-group diversity. X represents no relationship, + represents positive relationship, – represents negative relationship, * represents the relationship is significant at 95% level. Numbers in parenthesis represents how long (in years) the significant relationship lasts.

diversification is observed, would induce higher production. This could be achieved from improving farming efficiency through polyculture such as growing shrimp and finfish species (e.g., tilapia) together. Experimental studies have demonstrated that polyculture of tilapia with shrimp leads to better pond ecology, reducing shrimp diseases, and enhancing overall yields (Fitzsimmons and Shahkar, 2016; Wang and Lu, 2016). In addition, market demand is a key factor affecting diversification (Cai et al., 2022; Harvey et al., 2017; Yue et al., 2023). As consumer market is distinct for aquaculture in different species (Troell et al., 2014), a successful expansion of aquaculture in different species groups is likely to create a new market demand (such as the farming of introduced crayfish in China) or satisfy the demands of a diverse consumer market. This, in turn, could stimulate further growth in aquaculture production with the expansion of the consumer market. In Africa, on the other hand, diversification of any type has no impact on production, and there is an indication of a negative (not significant) relationship between within-group diversification and production. This could be due to the small and subsistence type of operations (Beveridge et al., 2013), under-utilized resources, poor infrastructure and technologies (Machena and Moehl, 2001), and low preferences/consumption of seafood (Cai and Leung, 2022) that make it difficult for African countries to create synergy in production while farming different species.

For responses to its own changes (i.e., production to production, ENS_α to ENS_α, ENS_β to ENS_β), the model results show that the responses of production to a change in production take a long time to subside. Especially in Asia and Africa, large positive effects remained for 10 years. This demonstrates that increase in aquaculture production is a long-term investment (e.g., additional farm site, upgrade infrastructure, market development), and impacts on aquaculture production are long lasting. Responses of within-species diversification to its own changes also take a long time to subside to almost zero for all regions except Asia, where the responses remain positive after 10 years. This demonstrates that spillover in within-species diversification is occurring in Asia. For example, spillover in technology for similar species and economies of scale in value chain that contribute to the highest ENS_α in Asia across all regions (Fig. 3). Responses of between-group diversification to its own changes subside in about 5–8 years for all regions but the Americas, where the responses remain positive after 8 years. This shows that spillover in between-group diversification is occurring in the Americas, which is coincident with the highest ENS_β in the Americas across the 5 regions (Fig. 4). This may result from the long history of aquaculture diversification efforts in South America that involve different species groups including molluscs in the 1950s, tilapias and other freshwater fishes in the 1970s, shrimp between late 1960s and early 1990s, and salmon in the 1960s through the present (Wurmann and Routledge, 2017). In North America, diversification is mostly driven by economic opportunities in the foreign markets that demand aquaculture species that are not consumed locally, such as sea cucumber, sea urchin, and seaweeds, which enhances diversification into different species groups (Cross et al., 2017).

An increase in between-group diversification leads to higher within-group diversification (only in Asia) but not vice versa. Increasing within-

Table 2
Variance decomposition (10 years effect) for world and regions.

	Production	ENS_α	ENS_β
World			
Production	86.2%	0.3%	13.5%
ENS_α	10.4%	80.0%	9.6%
ENS_β	0.01%	0.8%	99.2%
Asia			
Production	79.8%	4.2%	16.1%
ENS_α	15.3%	65.6%	19.2%
ENS_β	0.2%	0.7%	99.1%
Europe			
Production	65.9%	32.0%	2.1%
ENS_α	22.3%	70.4%	7.3%
ENS_β	4.5%	4.4%	91.1%
The Americas			
Production	66.5%	0.5%	33.0%
ENS_α	10.3%	82.9%	6.9%
ENS_β	15.9%	1.9%	82.2%
Africa			
Production	97.4%	2.5%	0.1%
ENS_α	0.7%	97.6%	1.7%
ENS_β	0.3%	1.0%	98.7%

Note: The contribution of column variable to the 10 periods ahead forecast error variance of row variable.

group diversity (i.e., more even distribution of production within a species group or adding a new species within a species group) does not lead to a higher number of species groups. This can be attributed to the additional start-up resources and different infrastructure and skills required for initiating the farming of a new species group. However, an increase in between-group diversity, such as adding a new species group, can foster greater within-group diversity within the newly developed species group. This can be attributed to the improved understanding of associated infrastructures, technological know-how, and market development when introducing a new species group, thereby facilitating the development of new species within that species group. As demonstrated in Cai et al. (2023), more countries in Asia than other regions have both relatively high between-group diversity and within-group diversity, reflecting the abundant and diverse natural resources are conductive to high species diversity. Our model result discovers the causal relationship between between-group and within-group diversity; a successful development of new species group in Asia would lead to more species diversification within species group.

Table 2 shows the variance decomposition derived from the PAVR models. The results are similar to the OIRFs results discussed earlier. The table shows the contribution of impulse variables (columns) to the 10-year forecast error variance of response variables (rows). Within-group diversification explains 32.0% of the variance in production in Europe and 4.2% in Asia. Bigger impacts on production are from between-group diversification which explains 13.5% of the variance in production in the world, 33.0% in the Americas, and 16.1% in Asia. It is important to note that only in the Americas does production explain variations in between-group diversification (15.9%) with a negative relationship. Although the negative relationship is not significant at 95% confidence level, it is significant at 90% level (Appendix D). This demonstrates that higher aquaculture production leads to lower diversification between species groups in the Americas. This is possible when resources are drawn away from developing new species groups as production on the existing species is expanding.

4. Conclusion and discussion

The future prospects of capture fisheries are considered saturated (Delgado et al., 2003), and the fisheries are impacted by many factors such as over-exploitation (Muir and Young, 1998), climate change (Cheung et al., 2013; Lam et al., 2020; Sumaila et al., 2011), habitat destruction (Delgado et al., 2003), and governance (Garcia and Rosenberg, 2010). The role of aquaculture is becoming increasingly important to support increasing seafood demand (Costello et al., 2020; Diana, 2009; Kobayashi et al., 2015). Therefore, sustainable development and management of aquaculture production and diversification are essential to our future food supply. The past three decades have shown that aquaculture production and diversification patterns vary by region. This is reasonable as each country has unique natural resources, technologies, infrastructure, government policies, and consumer preferences. The PVAR models developed in this study reveal the dynamic and causal relationships of aquaculture production and diversification at global and regional levels. Separating diversification by within and between species groups provides deeper insights into diversification strategies. The results show that between-group diversification is more conducive to production expansion globally, especially in the Americas and Asia, and the positive effects are long lasting. Within-group diversification also induces more production in Europe and, to a lesser extent, in Asia. Therefore, policies and market incentives that promote diversification across different species groups in the Americas and Asia, and diversification within the same species group in Europe and Asia, are potential strategies to expand aquaculture production. Relative to within-group diversification, between-group diversification is more likely to add resilience to country and global food security as different species groups have different production systems and feed requirements (Troell et al., 2014). Different species groups are distinguished in consumer markets and can add price stability (Troell et al., 2014). Diversification also promotes resilience to climate change on food supply as it provides a form of insurance for unexpected events under different climate change scenarios (De Silva and Soto, 2009), and species in different groups are likely to be impacted by climate factors differently. On the other hand, within-group diversification is likely to succeed when development costs are manageable within existing operations but it runs the risk of crowding the market with similar niches (Muir and Young, 1998).

This study also reveals the less obvious relationships of production leading within-group diversification in Asia and Europe, but not in the Americas and Africa, and no relationship about production leading between-group diversification. A possible explanation is that as production expands, knowledge is gained along the way. Companies take advantage of scope economy and emerging technologies as production expands. By accumulating experience and building up capacities, spillover effects occur that facilitate species diversification. This could be why production leads within-group diversification in Asia and Europe but not the Americas and Africa, as the latter two regions have a shorter history of aquaculture development and therefore less accumulated experience. However, it would be easier to diversify within the same species group compared to diversifying to a different species group. The empirical results support this notion that production expansion does not lead to diversification between species groups. One policy implication is that policies that merely promote higher aquaculture production may tend to raise within-group diversify through capacity building, spillover effects, etc., but may not have a significant impact on between-group diversity. In addition, the negative impact of a production change on the between-group diversity in the Americas should be monitored. This analysis demonstrates that tradeoffs are happening in the Americas as resources are diverted to promote higher production and lead to lower between-group diversity.

Aquaculture is the most diversified food production system in the world with >600 species being farmed world-wide since 1950 (FAO, 2022). New successful aquaculture species could expand seafood markets (Asche et al., 2001; Yue et al., 2023) and strengthen our food system. As demand for seafood is expected to increase with economic development (Delgado et al., 2003; Kidane and Brækkan, 2021), this study provides important evidence that promoting diversification is likely to expand production and help to fulfill the future seafood demand. However, diversification requires research and resources to develop, especially for species in different species groups. These may require different technologies and production methods. Private and small businesses tend to focus on the more successful species, leading to lower diversification (Harvey et al., 2017). It is crucial for government to provide incentives, infrastructure, and technical assistance to promote aquaculture development and diversification. However, government also plays a role in limiting aquaculture diversification with regulations that prohibit the farming of non-native species. Balancing environmental concerns, government support, food security, and consumer preferences is essential for supporting the long-term sustainability and resilience of aquaculture development.

This study only looks at the relationship between production and diversification in terms of volume, and does not consider the tradeoff of production of higher value species for export versus lower value species for local consumption (Cojocaru et al., 2022). Other factors such as production costs and profit margins also affect production and diversification decisions. Adding these factors in future analyses could add further insights into the dynamic relationships between aquaculture production and diversification. However, these data are difficult to obtain on a global scale. Using the best available FAO data, this study is the first to examine the causation and interrelationships between aquaculture production and diversification at global and regional scales.

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Author statement

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CRediT authorship contribution statement

Hing Ling Chan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Junning Cai:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **PingSun Leung:** Conceptualization, Investigation, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. PVAR model results

Table A1
Estimated PVAR coefficients.

	Production	ENS_α	ENS_β
World (number of observations = 5649, number of countries = 208)			
Production $_{t-1}$	0.9500***	0.0534*	−0.0009
	(0.0173)	(0.0254)	(0.0062)
$ENS_{\alpha\ t-1}$	0.0317	0.7850***	0.0068
	(0.0323)	(0.0400)	(0.0098)
$ENS_{\beta\ t-1}$	0.4862***	0.2823	0.7411***
	(0.1331)	(0.1746)	(0.0468)
Asia (number of observations = 1386, number of countries = 48)			
Production $_{t-1}$	0.9494***	0.1234	−0.0037
	(0.0354)	(0.0880)	(0.0251)
$ENS_{\alpha\ t-1}$	0.0509	0.8109***	0.0046
	(0.0329)	(0.0764)	(0.0302)
$ENS_{\beta\ t-1}$	0.3997*	0.6966	0.7964***
	(0.1997)	(0.5262)	(0.1134)
Europe (number of observations = 1201, number of countries = 41)			
Production $_{t-1}$	0.7504***	0.2962*	0.0169
	(0.1328)	(0.1350)	(0.0567)

(continued on next page)

Table A1 (*continued*)

	Production	ENS_{α}	ENS_{β}
$ENS_{\alpha\ t\text{-}1}$	0.2309*	0.6012***	0.0105
	(0.1100)	(0.1376)	(0.0509)
$ENS_{\beta\ t\text{-}1}$	−0.1229	0.7589	0.6319
	(0.5048)	(0.7175)	(0.6123)
The Americas (number of observations = 1194, number of countries = 47)			
Production $_{t\text{-}1}$	0.9295***	0.0317	−0.0299
	(0.0383)	(0.0358)	(0.0270)
$ENS_{\alpha\ t\text{-}1}$	0.0119	0.7813***	0.0028
	(0.1257)	(0.0997)	(0.0655)
$ENS_{\beta\ t\text{-}1}$	0.4308	−0.1515	0.9100***
	(0.2236)	(0.1751)	(0.2349)
Africa (number of observations = 1407, number of countries = 53)			
Production $_{t\text{-}1}$	0.9419***	−0.0198	0.0031
	(0.0288)	(0.0200)	(0.0240)
$ENS_{\alpha\ t\text{-}1}$	−0.0592	0.7879***	0.0104
	(0.0596)	(0.0370)	(0.0325)
$ENS_{\beta\ t\text{-}1}$	−0.0181	0.1898	0.6571
	(0.3052)	(0.3410)	(0.4326)

Note: Standard errors in parentheses. ***$p < 0.001$; ** < 0.01; *$p < 0.05$. The world model includes Oceania (number of observations = 461, number of countries = 19).

Appendix B. Panel granger causality test

Conducted Panel Granger causality test using R package "plm": Linear Models for Panel Data. Excluded countries with <8 years of sample, and countries with the no diversification for the whole time series, meaning ENS_{α}, or ENS_{β} equals to 1, $N = 3211$. This is because Granger causality test is unable to identify causation between production and diversification without enough degrees of freedom and when there is no variation in diversification over time. While this excludes approximately 40% of the total sample, the PVAR model results demonstrate long-lasting effects between the variables of interest, ranging from a minimum 6 years to 10 years (Table 1). Consequently, excluding countries with <8-years sample does not compromise the integrity of the main results. Excluding countries with no diversification for the whole time series also does not compromise the integrity of the main results as countries with and without diversification over time are included in the PVAR models.

Table B1
Panel Granger (non-)causality test (Ztilde value[1]).

	Production-led hypothesis	ENS_{α}-led hypothesis	ENS_{β}-led hypothesis
Production	–	9.7365**	7.2669**
ENS_{α}	7.7126**	–	6.7409**
ENS_{β}	5.8440**	5.4158**	–

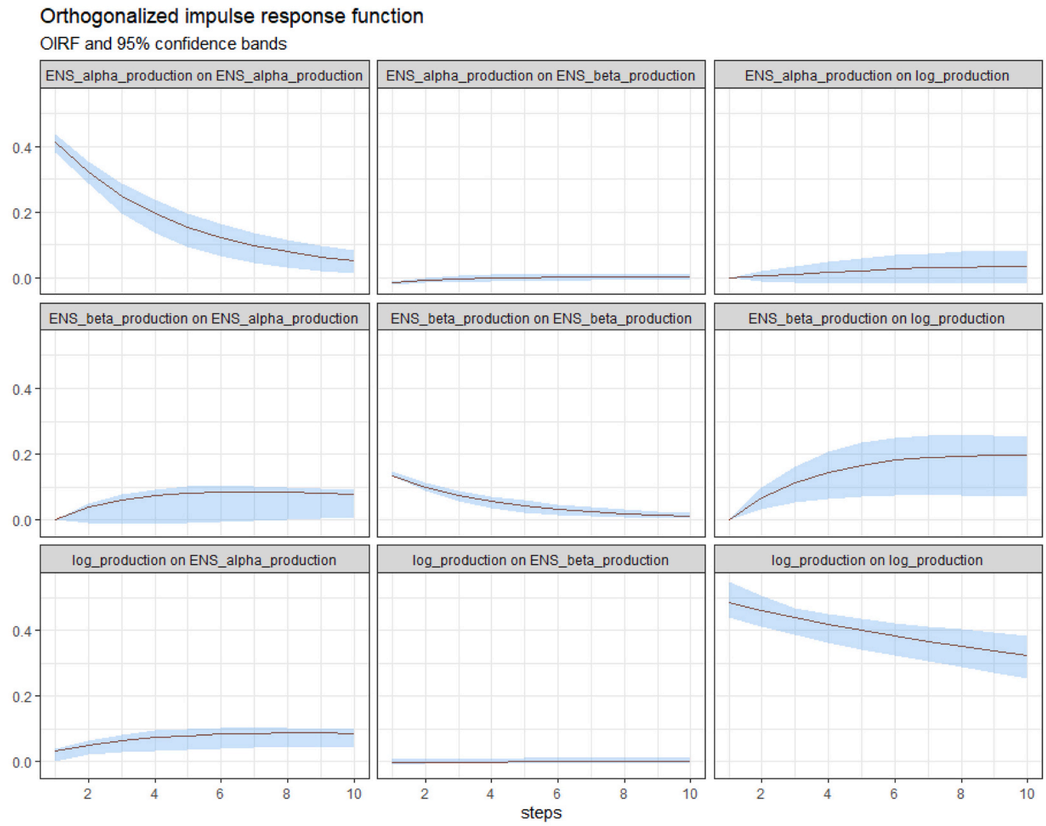
** $p < 0.01$.

[1] Ztilde value is the standardized statistic based on individual Wald statistics of Granger non causality averaged across cross-section units recommended in Dumitrescu and Hurlin (2012).

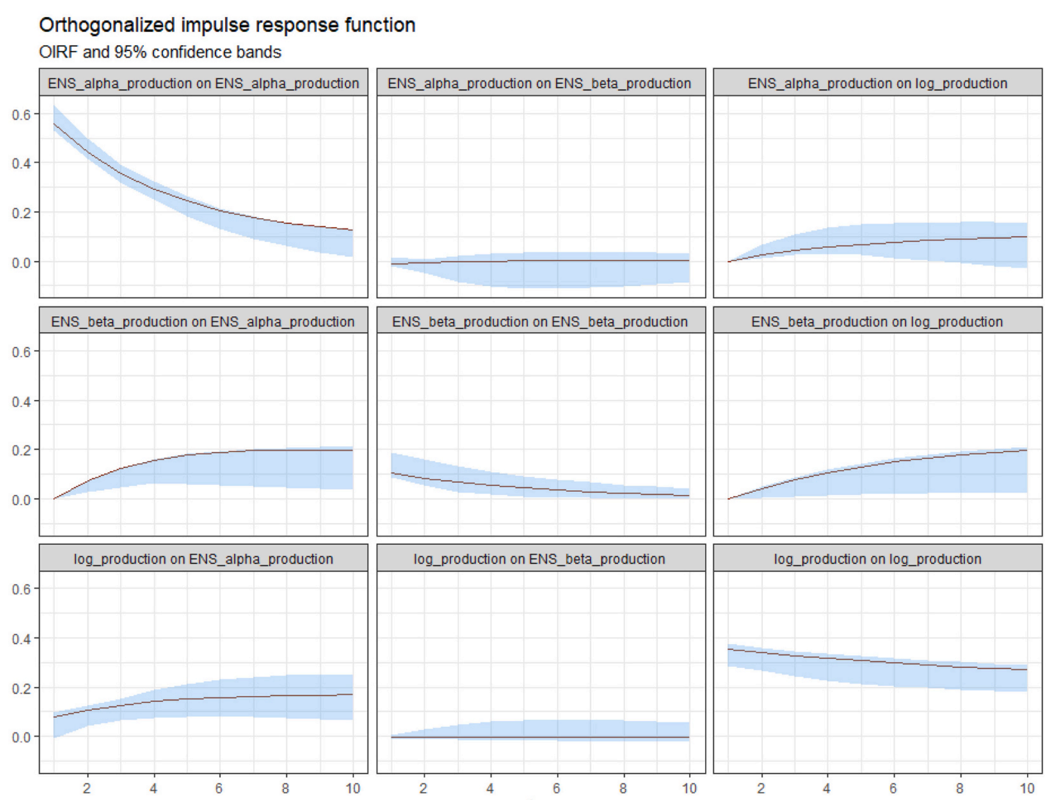
Dumitrescu, E., Hurlin, C., 2012. Testing for Granger non-causality in heterogeneous panels. Economic Modeling. 29 (4), 1450–1460. https://www.sciencedirect.com/science/article/pii/S0264999312000491.

Appendix C. Orthogonalized impulse response functions for the panel VAR model for (A) World, (B) Asia, (C) Europe, (D) the Americas, and (E) Africa

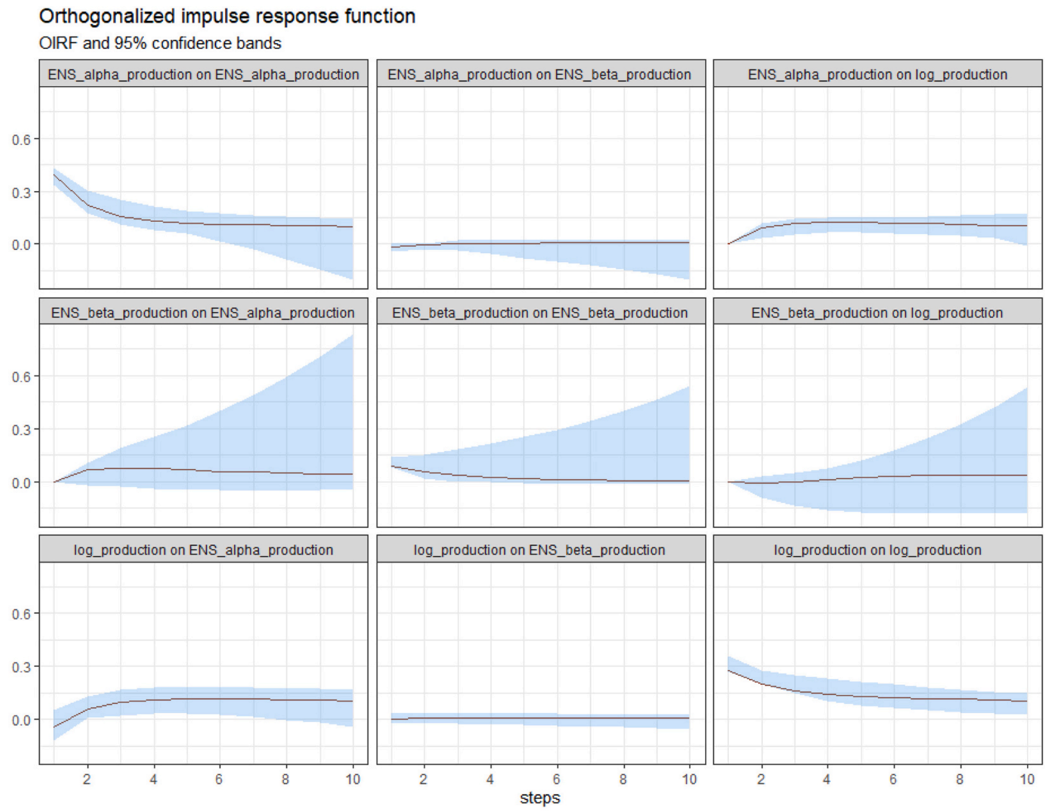
The nine plots in each figure represents the responses of the response variable (OIRF) to a change in the respective impulse variable by one standard deviation (Y-axis), for year 1 to 10 (X-axis), holding other variable constant. For example, the plot labeled "ENS_alpha on log_production" represents the responses of production to a one standard deviation change in ENS_{α} for year 1 to 10, holding ENS_{β} constant. The shaded area represents the 95% confidence interval bands, where a positive OIRF with the lower bound above the zero line representing a significant positive response and a negative OIRF with the upper bound below the zero line representing a significant negative response.



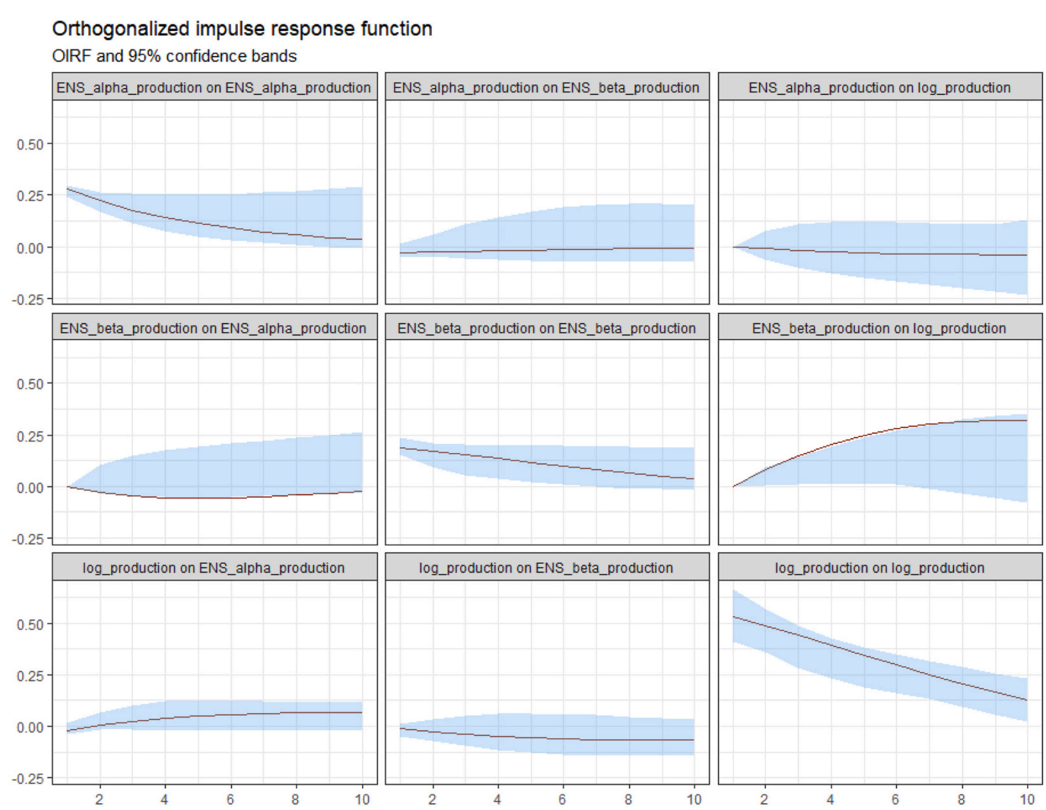
(A) World



(B) Asia

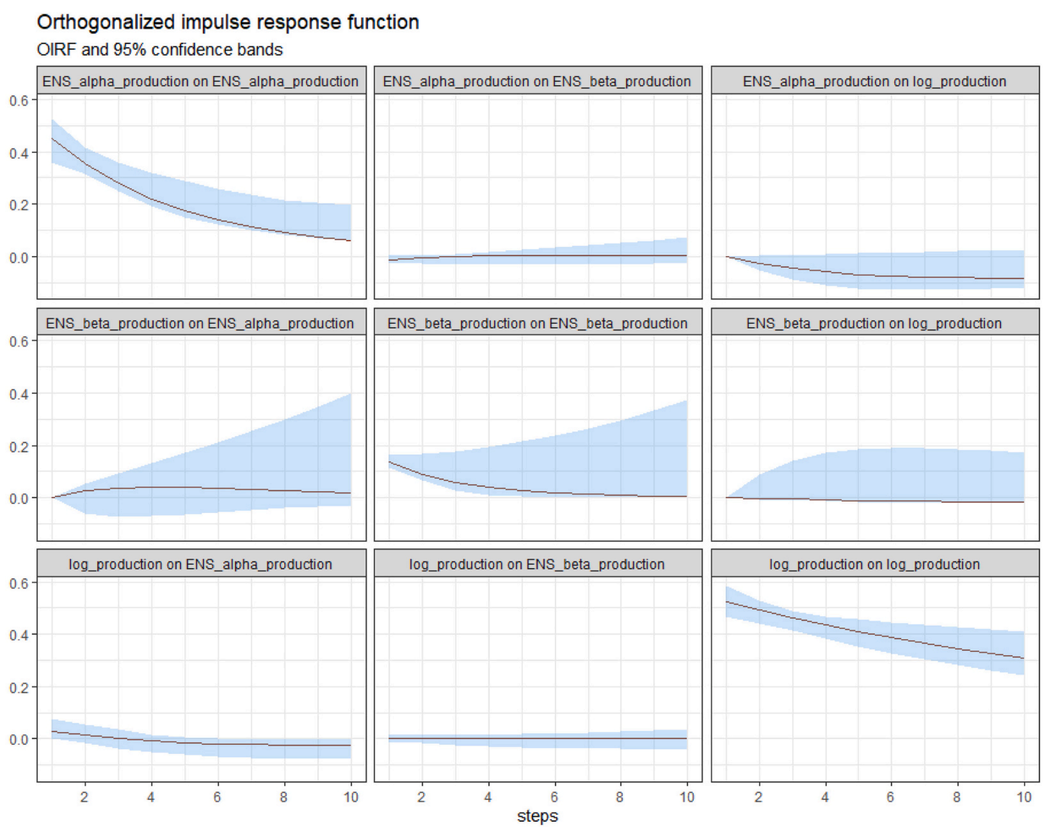


(C) Europe



(D) The Americas

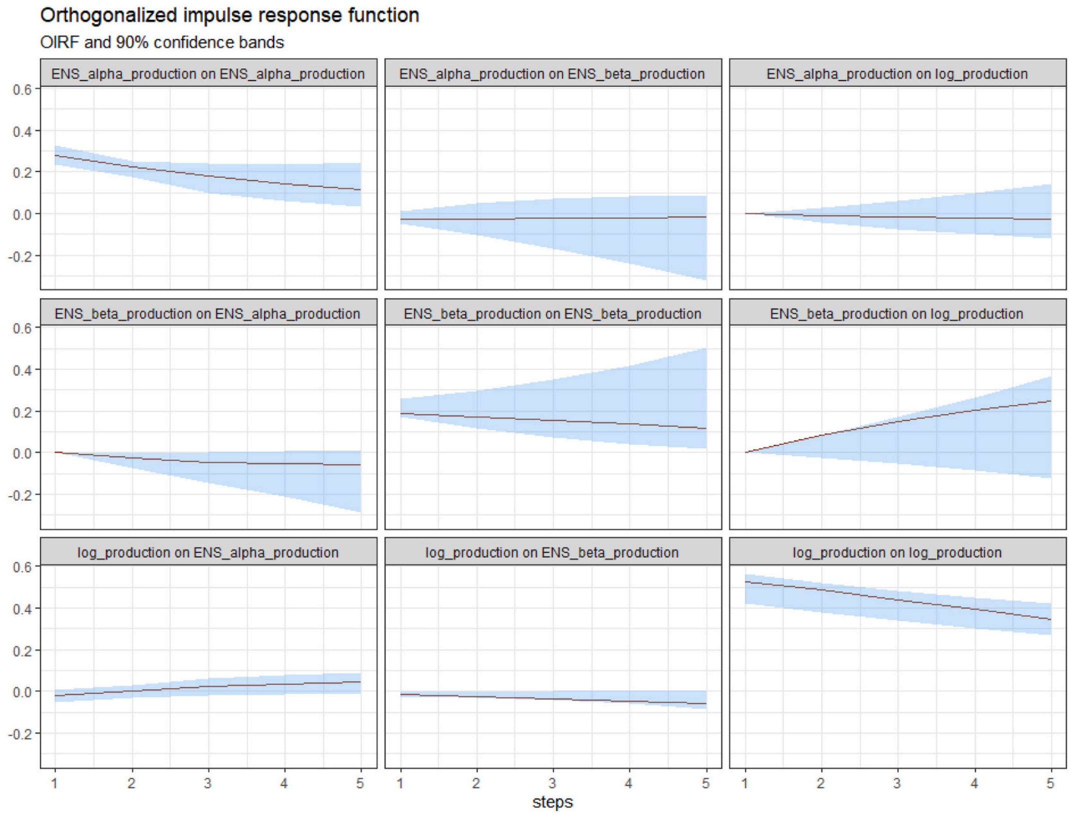
. (*continued*).



(E) Africa

. (*continued*).

Appendix D. OIRF for the Americas model at 90% confidence



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