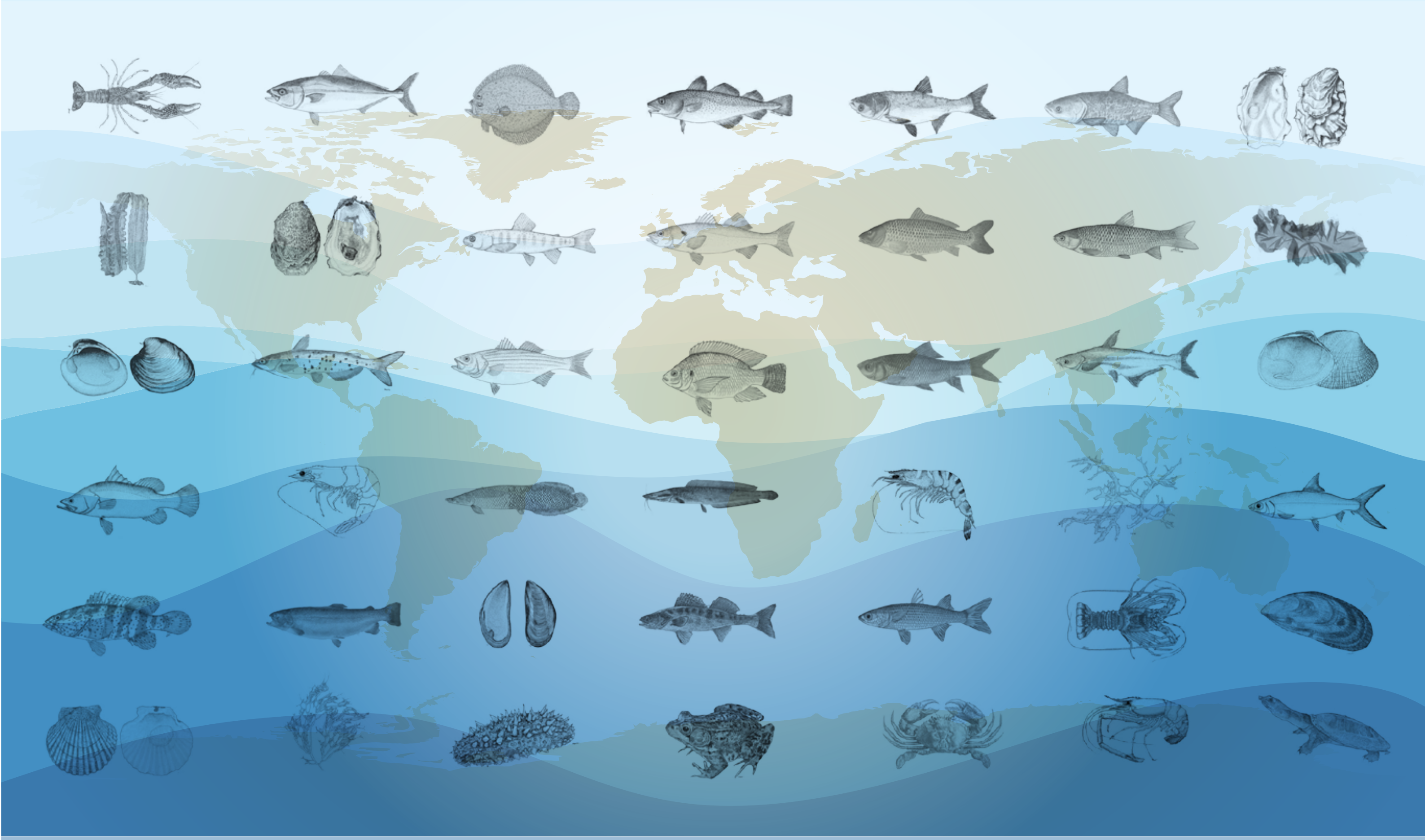
Food and Agriculture
Organization of the
United Nations

FAO
FISHERIES AND
AQUACULTURE
TECHNICAL
PAPER

605

ISSN 2070-7010

Benchmarking species diversification in global aquaculture



***Cover design*:**
José Luis Castilla Civit

Benchmarking species diversification in global aquaculture

FAO
FISHERIES AND
AQUACULTURE
TECHNICAL
PAPER

605

by

Junning Cai
Aquaculture Officer
FAO Fisheries and Aquaculture Division
Rome, Italy

Xue Yan
Associate Research Fellow
Chinese Academy of Fishery Sciences (CAFS), Beijing, China
Chinese Academy of Sciences, Beijing, China
University of Chinese Academy of Sciences, Beijing, China

and

PingSun Leung
Professor Emeritus
University of Hawai'i at Manoa
Honolulu, United States of America

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2022

Required citation:
Cai, J.N., Yan, X. and Leung, P.S. 2022. *Benchmarking species diversification in global aquaculture*. FAO Fisheries and Aquaculture Technical Paper No. 605. Rome, FAO. https://doi.org/10.4060/cb8335en

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISSN 2070-7010 [Print]
ISSN 2664-5408 [Online]

ISBN 978-92-5-135642-5
© **FAO,** 2022

Some rights reserved. This work is made available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo/legalcode).

Under the terms of this licence, this work may be copied, redistributed and adapted for non-commercial purposes, provided that the work is appropriately cited. In any use of this work, there should be no suggestion that FAO endorses any specific organization, products or services. The use of the FAO logo is not permitted. If the work is adapted, then it must be licensed under the same or equivalent Creative Commons licence. If a translation of this work is created, it must include the following disclaimer along with the required citation: “This translation was not created by the Food and Agriculture Organization of the United Nations (FAO). FAO is not responsible for the content or accuracy of this translation. The original [Language] edition shall be the authoritative edition.”

Disputes arising under the licence that cannot be settled amicably will be resolved by mediation and arbitration as described in Article 8 of the licence except as otherwise provided herein. The applicable mediation rules will be the mediation rules of the World Intellectual Property Organization http://www.wipo.int/amc/en/mediation/rules and any arbitration will be conducted in accordance with the Arbitration Rules of the United Nations Commission on International Trade Law (UNCITRAL).

Third-party materials. Users wishing to reuse material from this work that is attributed to a third party, such as tables, figures or images, are responsible for determining whether permission is needed for that reuse and for obtaining permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

Sales, rights and licensing. FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org. Requests for commercial use should be submitted via: www.fao.org/contact-us/licence-request. Queries regarding rights and licensing should be submitted to: copyright@fao.org.

Preparation of this document

This document is a technical paper under the FAO Fisheries and Aquaculture Division's initiative on the World Aquaculture Performance Indicators (WAPI). The paper enhances the understanding and measurement of species diversification in global aquaculture and facilitates the utilization of diversification indicators in policy and planning for sustainable aquaculture development. Xiaowei Zhou is acknowledged for his effort in improving FAO statistics on global aquaculture production and for sharing his insights regarding species diversification in global aquaculture. Renata Melon Barroso, Devin Bartley, Malcolm Beveridge, Randall Brummett, Emmanuel A. Frimpong, Audun Lem, Francisco Javier Martínez-Cordero, Weimin Miao, Doris Soto, Athanasius Ssekyanzi, Chen Sun, Xinhua Yuan and Wenbo Zhang are acknowledged for their peer review of the paper. Maria Giannini and Marianne Guyonnet are acknowledged for their assistance in editing and formatting, and José Luis Castilla is acknowledged for layout and graphic design.

Abstract

While diversified aquaculture could reduce both biological and financial risks, the private sector may lack incentives to diversify the species composition of aquaculture production because developing or adopting new species tends to be costly and risky. Conversely, concentrating on the most efficient species can benefit from economies of scale in both production and marketing. With ever-growing concerns over climate change, disease outbreaks, market fluctuations and other uncertainties, species diversification has become an increasingly prominent strategy for sustainable aquaculture development. Policy and planning on species diversification require a holistic, sector-wide perspective to assess the overall prospect of individually promising species that may not be entirely successful when competing for limited resources and markets. The historical experiences of species diversification in global aquaculture can provide guidance for the assessment. This paper develops a benchmarking system to examine species diversification patterns in around 200 countries for three decades to generate information and insights in support of evidence-based policy and planning in aquaculture development. The system uses "effective number of species" (ENS) as a diversity measure that is essentially equivalent to, yet more intuitive than, the widely used Shannon Index. A statistical model is established to estimate a benchmark ENS for each country and construct a benchmarking species diversification index (BSDI) to compare a country's species diversification with global experiences. Key results are presented and discussed in the main text; and more comprehensive results are documented in Appendix II. The benchmarking system can be used in foresight analyses to help design or refine future production targets (including species composition) in policy and planning for aquaculture development; an example is provided in Appendix I to help practitioners better understand and utilize the system.

Contents

Figures

Tables

Appendix I:

Appendix II:

Abbreviations and acronyms

ASFIS	Aquatic Sciences and Fisheries Information System
BSDI	benchmarking species diversification index
ENS	effective number of species
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
IMF	International Monetary Fund
ISSCAAP	International Standard Statistical Classification of Aquatic Animals and Plants
nei	not elsewhere included
PPP	purchasing power parity
WEO	World Economic Outlook

1. Introduction

Species diversification in aquaculture is a strategy favourable to many policy-makers and practitioners who believe that species diversification would lead to more sustainable aquaculture development; see, for example, the experiences in Mexico (Martínez-Cordero, 2007), Egypt (Megahed and Mesalhy, 2009), the Mediterranean (Abellán and Basurco, 1999), Africa (Brummett, 2007), Asia (Liao, 2000; Davy, 2017), Europe with a focus on Norway and Spain (Fernández-Polanco and Bjorndal, 2017), South America with a focus on Brazil and Chile (Wurmann and Routledge, 2017), North America (Cross, Flaherty and Byrne, 2017), and global aquaculture (Metian *et al*., 2020). With ever-growing concerns over climate change, disease outbreaks, market fluctuations and other uncertainties, the popularity of aquaculture species diversification tends to increase (Harvey *et al*., 2017).

Species diversification in aquaculture is under the influence of many factors that have both pros and cons (Le Francois *et al*., 2010; Harvey *et al*., 2017). In places where consumers have high preferences for various aquatic foods (e.g. Eastern and South-eastern Asia) and are willing to pay for variety, aquaculturists have incentives to try out new species in order to gain competitive advantage and expand the market. Additionally, diversified aquaculture could also enhance production efficiency (e.g. through polyculture or farming different species according to seasonality) and reduce both biological risks (e.g. diseases) and financial risks (e.g. price variations) (Wilson and Archer, 2010).

It has been observed, however, that the private sector generally lacks incentives to diversify the species composition of aquaculture production (Harvey *et al*., 2017) because concentrating on the most efficient species can derive benefits from economies of scale in both production and marketing, whereas developing or adopting new species tends to be costly and risky and may dilute resources and effort in research and development (New, 1999). The public sector is keener to pursue species diversification in aquaculture, yet many public efforts in developing new species to be farmed have been primarily driven by research interests, and few have become commercially viable (Wurmann and Routledge, 2017). Additionally, including more species in aquaculture could cause more widespread impacts on biodiversity through escapees and the use of wild seed resources (Bilio, 2008).

As developing new species to be farmed tends to be time consuming and financially costly, it is essential for policy-makers and planners to assess the prospects of successful commercialization of new species. While individual proposals or projects focus on the technical and market prospects of selected species based on various selection methods or criteria (Leung, Lee and O'Bryen, 2007; Le Francois *et al*., 2010; Suquet, 2010; Alvarez-Lajonchère and Ibarra-Castro, 2013), policy-makers and planners need to assess the overall prospect of potential species from a sector-wide perspective. The historical experiences of species diversification in global aquaculture could provide useful information and guidance to address this challenging task.

This paper examines the status and trends of species diversification in global aquaculture and establishes a benchmarking system to facilitate the comparison of species diversification patterns across countries (including non-sovereign territories).[1] The benchmarking results can provide points of reference to facilitate evidence-based policy and planning in sustainable aquaculture development. Section 2 uses

---

[1] For narrative convenience, in this document the term country includes non-sovereign territory.

"effective number of species" as a diversity measure that is essentially equivalent to yet more intuitive than the more widely used Shannon-Wiener-Weaver (entropy) index (Shannon index in short). Section 3 uses the diversity measure to provide an overview of species diversification in global aquaculture covering around 200 countries over a period of three decades (1988–2018). Based on global experiences, Section 4 examines the correlation between aquaculture production and species diversity and develops a statistical model to estimate the relationship between aquaculture species diversity and multiple factors. Using a modified version of the statistical model, Section 5 constructs two benchmarking indicators to compare a country's species diversification with global experiences. Section 6 concludes the paper with a summary of the key results and discussion on how the methods and results can be used for evidence-based policy and planning in aquaculture development. A numerical example is provided in Appendix I to help practitioners better understand and utilize the benchmarking indicators, and comprehensive results for individual countries are presented in Appendix II.

2. Measuring species diversity in aquaculture

2.1 DATA ON AQUACULTURE PRODUCTION

This paper uses aquaculture production data from the Food and Agriculture Organization of the United Nations (FAO) Global Aquaculture Production Statistics 1950–2018 (FAO, 2020a), which is the only global aquaculture production database readily available. Reporting entities in the database are denoted as countries, which include non-sovereign territories. While the database reports aquaculture production for mainland Tanzania and Zanzibar as separate reporting entities, they are aggregated into the United Republic of Tanzania to facilitate the statistical analyses in Section 4 and Section 5.[2] The scope of other countries in the database is adopted in this document; e.g. China refers to mainland China.

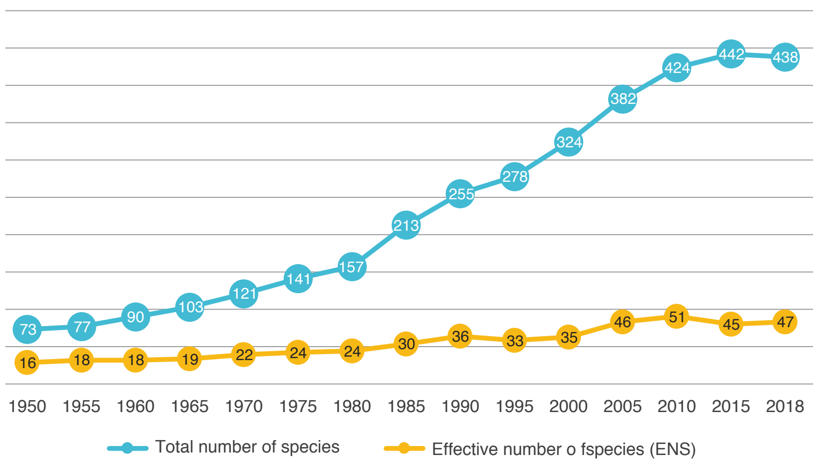
All ASFIS (Aquatic Sciences and Fisheries Information System) species items recorded in the database are covered, including eight ISSCAAP[3] divisions (i.e. marine fishes, freshwater fishes, diadromous fishes, crustaceans, molluscs, miscellaneous aquatic animals, miscellaneous aquatic animal products and aquatic plants). These species items could refer to either individual species, hybrids or groups of related species (e.g. families) when identification to species was not recorded (FAO, 2020b; Metian *et al.*, 2020).

2.2 TOTAL NUMBER OF SPECIES

The total number of ASFIS species items recorded in FAO statistics on global aquaculture increased from 73 in 1950 to 438 in 2018; the upward trend appeared to level off in the 2010s (Figure 1). It is important to note that an increase in the number of ASFIS species items in FAO statistics could reflect data improvement (e.g. an aggregate

FIGURE 1

Total number of species versus effective number of species in world aquaculture, 1950–2018



---

[2] Time series of population data, which are needed for the statistical analyses, are available in the United Nations population database (United Nations, 2019) for the United Republic of Tanzania, but not separately for mainland Tanzania or Zanzibar.

[3] ISSCAAP = International Standard Statistical Classification of Aquatic Animals and Plants.

"not elsewhere included" [nei] item being separated into individual species). On the other hand, as the production of new aquaculture species may be included in nei items because of their relatively small magnitude, ASFIS species items recorded in FAO statistics tend to underestimate the number of new species introduced in aquaculture. For example, while it was reported that over 200 aquaculture species were farmed in China (FAO, 2017), only 89 ASFIS species items were recorded in FAO statistics on aquaculture production in China (FAO, 2020a). More discussion on data imperfections and their implications can be found in the last section.

2.3 EFFECTIVE NUMBER OF SPECIES

There are different dimensions and measures of species diversity (Purvis and Hector, 2000). In this study, species diversity is measured by the "effective number of species" (ENS) defined as

$$\mathrm{ENS} = e^{-\sum_{i=1}^{n} s_i \ln(s_i)}, \tag{1}$$

where n denotes the total number of species, and s_i represents the share of species i in the production of all species. This indicator is essentially equivalent to the Shannon index, which is defined as $-\sum_{i=1}^{n} s_i \ln(s_i)$, i.e. the summation term in equation (1). The Shannon index is a widely used measure of species diversity, and it has been used in a recent study to map species diversity in global aquaculture (Metian *et al.*, 2020).

While the total number of species (n) measures the richness of species composition, the ENS defined in equation (1) captures both richness and evenness. Ranging between 1 and n, the ENS would be equal to n when the production is evenly distributed across all species, whereas it would be closer towards 1 as the lower bound when the distribution of production across species becomes more concentrated. This property makes the ENS a more intuitive diversity measure than the Shannon index (Hill, 1973). For example, when aquaculture production is evenly distributed between two species, the effective number of species would be 2, which is equal to the total number of species. When aquaculture production is dominated by one species with a trivial contribution from the other species, the effective number of species would be close to 1, which reflects that the production is effectively contributed by one species.

The ENS in world aquaculture increased from 16 to 47 between 1950 and 2018; the upward trend was much flatter than that of the total number of species (Figure 1). The two indicators mostly moved in the same direction with a few exceptions. For example, while the total number of species increased from 424 to 442 between 2010 and 2015, the ENS nevertheless declined from 51 to 45 (Figure 1).

3. Overview of species diversification in global aquaculture

In this section, ENS is used to examine species diversification patterns in around 200 countries during recent decades (1988–2018). The overview lays a foundation for more in-depth analysis of species diversification in Section 4.

3.1 INCREASING YET DECELERATING SPECIES DIVERSIFICATION IN GLOBAL AQUACULTURE

World aquaculture production increased from 16 million tonnes to 115 million tonnes between 1988 and 2018 with a clear pattern of species diversification – 158 countries (accounting for 83.4 percent of world production) had an increased ENS between 1988 and 2018 compared with only 34 countries where ENS declined (Table 1).

TABLE 1
Aquaculture species diversification patterns, 1988–2018

Period	Effective number of species (ENS) in aquaculture					
	Increased		Declined		Unchanged	
	Number of countries	Share of world aquaculture production during the period (%)	Number of countries	Share of world aquaculture production during the period (%)	Number of countries	Share of world aquaculture production during the period (%)
1988–2018	**158**	**83.4**	**34**	**16.6**	**5**	**0.0067**
1988–1998	113	91.9	40	8.0	17	0.0217
1998–2008	126	79.0	57	21.0	5	0.0014
2008–2018	111	20.3	82	79.7	4	0.0001

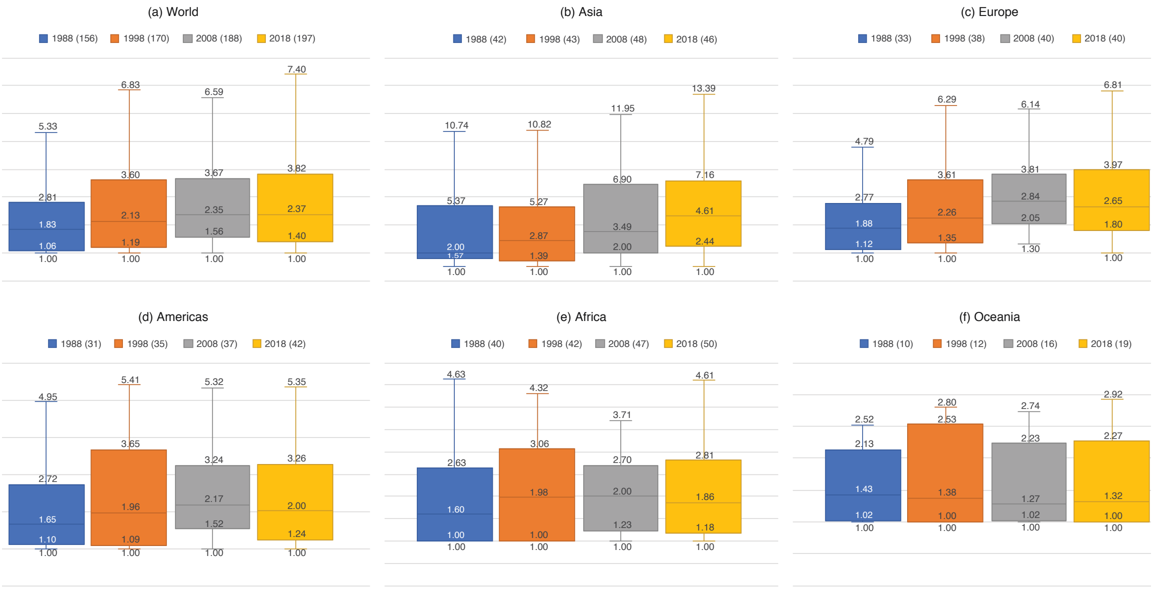
A similar pattern also occurred in the first two sub-decades (1988–1998 and 1998–2008), yet with a decelerating rate of species diversification (Table 1). During the last sub-decade (2008–2018), 111 countries had an increased ENS compared with 82 countries with a declined ENS. The 82 countries accounted for 79.7 percent of world production (Table 1) because the ENS of China (accounting for around 60 percent of world production) had reduced slightly from 28.2 to 27.7 between 2008 and 2018.[4]

Box and whisker plots were used to compare ENS over time (Figure 2) and across regions (Figure 3); see notes in Figure 2 on how to interpret the plots. Globally, almost all the four quartile ENS increased between 1988 and 2018 as well as within the three sub-periods (Figure 2-a), which indicates a clear pattern of increased species diversification in global aquaculture.

---

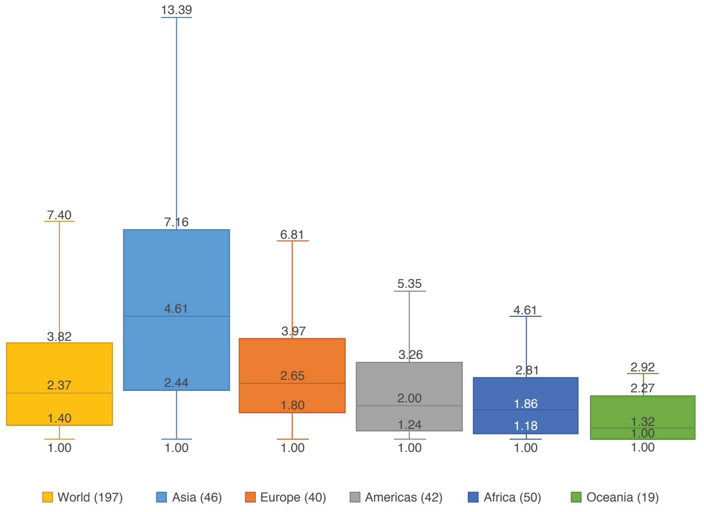
[4] The total number of ASFIS species items in China's aquaculture production during 2008–2018 remains stable in FAO statistics (around 85). Therefore, the decrease in the ENS of China between 2008 and 2018 reflects a slight decline in the evenness of the distribution of China's aquaculture production among the recorded species items. As the total number of ASFIS species items understates the richness of species composition in China's aquaculture production (see discussion in Section 2.2), the ENS variation may not adequately capture the appearance of new species in China's aquaculture.

FIGURE 2
Box and whisker plots of ENS at global and regional levels, 1988–2018



Notes: The five numerical labels in each bar from bottom to top represent, respectively, the minimum, the first quartile (25 percent), the median (50 percent), the third quartile (75 percent) and the "maximum" effective number of species (ENS) excluding the "outliers". Such outliers are extraordinarily large ENS with distance from the third quartile greater than 1.5 times of the height of the box (i.e. distance between the third quartile and the first quartile). The outliers are not shown in the chart for clarity but presented in Table 2. In the legends, numbers in the parentheses represent the number of countries in each region (including outliers).

FIGURE 3
Box and whisker plots of ENS across regions, 2018



Notes: This is a compilation of the box and whisker plots for 2018 in Figure 2. ENS = effective number of species.

3.2 REGIONAL DIFFERENCES IN AQUACULTURE SPECIES DIVERSIFICATION

Regionally, only Asia (Figure 2-b) and Europe (Figure 2-c) had a relatively clear pattern of increased quartile ENS during 1988–2018, whereas there were no obvious patterns for the Americas (Figure 2d), Africa (Figure 2-e) or Oceania (Figure 2-f). The box and whisker plots in Figure 3 indicate a clear regional variation in aquaculture species diversity: the highest was in Asia, followed by Europe, the Americas and Africa, and the lowest was in Oceania.

In 2018, ENS in a quarter of the total 197 countries (i.e. the first quartile) was no more than 1.4; ENS in half of these countries (i.e. the second quartile or median) was no more than 2.37; and ENS in three quarters of these countries (i.e. the third quartile) was no more than 3.82 (Figure 3). The 2018 median ENS in Asia (the largest aquaculture region accounting for over 90 percent of world production) was 4.61 (nearly twice as much as the world median). The 2018 median ENS in Europe was also higher than the world median, whereas in the Americas, Africa and Oceania it was lower (Figure 3).

3.3 COUNTRIES/TERRITORIES WITH EXTRAORDINARILY LARGE EFFECTIVE NUMBER OF SPECIES

Table 2 presents 17 extraordinarily large ENS (called "outliers" for narrative convenience), including 11 outliers at the global level and nine at the regional level, among which China in Asia and Portugal and the Russian Federation in Europe were both global and regional outliers (Table 2 compared with Figure 3). Among the 17 global and/or regional outliers, only China and Bangladesh had aquaculture production higher than 1 percent of the world total, yet six countries had a population greater than 1 percent of the world total, namely China, Bangladesh, Japan, the Russian Federation, the United States of America and Nigeria (Table 2).

TABLE 2

Extraordinarily large (i.e. outlier) ENS in global and regional aquaculture, 2018

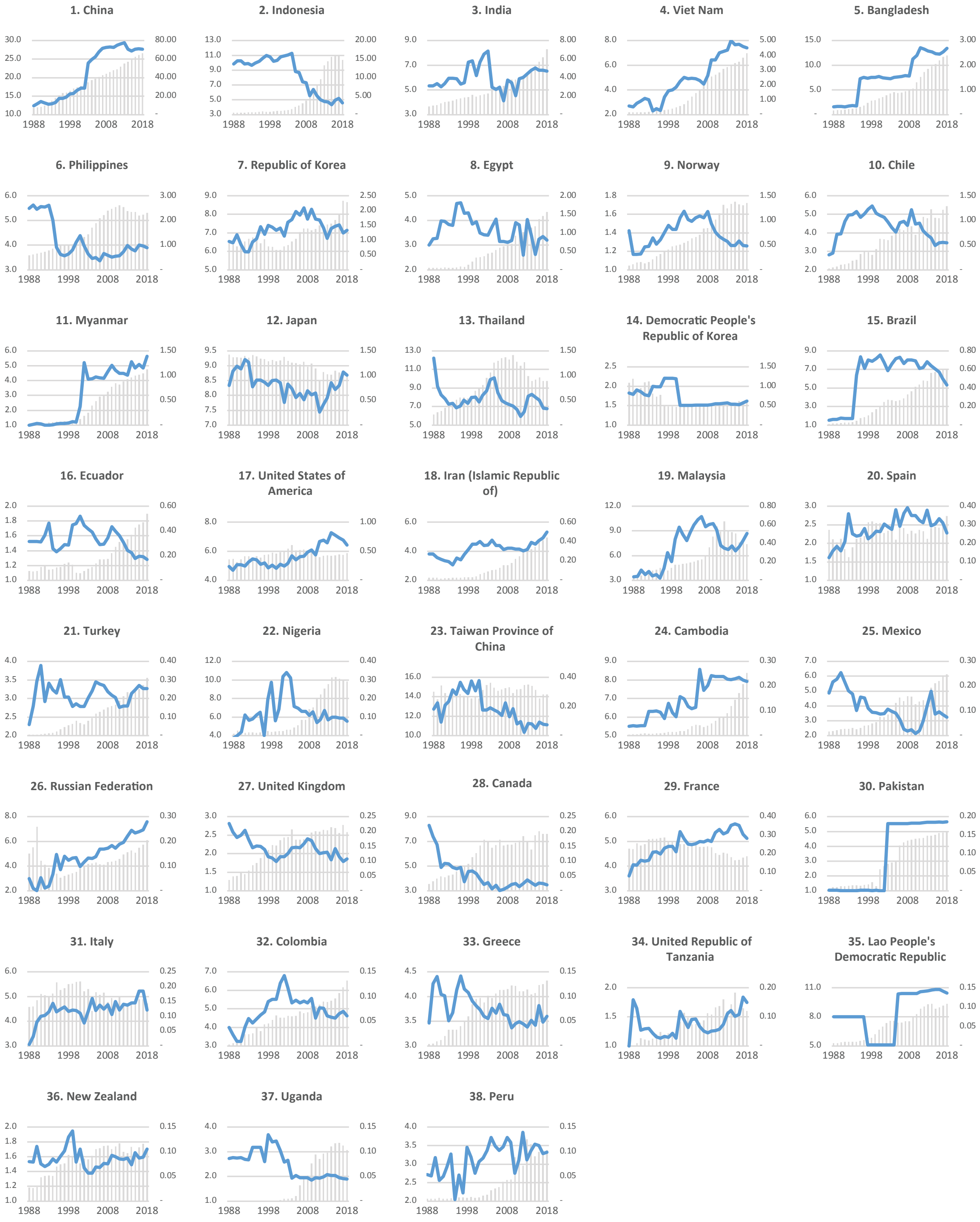
Country/territory	Outlier category	Total number of species	Effective number of species (ENS)	Share of world	
				Aquaculture production (%)	Population (%)
Asia					
China	Global and regional	85	27.67	57.756	18.71
Bangladesh	Global	31	13.39	2.101	2.11
Taiwan Province of China	Global	45	11.13	0.248	0.31
Lao People's Democratic Republic	Global	14	10.47	0.094	0.09
Singapore	Global	44	10.45	0.005	0.08
Japan	Global	28	8.69	0.902	1.67
Malaysia	Global	47	8.67	0.342	0.41
Cambodia	Global	25	7.91	0.222	0.21
China, Hong Kong SAR	Global	16	7.62	0.004	0.10
Europe					
Portugal	Global and regional	20	8.16	0.010	0.13
Russian Federation	Global and regional	28	7.58	0.178	1.91
Americas					
Dominican Republic	Regional	11	6.96	0.002	0.14
United States of America	Regional	28	6.42	0.409	4.29
Africa					
Nigeria	Regional	16	5.54	0.254	2.57
Morocco	Regional	7	5.52	0.001	0.47
South Africa	Regional	29	5.35	0.007	0.76
Oceania					
Australia	Regional	19	4.21	0.085	0.33

Notes: See the notes in Figure 2 on the criterion used to designate extraordinarily large ENS (called "outlier" for narrative convenience).

3.4 COUNTRIES/TERRITORIES WITH LARGE AQUACULTURE PRODUCTION

ENS trends in the top 38 countries/territories with the largest aquaculture production in 2018 (no less than 100 000 tonnes) are presented in Figure 4. Most of these 38 countries/territories increased their aquaculture production during the period, with Japan (ranked 12), the Democratic People's Republic of Korea (14), Taiwan Province of China (23) and France (29) being the only four exceptions. Most of the 38 countries/territories increased their ENS during the period, except for 11 cases of a lower ENS in 2018 than in 1988, namely Indonesia (2), the Philippines (6), Norway (9),

FIGURE 4
ENS trends in large aquaculture countries/territories, 1988–2018



Notes: Including the top 38 countries/territories with the greatest aquaculture production in 2018 (no less than 100 000 tonnes; they are indexed according to production in descending order). A solid line depicts the trend of effective number of species (ENS, left y-axis) between 1988 and 2018 (x-axis); the corresponding bars show the trend of aquaculture production (right y-axis, million tonnes).

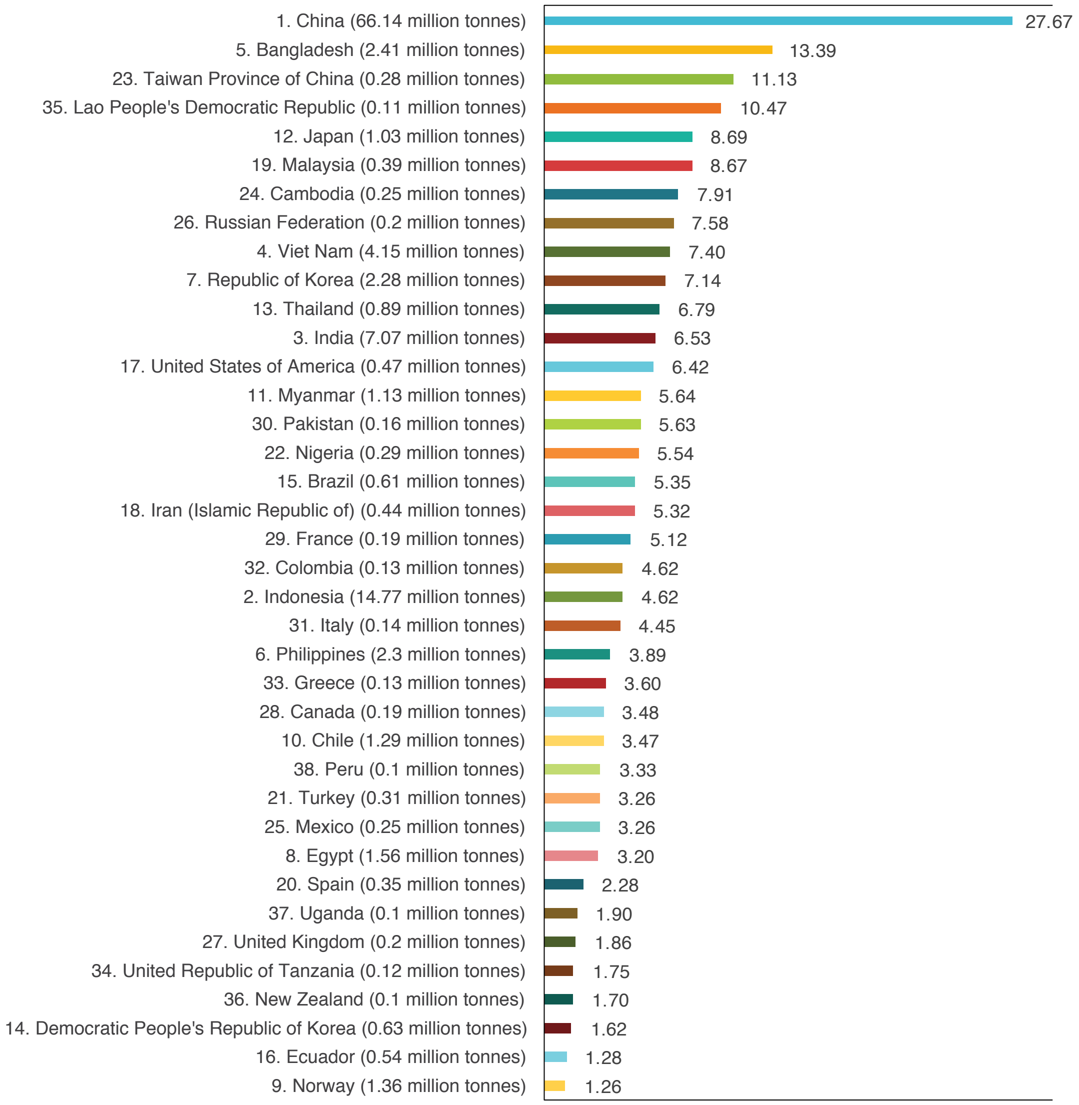
Thailand (13), the Democratic People's Republic of Korea (14), Ecuador (16), Taiwan Province of China (23), Mexico (25), the United Kingdom of Great Britain and Northern Ireland (27), Canada (28) and Uganda (37).

Only seven countries – China (1), Viet Nam (4), Bangladesh (5), Myanmar (11), the United States of America (17), the Russian Federation (26) and France (29) – had an outright upward ENS trend for the entire period, whereas Canada was the only country with an outright downward ENS trend during the period (Figure 4).

Most of the 38 countries/territories had fluctuated ENS during 1988–2018, with an inverted U-shape being a common trend in Norway (9), Chile (10) and Colombia (32) for the entire period and in many other countries/territories for part of the period. In 2018, most of the 38 countries/territories had a higher ENS than the world median (2.37), except for eight countries with a lower ENS (Figure 5).

FIGURE 5

ENS in large aquaculture countries/territories, 2018



Notes: Including the top 38 countries/territories with the greatest aquaculture production in 2018 (no less than 100 000 tonnes). The 2018 aquaculture production of each country/territory is shown in parenthesis, and the countries/territories are indexed according to production in descending order. ENS = effective number of species.

4. Factors affecting aquaculture species diversification

4.1 EFFECTIVE NUMBER OF SPECIES (ENS) BY PRODUCTION CATEGORY

By catering to diverse consumer preferences and love of variety (Montagna, 2001), species diversification is an important way to increase the demand for aquaculture products. On the supply side, the utilization of diverse natural resources, farming environments or farming systems and technologies tends to increase species diversity together with aquaculture production. Therefore, large aquaculture production may be associated with high species diversity.

This hypothesis is supported by the positive correlation between aquaculture production and ENS (the Pearson correlation coefficient $r = 0.5772$, p-value = 0.0000), revealed by the experiences of 211 countries during 1988–2018 (a total of 5 550 cases).[5] The positive correlation is also manifested in the distribution of the median or mean ENS across escalating production categories (Table 3). However, the relatively low variabilities of the minimum ENS and maximum ENS across the production categories (Table 3) indicate that low (or high) ENS can be associated with high (or low) production; see Table 2 and Figure 5 for some examples.

TABLE 3
ENS by production category, 1988–2018

Annual aquaculture production (tonnes)	Number of countries	Number of cases	Effective number of species			
			Minimum	Median	Mean	Maximum
< 100	103	1 251	1.00	1.38	1.68	7.29
100–1 000	98	1 054	1.00	2.00	2.27	7.72
1 000–10 000	107	1 380	1.00	2.22	2.85	15.20
10 000–50 000	71	772	1.00	2.81	3.25	12.05
50 000–100 000	36	250	1.00	2.93	3.41	10.82
100 000–500 000	35	485	1.00	4.00	4.61	15.66
500 000–1 000 000	17	144	1.28	5.38	5.34	11.01
1 000 000–5 000 000	13	170	1.26	6.69	6.41	13.54
≥ 5 000 000	3	44	4.35	14.61	16.55	29.41
All	**211**	**5 550**	**1.00**	**2.18**	**2.99**	**29.41**

Note: For a production range, the lower bound is inclusive, whereas the upper bound is exclusive. ENS = effective number of species.

The ENS distribution across production categories in Table 3 can be used to provide guidance for policy and planning on aquaculture development. For example, when planning to expand its aquaculture production to 50 000 tonnes, a country could use the following evidence as benchmarks (i.e. points of reference): According to past experiences in global aquaculture (772 cases from 71 countries), the average ENS for aquaculture production between 10 000 tonnes and 50 000 tonnes was 3.25; half of the cases had an ENS less than 2.81; and the minimum and maximum ENS were, respectively, 1 and 12.05 (Table 3).

---

[5] The number of countries here (i.e. 211) is for the period 1988–2018, which is different from the number of countries for individual years (e.g. 197 for 2018).

4.2 STATISTICAL ANALYSIS OF EFFECTIVE NUMBER OF SPECIES (ENS)

Besides the production level, many other factors can affect species diversity in aquaculture production, such as climate conditions, natural resource endowments (e.g. land and water), demographic characteristics (e.g. population and urbanization), economic conditions (e.g. household income), dietary habits and consumer preferences, among many others (Harvey *et al.*, 2017). This section uses a statistical model to examine the relationship between aquaculture species diversity and several key factors with available data.

4.2.1 The statistical model

The following panel model is used to examine the effects of selected factors on ENS:

$$\ln(ENS_{it}) = \sum_k \beta_k \ln(x_{it,\,k}) + u_i + \varepsilon_{it}, \tag{2}$$

where i and t denote, respectively, different countries and time, whereas k denotes different explanatory variables with coefficient β_k measuring the impact of each explanatory variable on ENS that is defined in equation (1).

Based on data availability and their potential impacts on aquaculture species diversity, the following six explanatory variables are included in $x_{it,k}$: (i) aquaculture production; (ii) population; (iii) the ratio of urban population to total population (urban ratio in short); (iv) GDP per capita (as a proxy of household income); (v) fish export (as a proxy of farmed fish export); and (vi) per capita fish consumption (as a proxy of farmed fish consumption).

The intercept u_i is a parameter that captures the impact of unspecified structural factors (e.g. geolocation, climate conditions, resource endowments, dietary habits, long-term government policies and business strategies, among others) on ENS. u_i is constant over time for each country yet varies across countries. It is assumed that the average of u_i across countries is zero. This zero-mean assumption allows us to construct a benchmarking index in Section 5 to measure the deviation of a country's ENS from its benchmark level.

ε_{it}, which varies across countries and over time, is an independent and identically distributed error term that captures transitory random shocks on ENS.

4.2.2 Estimated relationships between ENS and selected factors

The model in equation (2) was used to examine the relationships between the six explanatory variables and ENS during three sub-decades (1988–1998, 1998–2008 and 2008–2018). A random-effects estimator (Wooldridge, 2020) is used to extract information from the underlying data; the results are presented in Table 4 with the data sources explained in the table notes.

Aquaculture production

The coefficient of aquaculture production is positive and statistically significant (p-value ≤ 0.05)[6] for all three periods, which is consistent with the positive correlation between aquaculture production and ENS measured by Pearson's r in Section 4.1. Magnitude and species diversity are two dimensions of aquaculture production. The positive Pearson's r indicates that the two dimensions mostly moved in the same direction, whereas the positive coefficient (β) for aquaculture production in the statistical model (equation 2) indicates that the positive relationship between the two dimensions persists when the effects of other explanatory variables on ENS are controlled.

---

[6] Unless specified otherwise, a relationship with p-value ≤ 0.05 is deemed statistically significant, whereas one with p-value > 0.05 is deemed not statistically significant.

TABLE 4
Estimation results of the six-variable model

Dependent variable (in log form): Effective number of species (ENS) **Six explanatory variables (in log form):**	**Period I (1988–1998)**		**Period II (1998–2008)**		**Period III (2008–2018)**	
	146 countries; 1 271 observations		169 countries; 1 640 observations		174 countries; 1 607 observations	
	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
(i) Aquaculture production	0.0444	0.000	0.0276	0.001	0.0264	0.001
(ii) Population	0.0810	0.000	0.1172	0.000	0.1234	0.000
(iii) Per capita GDP	0.0831	0.041	0.1894	0.000	0.1302	0.000
(iv) Urban ratio	-0.2478	0.009	-0.4800	0.000	-0.3475	0.000
(v) Fish export	-0.0102	0.216	-0.0212	0.008	-0.0153	0.025
(vi) Per capita fish consumption	0.0586	0.019	0.0282	0.274	-0.0146	0.570

Notes: The dependent variable ENS is calculated from equation (1) based on aquaculture production data in the FAO Fishery and Aquaculture Statistics – Global aquaculture production 1950–2018 (FAO, 2020a). The six explanatory variables include: (i) aquaculture production volume from FAO (2020a); (ii) population data from the United Nations World Population Prospects 1950–2100 (2019 Revision; United Nations, 2019); (iii) per capita GDP calculated from total GDP (measured in international dollar adjusted for purchasing power parity, or "PPP dollar" in short) from the International Monetary Fund World Economic Outlook (WEO) Database 1980–2024 (IMF, 2019) divided by population from United Nations (2019); (iv) urban ratio from the United Nations World Urbanization Prospects 1950–2030 (2018 revision; United Nations, 2018); (v) fish export volume from the FAO Fishery and Aquaculture Statistics – Global fisheries commodities production and trade 1976–2018 (FAO, 2020c); and (vi) per capita fish consumption calculated from total fish consumption from the FAO Fishery and Aquaculture Statistics – food balance sheets of fish and fishery products 1961–2017 (FAO, 2020d) divided by population from United Nations (2019).

Intuitively, aquaculture production expansion can facilitate species diversification through better infrastructure, material (e.g. feed and seed) supply, technical know-how and supply-chain logistics, whereas species diversification can enlarge market demand to facilitate production expansion. As the statistical model does not account for simultaneity (i.e. two-way causality) between aquaculture production magnitude and species diversity, the estimated coefficient for aquaculture production in equation (2) may not accurately measure its impact on species diversity.

Population and per capita GDP

The coefficients of population and per capita GDP are also positive and statistically significant for all three periods. The results are not surprising: A larger population tends to have more diverse dietary habits, whereas wealthy consumers tend to demand more variety in fish and seafood.

Urban ratio

The coefficient of urban ratio is negative and statistically significant for all three periods. This interesting result is less intuitive yet could be interpreted from both the supply- and demand-side perspectives. Aquaculture has traditionally been a rural business dominated by small-scale operations. Facing more competition over natural and human resources, aquaculture in a more urbanized economy may become more industrialized with larger farm size and increasing global market access. This tends to make economies of scale a more significant factor affecting the selection of aquaculture species. With a more developed fish and seafood supply chain, more urbanized economy can focus on culturing species on which it has the greatest comparative advantage and satisfy consumer preference for variety through fish trade.

While urban ratio is highly correlated with per capita GDP (Pearson's $r > 0.7$ for all three periods), the issue of collinearity nevertheless does not affect the stability of the estimated coefficients of the two variables. The negative sign of the coefficient for urban ratio persists not only in all three periods but also in more refined estimations (e.g. applying the model to developed and developing countries separately). While some preliminary interpretations of the negative coefficient were provided in earlier text, more in-depth analysis is needed to fully understand the relationship.

Fish export

The coefficient of fish export is negative and statistically significant for Period II (1998–2008) and Period III (2008–2018) yet not significant for Period I (1988–1998), reflecting that export-oriented aquaculture tends to have a less diverse species composition. Compared with limited domestic demand, the large capacity of international markets is more conducive to the realization of economies of scale derived from concentrating on species with comparative advantage. The negative relationship appeared to become significant in the last two periods with the rapid growth in global fish trade. More discussion on species composition in export-oriented aquaculture can be found in Section 5.4.2.

Per capita fish consumption

Contrary to the case of fish export, the coefficient of per capita fish consumption is positive and statistically significant for Period I (1988–1998) yet not significant for the next two periods. Consumers with high fish consumption tend to demand more variety of fish and seafood, which can be satisfied either through domestic production or international trade. The rapid growth in global fish trade may be a factor behind the lack of a significant relationship between domestic aquaculture species diversity and fish consumption in the latter two periods, which coincide with increasing global seafood trade.

Technical notes

The main purpose of the statistical model in equation (2) is to estimate benchmarking indicators that will be discussed in Section 5. Thus, the specification of the model is solely to facilitate the benchmarking process and may not have taken full consideration of some estimation technicalities (e.g. simultaneity between ENS and explanatory variables and multicollinearity among explanatory variables) to ensure precise estimation of individual coefficients. Therefore, interpretations of the estimated coefficients in earlier text should be treated as preliminary and warranting further study.

5. Benchmarking species diversification in global aquaculture

While the relationship of each explanatory variable with ENS revealed by the statistical model (i.e. equation 2) was discussed in the previous section, the ultimate goal of the model is to develop benchmarking indicators to facilitate the comparison of countries' experiences in species diversification for evidence-based policy and planning.

5.1 BENCHMARKING INDICATORS OF SPECIES DIVERSIFICATION IN AQUACULTURE

Equation (2) can be transformed into

$$ENS_{it} = \overline{ENS}_{it} \times BSDI_i \times e^{\varepsilon_{it}} \,, \tag{3}$$

where the first term on the right-hand side represents country *i*'s benchmark ENS in time *t* defined as

$$\overline{ENS}_{it} = e^{\sum_k \beta_k \ln(x_{it,\,k})} \,, \tag{4}$$

The benchmark $\overline{ENS}_{it}$ represents an average ENS given country *i*'s specific situation at time *t* (reflected by x_{it}), and the average ENS is set against global experiences (captured by the estimated coefficients β).

The second term on the right-hand side of equation (3) represents a benchmarking species diversification index (BSDI) defined as

$$BSDI_i = e^{u_i} \,, \tag{5}$$

which measures the long-term, structural deviation of country *i*'s actual ENS from the benchmark ENS during the examined period. As opposed to $\overline{ENS}_{it}$ being the benchmark ENS for country *i* at a specific time *t*, BSDI is an index for country *i* during the entire examined period. With zero-mean u_i across countries, the average BSDI across countries is 1. Therefore, a BSDI greater (or lower) than 1 indicates that the country's aquaculture tends to be structurally more (or less) diversified in terms of species than its benchmark set according to global experiences.

The third term on the right-hand side of equation (3), $e^{\varepsilon_{it}}$ measures the fluctuation of ENS_{it} around the benchmark $\overline{ENS}_{it}$ caused by random shocks. For a specific country *i*, ε_{it} fluctuates over time with zero mean, i.e. $\mathrm{E}(\varepsilon_{it}) = 0$. Therefore, according to equation (3), country *i*'s expected ENS at a future time T is determined by its expected benchmark ENS at time T and its BSDI, i.e.

$$\mathrm{E}(ENS_{iT}) = \mathrm{E}(\overline{ENS}_{iT}) \times BSDI_i \tag{6}$$

A numerical example is provided in Appendix I to help practitioners better understand the benchmarking system and its utilization.

5.2 MODEL SPECIFICATION FOR QUANTIFYING THE BENCHMARKING INDICATORS

The model specification in Table 4 needs to be modified to facilitate the quantification and application of the benchmarking indicators specified in Section 5.1. Only the first four explanatory variables in Table 4 would be used, whereas the last two (i.e. fish export and per capita fish consumption) are excluded, primarily because of data limitations. There are readily available official statistics on projections of population, urban ratio and per capita GDP (see notes in Table 4), and future aquaculture production can be set as a policy target. However, it is usually difficult to specify future fish export and per capita fish consumption in a non-arbitrary way for the estimation of future ENS based on equation (6); they are hence excluded in the model specification. In addition, fish export and per capita fish consumption are used as the proxies of farmed fish export and farmed fish consumption, respectively; and unlike the first four explanatory variables, fish export and per capita fish consumption do not have statistically significant coefficients for all three periods examined (Table 4).

Based on the four-variable model specification, the most recent sub-period (i.e. 2008–2018, when the data are generally more consistent and representative of the current situation) is used to estimate the benchmark ENS and the BSDI based on equations (4) and (5), respectively. The coefficients estimated in the four-variable model (Table 5) do not differ much from those in the six-variable model (Table 4).

TABLE 5
Estimation results of the four-variable model for 2008–2018

Dependent variable (in log form): Effective number of species	**Period III (2008–2018)**		
	180 countries 1 892 observations		
Explanatory variables (in log form):	Coefficient	*p*-value	95 percent confidence interval
(i) Aquaculture production	0.0245	0.001	[0.0107, 0.0384]
(ii) Population	0.1117	0.000	[0.0762, 0.1472]
(iii) Per capita GDP	0.0934	0.001	[0.0390, 0.1477]
(iv) Urban ratio	-0.2796	0.000	[-0.4243, -0.1350]

Notes: See the notes in Table 4 for data sources.

5.3 BENCHMARK EFFECTIVE NUMBER OF SPECIES

Based on the coefficients in Table 5, the estimated benchmark ENS for 171 countries in 2018 ranges from 1 to 6.14 (with the median being 2.67), which is much smaller than the range of the actual ENS from 1 to 27.67. The 2018 benchmark ENS was less than 2 in only 28 countries (Figure 6-a), with the actual 2018 ENS in 67 countries less than 2 (Figure 6-b). While the 2018 benchmark ENS in only two countries was greater than 5 (Figure 6-a), the actual 2018 ENS in 32 countries was greater than 5 (Figure 6-b).

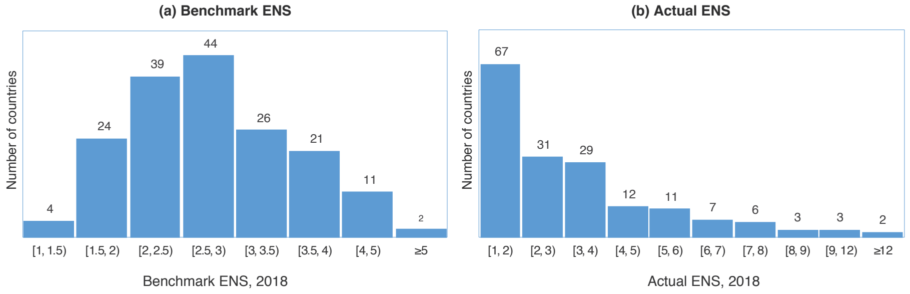
The top 20 highest benchmark ENS in 2018 ranged from 3.75 to 6.14 (Table 6). Most of these top 20 countries are from Asia (14); the rest include two countries in Africa, two in the Americas and two in Europe (Table 6).

Most of the top 20 countries have a large aquaculture production (including 10 of the 12 countries with over 1 million tonnes of aquaculture production in 2018, excluding Chile and Norway), and the top 20 countries together accounted for 92 percent of the world aquaculture production tonnage in 2018. All the top 20 countries had a population of over 20 million in 2018 (including 11 of the 13 countries with a population of over 100 million, excluding Ethiopia and Mexico), and together they accounted for two-thirds of the world population in 2018. The 2018 urban ratio was above 50 percent in half of the top 20 countries and below 50 percent in the other half.

The per capita GDP in most of the top 20 countries was below the world average, and most of them had BSDI values greater than 1 during 2008–2018 (Table 6).

FIGURE 6

Distribution of actual ENS versus benchmark ENS, 2018



Note: The lower bound of an effective number of species (ENS) range is inclusive, whereas its upper bound is exclusive.

TABLE 6

Top 20 countries/territories with the highest benchmark ENS, 2018

Region	**Country/ territory** (ranked by benchmark ENS in descending order)	**ENS benchmarking system**			**Aquaculture production**		**Population**		**Urban ratio (%)**	**Per capita GDP (PPP)**	
		Benchmark ENS	Actual ENS	BSDI (2008–2018)	Tonnes	Share of world total (%)	Thousand	Share of world total (%)		PPP dollar	Ratio to the world average (%)
Asia	1. India	6.14	6.53	1.03	7 071 302	6.18	1 352 642	17.73	34.0	7 752	43
Asia	2. China	6.04	27.67	4.73	66 135 059	57.76	1 427 648	18.71	59.2	17 707	99
Asia	3. Indonesia	4.78	4.62	1.13	14 772 104	12.90	267 671	3.51	55.3	13 061	73
Americas	4. United States of America	4.65	6.42	1.43	468 185	0.41	327 096	4.29	82.3	62 918	352
Asia	5. Viet Nam	4.42	7.40	1.61	4 153 323	3.63	95 546	1.25	35.9	7 437	42
Asia	6. Bangladesh	4.41	13.39	2.79	2 405 416	2.10	161 377	2.11	36.6	4 731	26
Africa	7. Egypt	4.35	3.20	0.79	1 561 457	1.36	98 424	1.29	42.7	13 162	74
Asia	8. Pakistan	4.30	5.63	1.33	159 083	0.14	212 228	2.78	36.7	5 387	30
Asia	9. Sri Lanka	4.22	4.68	1.19	30 921	0.03	21 229	0.28	18.5	13 734	77
Asia	10. Philippines	4.16	3.89	0.93	2 304 361	2.01	106 651	1.40	46.9	8 938	50
Asia	11. Myanmar	4.14	5.64	1.21	1 131 706	0.99	53 708	0.70	30.6	6 125	34
Asia	12. Thailand	4.09	6.79	1.74	890 864	0.78	69 428	0.91	49.9	19 025	106
Asia	13. Japan	4.01	8.69	2.05	1 032 675	0.90	127 202	1.67	91.6	44 001	246
Africa	14. Nigeria	4.00	5.54	1.49	291 323	0.25	195 875	2.57	50.3	5 967	33
Europe	15. Russian Federation	3.98	7.58	1.61	204 032	0.18	145 734	1.91	74.4	29 008	162
Americas	16. Brazil	3.87	5.35	1.86	605 730	0.53	209 469	2.74	86.6	16 071	90
Asia	17. Republic of Korea	3.80	7.14	2.01	2 278 850	1.99	51 172	0.67	81.5	43 682	244
Asia	18. Nepal	3.78	7.24	1.77	59 000	0.05	28 096	0.37	19.7	3 084	17
Asia	19. Turkey	3.75	3.26	0.85	311 681	0.27	82 340	1.08	75.1	27 930	156
Europe	20. Germany	3.75	4.92	1.26	34 196	0.03	83 124	1.09	77.3	52 246	292

Notes: BSDI = benchmarking species diversification index; ENS = effective number of species; PPP = purchasing power parity.

5.4 BENCHMARKING SPECIES DIVERSIFICATION INDEX (BSDI)

As defined in equation (5), a country's benchmarking species diversification index (BSDI) measures the long-term, structural deviation of its actual ENS from its benchmark ENS, which, according to equation (4), represents the average ENS given the country's aquaculture production, population, urban ratio and per capita GDP. For example, a BSDI equal to 2 indicates that the country's ENS was on average twice as high as its benchmark level, whereas a BSDI equal to 0.5 indicates that its ENS was on average only half of its benchmark level.

Data availability allowed us to estimate the BSDI during 2008–2018 for 171 countries, including 86 countries with a BSDI > 1 and 85 countries with a BSDI < 1. The nearly equal number of countries with BSDI > 1 or BSDI < 1 at the global level reflects the zero-mean assumption on u_i in the model design, yet the distribution of BSDI across or within geographical regions is less even (Figure 7). A majority of countries in Asia (30 out of 43) had a BSDI > 1; so did most countries in Europe (21 out of 38). In contrast, a minority of countries in Africa (17 out of 46), the Americas (14 out of 33) and Oceania (4 out of 11) had a BSDI > 1.

5.4.1 Countries with a high BSDI

A total of 17 countries had a BSDI > 2 during 2008–2018, including 12 countries in Asia, 3 in Europe, 1 in the Americas, 1 in Oceania and none in Africa (Figure 7; Table 7). The 2018 aquaculture production of these 17 countries varied from less than 100 tonnes to over 10 million tonnes. The top 50 countries with the highest BSDI during 2008–2018 include 22 countries in Asia, 12 in Europe, 8 in Africa, 6 in the Americas and 2 in Oceania (Table 7).

Large aquaculture countries with high BSDI: the case of China

China has the largest and most species diversified aquaculture production. In 2018, China's 66 million tonnes of aquaculture production were spread across 85 species items, resulting in a 27.67 ENS that was much higher than that of other countries (Table 2). Its 4.73 BSDI, which was also the highest in the world, indicates that its actual ENS was nearly five times as high as its benchmark ENS. Indeed, China's 6.04 benchmark ENS in 2018 was only the second largest and slightly lower than India's 6.14 benchmark ENS (Table 6).

China's uniquely high aquaculture species diversification can be attributed to multiple factors, including, among others, its (i) long history and tradition in aquaculture; (ii) diverse aquaculture resources, systems and technologies; (iii) large, diverse and highly competitive domestic fish and seafood markets; and (iv) strong public support to aquaculture species diversification (Wang, 2001).

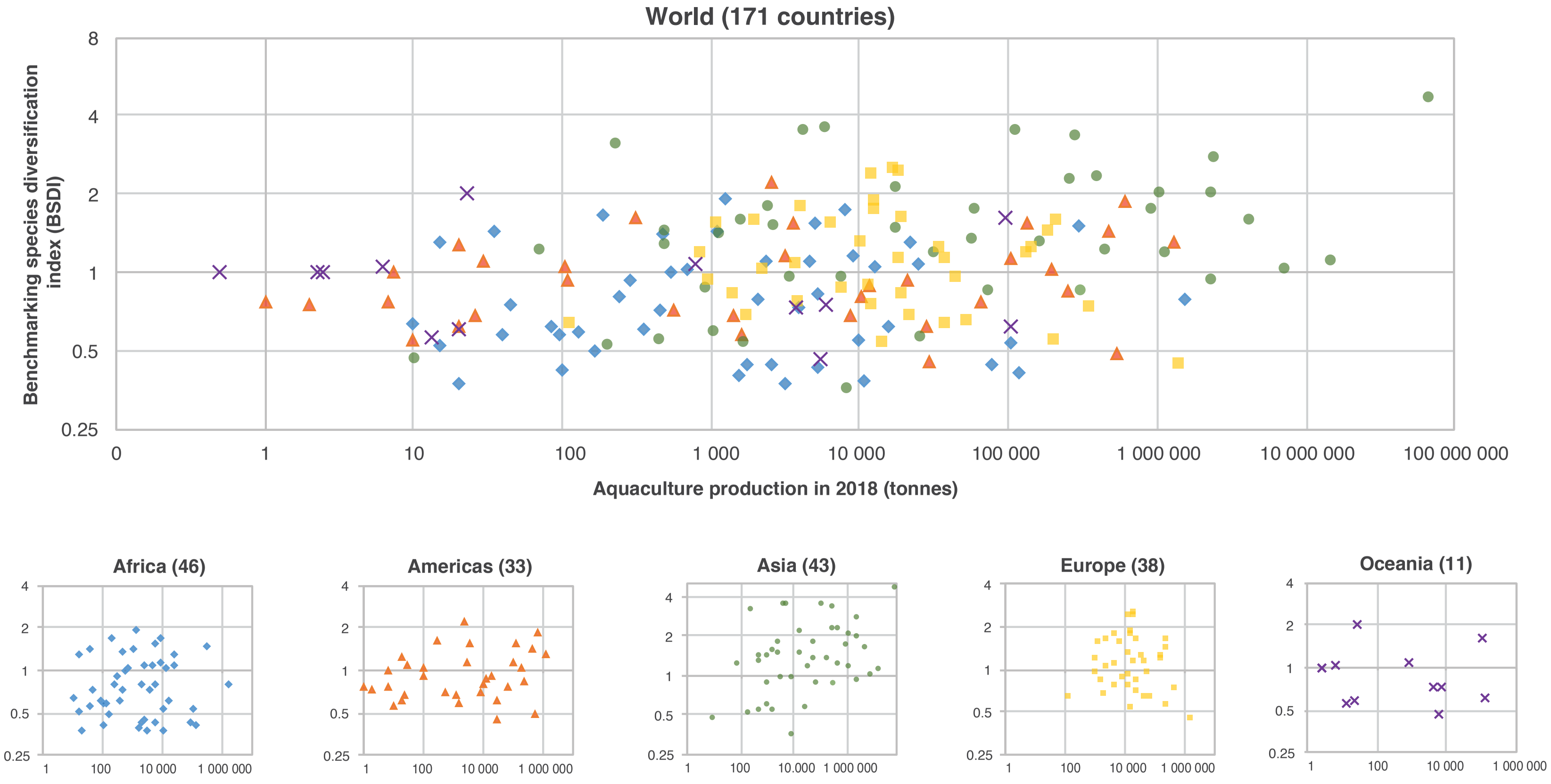
Besides China, other large aquaculture countries/territories (with 2018 production over 100 000 tonnes) on the top 50 highest BSDI list (Table 7) include the Lao People's Democratic Republic (#4), Taiwan Province of China (#5), Bangladesh (#7), Malaysia (#11), Cambodia (#12), Japan (#15), the Republic of Korea (#16), Brazil (#20), Thailand (#25), Viet Nam (#31), the Russian Federation (#33), Colombia (#38), Nigeria (#43), France (#47) and the United States of America (#47).

Small aquaculture sectors with extraordinarily large ENS: the cases of Singapore and China, Hong Kong SAR

In 2018, aquaculture production in Singapore and China, Hong Kong Special Administrative Region (China, Hong Kong SAR in short) was relatively small (around 5 700 tonnes and 4 100 tonnes, respectively), and their benchmark ENS (2.63 and 2.58, respectively) was slightly below the world median (2.67). However, they are among the 11 global outliers in Table 2 with extraordinarily large actual ENS (10.45 and 7.62, respectively). This reflects their high BSDI (3.63 for Singapore and 3.58 for China,

FIGURE 7

Benchmarking species diversification index (BSDI) during 2008–2018



Note: Numbers in parentheses represent the number of countries in each region with an estimated BSDI.

TABLE 7

Top 50 countries/territories with the highest BSDI

Top 25 countries/territories with the highest BSDI							Top 26–50 countries/territories with the highest BSDI						
Region	Country/territory (ranked by BSDI in descending order)	BSDI (2008–2018)	Effective number of species (ENS), 2018		Total number of species, 2018	Aquaculture production, 2018 (tonnes)	Region	Country/territory (ranked by BSDI in descending order)	BSDI (2008–2018)	Effective number of species (ENS), 2018		Total number of species, 2018	Aquaculture production, 2018 (tonnes)
			Benchmark ENS	Actual ENS						Benchmark ENS	Actual ENS		
Asia	1. China	4.73	6.04	27.67	85	66 135 059	Africa	26. South Africa	1.73	3.19	5.35	9	7 868
Asia	2. Singapore	3.63	2.63	10.45	44	5 702	Africa	27. Central African Republic	1.66	1.92	3.44	5	190
Asia	3. China, Hong Kong SAR	3.58	2.58	7.62	16	4 133	Europe	28. Iceland	1.65	1.91	2.18	6	19 185
Asia	4. Lao People's Democratic Republic	3.54	3.05	10.47	14	108 200	Americas	29. Guyana	1.63	2.25	2.82	4	307
Asia	5. Taiwan Province of China	3.34	3.42	11.13	45	283 891	Oceania	30. Australia	1.62	3.26	4.21	19	96 799
Asia	6. Bhutan	3.17	2.01	6.48	7	224	Asia	31. Viet Nam	1.61	4.42	7.40	22	4 153 323
Asia	7. Bangladesh	2.79	4.41	13.39	31	2 405 416	Europe	32. Slovenia	1.61	2.46	3.76	8	1 919
Europe	8. Bulgaria	2.50	2.61	6.24	35	16 342	Europe	33. Russian Federation	1.61	3.98	7.58	28	204 032
Europe	9. Croatia	2.49	2.69	5.64	22	18 067	Asia	34. Kazakhstan	1.60	3.01	5.73	8	1 600
Europe	10. Portugal	2.41	2.89	8.16	20	11 814	Europe	35. Montenegro	1.57	1.89	2.67	5	1 097
Asia	11. Malaysia	2.32	3.42	8.67	47	391 977	Americas	36. Bolivia (Plurinational State of)	1.56	2.43	3.43	5	3 500
Asia	12. Cambodia	2.31	3.63	7.91	25	254 050	Europe	37. Albania	1.56	2.33	3.77	4	6 258
Americas	13. Dominican Republic	2.20	2.49	6.96	11	2 500	Americas	38. Colombia	1.55	3.21	4.62	11	132 756
Asia	14. Israel	2.15	2.64	4.98	13	17 000	Africa	39. Algeria	1.53	3.01	4.44	14	5 100
Asia	15. Japan	2.05	4.01	8.69	28	1 032 675	Asia	40. Kyrgyzstan	1.51	2.55	3.91	5	2 559
Asia	16. Republic of Korea	2.01	3.80	7.14	62	2 278 850	Asia	41. Armenia	1.50	2.31	2.76	7	17 000
Oceania	17. Palau	2.01	1.08	2.90	7	23	Africa	42. Nigeria	1.49	4.00	5.54	16	291 323
Africa	18. Morocco	1.91	2.83	5.52	7	1 267	Europe	43. France	1.46	3.71	5.12	28	185 650
Europe	19. Romania	1.91	3.22	5.60	17	12 298	Asia	44. Azerbaijan	1.44	2.64	4.61	6	478
Americas	20. Brazil	1.86	3.87	5.35	29	605 730	Africa	45. Senegal	1.43	2.57	4.61	7	1 108
Asia	21. Georgia	1.82	2.33	3.28	8	2 382	Africa	46. Gambia	1.43	1.71	2.59	4	35
Europe	22. Austria	1.81	2.99	6.81	18	3 991	Americas	47. United States of America	1.43	4.65	6.42	28	468 185
Asia	23. Nepal	1.77	3.78	7.24	11	59 000	Asia	48. Brunei Darussalam	1.42	1.99	3.14	12	1 116
Europe	24. Republic of Moldova	1.77	2.53	4.03	7	12 530	Africa	49. Namibia	1.39	2.22	2.81	9	472
Asia	25. Thailand	1.74	4.09	6.79	34	890 864	Asia	50. Uzbekistan	1.37	3.22	4.97	14	57 384

Notes: BSDI = benchmarking species diversification index; ENS = effective number of species.

Hong Kong SAR), which were, respectively, the second and third highest among all countries and territories (Table 7).

High and diverse demands for fish and seafood (particularly live/fresh products) are key demand-side factors that contribute to high aquaculture species diversity in these two international metropolitans. Their geographical proximity and economic linkages to large aquaculture countries (e.g. China and Malaysia), which provide easy access to key material inputs (particularly seed supply) and technical know-how, are supply-side factors that help sustain high species diversity in the two relatively small aquaculture sectors.

Countries/territories with large carp aquaculture production

Carps, barbels and other cyprinids (carps in short) are the largest aquaculture species group farmed in 93 countries worldwide with 30 million tonnes of production accounting for a quarter of the world aquaculture production in 2018 (FAO, 2020b). Among the top 50 countries with the highest BSDI (Table 7), the share of carps in total aquaculture production was above 10 percent in 23 countries, above 25 percent in 18 countries, and above 50 percent in 10 countries. There were 50 countries where carp farming accounted for over 10 percent of their aquaculture production in 2018. Among them, 35 countries had a BSDI > 1. These patterns indicate that countries with substantial carp farming tend to have relatively high aquaculture species diversity.

The dominance of polyculture systems in carp farming is a key factor contributing to relatively high species diversity in carp farming. The long history and domestic market orientation of carp farming also help the establishment of a variety of different major carp species, including grass carp (*Ctenopharyngodon idellus*), silver carp (*Hypophthalmichthys molitrix*), common carp (*Cyprinus carpio*), bighead carp (*Hypophthalmichthys nobilis*), crucian carps (*Carassius* spp.), and Indian major carps such as catla (*Catla catla*) and roho labeo (*Labeo rohita*).

5.4.2 Countries/territories with a low BSDI

During 2008–2018, 17 countries had a BSDI < 0.5. Among these, 11 countries were in Africa; the Americas and Asia had two countries each; and Europe and Oceania had one each (Figure 7; Table 8). The 2018 aquaculture production of these countries varied from less than 100 tonnes to over 1 million tonnes (Table 8). Nearly half of the 50 countries with the lowest BSDI during 2008–2018 (Table 8) were located in Africa (21 countries to be exact), and the rest spread across the other four continents: the Americas (ten countries), Europe (eight countries), Asia (seven countries) and Oceania (four countries).

Large, export-oriented aquaculture countries with a low BSDI: the cases of Norway and Ecuador

The historical experiences indicate that the ENS of most countries with aquaculture production over 100 000 tonnes were greater than 4 (Table 3). In 2018, the aquaculture production of Norway and Ecuador were, respectively, 1.4 million tonnes and 0.5 million tonnes, yet their ENS were only 1.26 and 1.28, respectively (Table 8). The corresponding low BSDI (0.45 for Norway and 0.49 for Ecuador) reflect a tendency of species concentration in large, export-oriented aquaculture sectors.

With abundant suitable sites for salmon farming and substantive investments in the salmon value chain (farming system and technology, seed, feed, marketing, etc.), Norway has developed a strong competitive and comparative advantage in farming Atlantic salmon (*Salmo salar*), which dominates its aquaculture production. For Norway's highly industrialized salmon industry that exports most of its produce to a growing world market, focusing on expanding and improving the production and marketing of an established species (i.e. Atlantic salmon) tends to be more profitable than diversifying into new species, at least in the short run. Despite efforts from both

TABLE 8

Top 50 countries/territories with the lowest BSDI

Top 25 countries/territories with the lowest BSDI							Top 26–50 countries/territories with the lowest BSDI						
Region	Country/territory (ranked by BSDI in ascending order)	BSDI (2008–2018)	Effective number of species (ENS), 2018		Total number of species, 2018	Aquaculture production, 2018 (tonnes)	Region	Country/territory (ranked by BSDI in ascending order)	BSDI (2008–2018)	Effective number of species (ENS), 2018		Total number of species, 2018	Aquaculture production, 2018 (tonnes)
			Benchmark ENS	Actual ENS						Benchmark ENS	Actual ENS		
Asia	1. Afghanistan	0.36	3.31	1.04	2	7 950	Europe	26. United Kingdom of Great Britain and Northern Ireland	0.56	3.69	1.86	15	197 618
Africa	2. South Sudan	0.37	2.66	1.00	1	20	Oceania	27. Samoa	0.56	1.92	1.12	2	13
Africa	3. Democratic Republic of the Congo	0.37	2.82	1.03	2	3 200	Asia	28. Iraq	0.57	3.16	1.72	3	25 737
Africa	4. Zimbabwe	0.38	2.92	1.05	3	10 585	Africa	29. Guinea-Bissau	0.57	1.78	1.00	1	40
Africa	5. Burundi	0.40	3.06	1.29	3	1 550	Africa	30. Congo	0.57	2.02	1.23	2	95
Africa	6. United Republic of Tanzania	0.41	3.58	1.75	9	120 086	Americas	31. Jamaica	0.58	2.23	1.78	4	1 616
Africa	7. Eswatini	0.42	2.41	1.00	1	100	Asia	32. Lebanon	0.59	2.20	1.17	5	1 031
Africa	8. Rwanda	0.43	3.27	1.56	4	5 128	Africa	33. Mozambique	0.59	2.56	1.00	1	127
Africa	9. Ghana	0.44	3.06	1.39	5	76 630	Oceania	34. Tonga	0.60	1.69	1.00	1	20
Africa	10. Angola	0.44	2.69	1.00	1	1 752	Africa	35. Niger	0.60	3.10	1.90	2	350
Africa	11. Lesotho	0.44	2.39	1.00	2	2 500	Africa	36. Sierra Leone	0.61	2.12	1.25	2	85
Europe	12. Norway	0.45	3.06	1.26	13	1 355 117	Oceania	37. New Zealand	0.61	2.65	1.70	4	104 549
Americas	13. Nicaragua	0.45	2.46	1.00	2	29 468	Americas	38. Guatemala	0.61	2.96	2.00	4	28 317
Oceania	14. Solomon Islands	0.46	2.15	1.00	2	5 520	Africa	39. Kenya	0.62	3.62	2.15	6	15 524
Asia	15. Qatar	0.47	2.13	1.00	1	10	Americas	40. Grenada	0.62	1.65	1.00	1	20
Americas	16. Ecuador	0.49	3.08	1.28	9	539 755	Africa	41. Libya	0.63	1.98	1.00	1	10
Africa	17. Ethiopia	0.50	3.61	1.84	3	165	Europe	42. Belgium	0.64	2.42	1.00	1	111
Africa	18. Botswana	0.52	1.94	1.00	1	15	Europe	43. Denmark	0.65	2.69	1.99	13	36 453
Asia	19. Kuwait	0.53	2.27	1.23	2	198	Europe	44. Netherlands	0.65	3.05	1.69	11	52 285
Africa	20. Uganda	0.53	3.71	1.90	3	103 737	Americas	45. Haiti	0.68	2.23	1.49	5	1 400
Europe	21. Finland	0.53	2.60	1.33	3	14 164	Americas	46. Barbados	0.68	1.95	1.10	2	26
Asia	22. Timor-Leste	0.55	2.28	1.35	5	1 610	Europe	47. Switzerland	0.68	2.79	2.30	7	1 743
Africa	23. Sudan	0.55	3.33	1.65	2	10 000	Americas	48. El Salvador	0.69	2.34	1.52	8	8 600
Asia	24. Oman	0.55	2.34	1.70	2	451	Europe	49. Czechia	0.69	2.89	2.10	14	21 751
Americas	25. Antigua and Barbuda	0.55	1.86	1.00	1	10	Americas	50. Belize	0.72	1.82	1.45	3	563

Notes: BSDI = benchmarking species diversification index; ENS = effective number of species.

the public and private sectors in species diversification for long-term sustainability (Fernández-Polanco and Bjorndal, 2017), the share of Atlantic salmon in the country's aquaculture production increased from 90 percent to 95 percent between 2000 and 2018, and its ENS declined from 1.44 to 1.26 accordingly (Figure 4). The country's aquaculture production of Atlantic cod (*Gadus morhua*) once exceeded 20 000 tonnes in the late 2000s, which nevertheless declined to less than 500 tonnes in the late 2010s because of competition from increased wild cod production as well as technical difficulties such as high mortality (Fernández-Polanco and Bjorndal, 2017).

A similar trend of species concentration has also occurred in Ecuador, one of the largest shrimp exporters in the world. In 1999, 100 000 tonnes of whiteleg shrimp (*Litopenaeus vannamei*) contributed to 85 percent of Ecuador's aquaculture production. The shrimp production was reduced by half in 2000 due to disease outbreaks, which caused a loss of about half a million jobs and forced the government to declare a state of emergency to help workers and growers who suffered from income and employment losses (FAO, 2006). Yet the shrimp industry survived the crisis and, along with the growing international shrimp market, increased its production 10 times to half a million tonnes in 2018, accounting for 94 percent of its total aquaculture production. The increased species concentration is captured by the decline of its ENS from 1.77 to 1.28 between 2000 and 2018 (Figure 4).

Tilapia farming countries

Tilapias and other cichlids (tilapias in short) are the most popular species group farmed in over 120 countries worldwide with 6 million tonnes of production in 2018, making it the fourth largest species group in global aquaculture (FAO, 2020b). In more than half (26 to be exact) of the top 50 countries with the lowest BSDI (Table 8), tilapia farming accounted for over half of total aquaculture production in 2018. Among 80 countries whose tilapia share in aquaculture production was above 10 percent in 2018, 46 countries had a BSDI < 1. These patterns indicate that countries with substantial tilapia farming tend to have relatively low aquaculture species diversity.

As opposed to carp aquaculture spreading across a number of species, tilapia aquaculture has been contributed primarily by Nile tilapia (*Oreochromis niloticus*). The dominance of monoculture farming systems and the globalization of tilapia aquaculture (in terms of information and technology dissemination, production and trade) have led to the concentration of tilapia production (including research and development) towards the most productive species (i.e. Nile tilapia).

Other tilapia species have been cultured for specific traits, such as Mozambique tilapia (*Oreochromis mossambicus*) for high salinity tolerance; hybrid of Nile tilapia and blue tilapia (*O. niloticus* × *O. aureus*) for monosex seed; red tilapia (*O. mossambicus* × *O. niloticus*) for preferable colour; and *Cichlasoma managuense* (marketed in China as freshwater grouper) for high meat quality, among others. Yet none of these niche species has become significant enough to result in increased species diversification in tilapia aquaculture.

Despite that 95 percent of Malawi's 9 000 tonnes of aquaculture production in 2018 came from tilapia farming, its ENS in 2018 (3.57) was higher than the world median (2.37), and its BSDI (1.16) indicates above-benchmark aquaculture species diversity. As opposed to most tilapia farming countries concentrating on Nile tilapia, Malawi's tilapia aquaculture production was diversified across four species items: Tilapia shiranus (*Oreochromis shiranus*, 59 percent), Mozambique tilapia (*O. mossambicus*, 23 percent) Redbreast tilapia (*Tilapia rendalli*, 9 percent) and Tilapias nei (9 percent). An underlying force behind the exceptionally high species diversification in Malawi's tilapia aquaculture was public intervention for biodiversity conservation, i.e. restrictions over the introduction of non-native species (e.g. fast-growing Nile tilapia) to protect endemic cichlid species in Lake Malawi.

6. Discussion

The previous sections assess the status and trends of species diversification in global aquaculture and develop benchmarking indicators to facilitate comparison of countries' experiences in aquaculture species diversification. Some key results are discussed in the main text, whereas more comprehensive results are documented in Appendix II. Interested readers can use the results to conduct further investigations to deepen the understanding of species diversification in global, regional or national aquaculture.

The ENS used in the paper is one of many ENS measures that can be specified according to the different balance between richness and evenness (Hill, 1973).[7] The ENS used here is equivalent to, yet more intuitive than, the more well-known Shannon index (see the discussion in Section 2) and hence can become a more widely used diversity measure in policy and planning on species composition in aquaculture.

The experiences of around 200 countries in recent decades indicate a general trend of species diversification in global aquaculture (Table 1), yet the diversification patterns differ by geographic regions and across countries (Table 2, Figure 2 and Figure 3). The experiences also reveal positive relationships between species diversity and some factors (e.g. aquaculture production, population, income and fish consumption) and its negative relationships with other factors (e.g. urbanization and fish export) (Table 4).

While high species diversity is often associated with large aquaculture production, a country with small aquaculture production can have relatively high species diversification driven by strong consumer demand for variety with an accommodating aquaculture value chain (e.g. the cases of Singapore and China, Hong Kong SAR discussed in Section 5.4.1). Compared with aquaculture production that serves domestic markets, export-oriented aquaculture tends to have relatively low species diversification (e.g. the cases of Norway and Ecuador discussed in Section 5.4.2). Farming systems and technology also matter. For example, polyculture-oriented carp farming (discussed in Section 5.4.1) generally has higher species diversity than monoculture-dominated tilapia aquaculture (see Section 5.4.2). Interestingly, public policies and regulations for the same purpose may yield opposite impacts on species diversification. For example, while conservation of biodiversity may constrain species diversification via non-native species, it has resulted in relatively high species diversity in Malawi's aquaculture compared with other aquaculture sectors dominated by tilapia farming (see discussion in Section 5.4.2).

The characteristics of traditional aquaculture, such as localized production and markets, integrated farming systems and small-scale operations, are conducive to species diversification. In contrast, modern aquaculture, which tends to be characterized by monoculture, formulated feed, specialized seed production, global markets and industrialized operations, has a tendency to become concentrated towards a few "winner" species (e.g. Nile tilapia, Atlantic salmon and whiteleg shrimp), especially when the long-term benefits of species diversification are inadequately factored into decision-making in the private sector. Though there have been substantial, increasing

---

[7] Hill (1973) introduced "effective number of species" as a unifying notation of commonly used measures of diversity. The generalized effective number of species is defined as $D_q = \left(\sum_{i=1}^{n} s_i^q\right)^{\frac{1}{1-q}}$, where n represents the total number of species, and q is a parameter that defines different measures of effective number of species. For example, when $q = 0$, $D_0 = n$ is equal to the total number of species. When $q = 1$, $D_1 = e^{-\sum_{i=1}^{n} s_i \ln(s_i)}$ is equivalent to the Shannon-Wiener-Weaver (entropy) index, which is used as the diversity measure in this paper. When $q = 2$, $D_2 = \left(\sum_{i=1}^{n} s_i^2\right)^{-1}$ is equivalent to the inverse Simpson-Hirschman-Herfindahl index, which is another widely used diversity measure.

public efforts in facilitating aquaculture species diversification, they have yet to yield encouraging results (Harvey *et al*., 2017).

Aquaculture species that appear promising individually may not be entirely successful when competing for limited resources and markets. Therefore, when designing policies or programmes for aquaculture development, it is essential to adopt a holistic, sector-wide perspective. The results and methods in this paper can assist in this regard. Based on equation (6) and the estimated coefficients in Table 5 as well as the BSDI presented in Appendix II, a country could estimate its potential future ENS given its targeted aquaculture production and the projections of its population, income and urbanization. The results can be used as benchmarks to assess aquaculture development plans and provide guidance to their implementation; see the example in Appendix I.

For countries that lack data to estimate potential future ENS based on equation (6), simple correlation between ENS and production based on historical, global experiences could be used as a rule of thumb to help set or refine production targets. For example, as the ENS in most countries with aquaculture production lower than 100 000 tonnes was between 2 and 3 (Table 3), a country in this category may prioritize public supports to two or three potential core species to make the allocation of public resources more efficient and effective.

The BSDI could be used as another benchmarking indicator to examine species diversification in a country's aquaculture. A BSDI < 1 indicates that the country's actual ENS was persistently lower than its benchmark ENS set according to global experiences. This may suggest that some intrinsic features in the country's aquaculture naturally lead to relatively more concentrated species composition, or it may reflect market failures or institutional imperfections that warrant public interventions.

The benchmarking system developed here, which comprises ENS, benchmark ENS and BSDI as three basic benchmarking indicators, is intended to set points of reference based on global experiences to guide policy and planning in aquaculture development. Not only can the system help a country better understand the status and trends of its own aquaculture, but this tool can also enable it to learn from the experiences of other countries. While each country has its own idiosyncratic characteristics that may not be replicated by other countries, global experiences can be useful to set boundaries and avoid wishful, far-fetched plans in aquaculture development. As the species composition of aquaculture production is shaped by the demand and supply of aquaculture products, the ENS benchmarking system can help decision-makers take a holistic view in aquaculture development planning to account for both supply-side factors (technical feasibility, resource availability, productivity, etc.) and demand-side factors (e.g. consumer preference and market capacity).

The usefulness of the system relies on the quality of the underlying data. As mentioned in Section 2.1, a species item in FAO aquaculture production statistics (FAO, 2020a) may not represent an individual specie but could be a group of related species when identification to species is impossible. This could result in inaccuracies in the measure of species diversity and cause "seemingly diversification" when species groups are disaggregated.

The use of more disaggregated data from the most recent decade (2008–2018) to quantify the benchmarking system helps mitigate such inaccuracies. In addition, as an aggregate species item in FAO data is usually a group of minority species, its disaggregation may not significantly affect ENS. For example, as seven marine fish species were disaggregated from the species item "marine fish nei" in Greece's aquaculture, the number of species items in its aquaculture production increased from 15 to 25 between 2010 and 2011. As the species item "marine fish nei" accounted for only 3 percent of Greece's aquaculture production in 2010, its ENS increased only slightly from 3.45 to 3.49 between 2010 and 2011 despite the large increase in the total number of species.

Although data imperfections do not invalidate the analyses and results of the paper, joint efforts from all stakeholders (governments, international organizations, research communities, the private sector, etc.) are needed to continue improving global data on aquaculture species as well as on the use of genetic resources in aquaculture (FAO, 2019). This paper, which shows the usefulness of global experiences in guiding policy and planning in individual countries, can hopefully motivate more efforts in strengthening global data on aquaculture. Improved global data would not only enhance the quality of information generated from the benchmarking system but could also expand the system to include more indicators, such as separate measures of the richness and evenness of species composition.

Species diversification is not an end but rather one of many means for sustainable aquaculture development. There is no one-size-fits-all aquaculture development strategy. Some countries may pursue species diversification for a more resilient aquaculture sector, while other countries may concentrate on developing aquaculture species with the greatest socio-economic benefits (e.g. food security and poverty alleviation). More case studies are needed to examine national or sub-national experiences to better understand the drivers of species diversification in both the private and public sectors. Further studies are also needed to assess the impacts of species diversification on the performance of aquaculture development and to investigate proper ways to integrate species diversity measures and diversification indicators into evidence-based policy and planning for sustainable aquaculture development.

References

Abellán, E. & Basurco, B., eds. 1999. *Marine finfish species diversification: current situation and prospects in Mediterranean aquaculture*. Zaragoza: CIHEAM.

Alvarez-Lajonchère, L. & Ibarra-Castro, L. 2013. Aquaculture species selection method applied to marine fish in the Caribbean. *Aquaculture*, 408–409: 20–29. doi: 10.1016/j.aquaculture.2013.05.020

Bilio, M. 2008. Controlled reproduction and domestication in aquaculture – the current state of the art. Part IV. *Aquaculture Europe*, 33(2): 12–24.

Brummett, R.E. 2007. Indigenous species for African aquaculture development. In: T.M. Bert, eds. *Ecological and genetic implications of aquaculture activities.* Methods and technologies in fish biology and fisheries, vol 6. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6148-6_13

Cross, S.F., Flaherty, M. & Byrne, A. 2017. Diversification of aquaculture in North America. In B. Harvey, D. Soto, J. Carolsfeld, M. Beveridge & D.M. Bartley, eds. 2017. *Planning for aquaculture diversification: the importance of climate change and other drivers*, pp. 93–110. FAO Technical Workshop, 23–25 June 2016, FAO Rome. FAO Fisheries and Aquaculture Proceedings No. 47. Rome, FAO.

Davy, F.B. 2017. Aquaculture diversification in Asia. In B. Harvey, D. Soto, J. Carolsfeld, M. Beveridge & D.M. Bartley, eds. *Planning for aquaculture diversification: the importance of climate change and other drivers*, pp. 111–122. FAO Technical Workshop, 23–25 June 2016, FAO Rome. FAO Fisheries and Aquaculture Proceedings No. 47. Rome, FAO.

FAO. 2006. *The State of World Aquaculture 2006*. FAO Fisheries Technical Paper No. 500. Rome. 2006. 134 pp.

FAO. 2017. *Country brief on the People's Republic of China* (prepared December 2017). Fishery and Aquaculture Country Profiles. [cited 15 October 2021]. www.fao.org/fishery/facp/chn/en

FAO. 2019. *The State of the World's Aquatic Genetic Resources for Food and Agriculture*. FAO Commission on Genetic Resources for Food and Agriculture assessments. Rome.

FAO. 2020a. *Fishery and Aquaculture Statistics*. Global aquaculture production 1950–2018 (FishStatJ). www.fao.org/fishery/statistics/software/fishstatj/en

FAO. 2020b. *Top 10 species groups in global aquaculture 2018*. World Aquaculture Performance Indicators (WAPI) factsheet. Rome, FAO. 4 pp.

FAO. 2020c. *Fishery and Aquaculture Statistics*. Global fisheries commodities production and trade 1976–2018 (FishStatJ). www.fao.org/fishery/statistics/software/FishStatJ/en

FAO. 2020d. *Fishery and Aquaculture Statistics*. Food balance sheets of fish and fishery products 1961–2017 (FishStatJ). www.fao.org/fishery/statistics/software/fishstatj/en

Fernández-Polanco, J. & Bjorndal, T. 2017. Aquaculture diversification in Europe: the Kingdom of Spain and the Kingdom of Norway. In B. Harvey, D. Soto, J. Carolsfeld, M. Beveridge & D. M. Bartley, eds. *Planning for aquaculture diversification: the importance of climate change and other drivers*, pp. 37–49. FAO Technical Workshop, 23–25 June 2016, FAO, Rome. FAO Fisheries and Aquaculture Proceedings No. 47. Rome, FAO.

Harvey, B., Soto, D., Carolsfeld, J., Beveridge, M. & Bartley, D.M., eds. 2017. *Planning for aquaculture diversification: the importance of climate change and other drivers*. FAO Technical Workshop, 23–25 June 2016, FAO, Rome. FAO Fisheries and Aquaculture Proceedings No. 47. Rome, FAO. 166 pp.

Hill, M.O. 1973. Diversity and evenness: a unifying notation and its consequences. *Ecology*, 54(2): 427–432.

IMF. 2019. *International Monetary Fund World Economic Outlook (WEO) database* (October 2019). www.imf.org/en/Publications/WEO/weo-database/2019/October

Le Francois, N.R., Jobling, M., Carter, C., Blier, P.U. & Savoie, A., eds. 2010. *Finfish aquaculture diversification*. CAB International, Oxford, United Kingdom.

Leung, P.S., Lee, C.S. & O'Bryen P.J., eds. 2007. *Species and system selection for sustainable aquaculture*. Blackwell Publishing.

Liao I.C. 2000. *The state of finfish diversification in Asian aquaculture. Recent advances in Mediterranean aquaculture finfish species diversification*. Zaragoza: CIHEAM. pp. 109–125. (Cahiers Options Méditerranéennes, No. 47.) Seminar of the CIHEAM Network on Technology of Aquaculture in the Mediterranean on "Recent advances in Mediterranean aquaculture finfish species diversification", 1999/05/24–28, Zaragoza (Spain) http://om.ciheam.org/om/pdf/c47/00600610.pdf

Megahed, M.E. & Mesalhy, S. 2009. Domestication and species diversification to improve marine aquaculture in Egypt (a prospective view). *Abbassa International Journal for Aquaculture*, pp. 529–546. Special issue for Global Fisheries and Aquaculture Research Conference, Cairo International Convention Center, 24–26 October 2008.

Metian, M., Troell, M., Christensen, V., Steenbeek, J. & Pouil, S. 2020. Mapping diversity of species in global aquaculture. *Reviews in Aquaculture*, 12: 1090–1100. doi:10.1111/raq.12374.

Martínez-Cordero, F.J. 2007. Socioeconomic aspects of species and system selection for sustainable aquaculture development in Mexico: historic overview and current general trends. In P.S. Leung, C.S. Lee & P.J. O'Bryen, eds. *Species and system selection for sustainable aquaculture*, pp. 225–239. Ames, IA, Blackwell Publishing.

Montagna, C. 2001. Efficiency gaps, love of variety and international trade. *Economica*, 68(269): 27–44.

New, M. 1999. Global aquaculture: current trends and challenges for the 21st century. *World Aquaculture*, 30(1): 8–13.

Purvis, A. & Hector, A. 2000. Getting the measure of biodiversity. *Nature*, 405: 212–219.

Suquet, M. 2010. A systematic market approach to species diversification: a French case study. In Le N.R. Francois, M. Jobling, C. Carter, P.U. Blier & A. Savoie, eds. *Finfish aquaculture diversification*. Oxford, United Kingdom, CAB International.

United Nations. 2018. *United Nations World Urbanization Prospects* (2018 revision). https://population.un.org/wup

United Nations. 2019. *United Nations World Population Prospects* (2019 revision). https://esa.un.org/unpd/wpp/Download/Standard/Population

Wang, Y. 2001. China P.R.: a review of national aquaculture development. In R.P. Subasinghe, P. Bueno, M.J. Phillips, C. Hough, S.E. McGladdery & J.R. Arthur, eds. *Aquaculture in the third millennium,* pp. 307–316. Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20–25 February 2000. NACA, Bangkok and FAO, Rome.

Wilson, J.R. & Archer, B. 2010. Diversification pays: economic perspectives on investment in diversified aquaculture. In N. R. Le Francois, M. Jobling, C. Carter, P. U. Blier & A. Savoie, eds. *Finfish aquaculture diversification*. Oxford, United Kingdom, CAB International.

Wooldridge, J.M. 2020. *Introductory econometrics: a modern approach*. 7th ed. Boston, Cengage.

Wurmann G.C. & Routledge, E.A.B. 2017. Aquaculture diversification in South America: general views and facts and case studies of the Republic of Chile and the Federative Republic of Brazil. In B. Harvey, D. Soto, J. Carolsfeld, M. Beveridge & D.M. Bartley, eds. 2017. *Planning for aquaculture diversification: the importance of climate change and other drivers*. FAO Technical Workshop, 23–25 June 2016, FAO, Rome.

Appendix I – Understanding and utilization of the ENS benchmarking system: an example

A numerical example is used to help practitioners better understand and utilize the effective number of species (ENS) benchmarking system. The calculations in the example may not add up precisely due to rounding.

UNDERSTANDING THE BENCHMARKING SYSTEM

As indicated in Table A1, a hypothetical country *i*'s 6 000 tonnes of aquaculture production at baseline time *t* comprises three species (5 600 tonnes, 300 tonnes and 100 tonnes, respectively). Then its actual ENS at time *t* can be calculated by equation (1) in the main text as

$$\mathrm{ENS}_{it} = e^{-\sum_{i=1}^{n} s_i \ln(s_i)} = e^{-\left[\frac{5600}{6000} \times \ln\left(\frac{5600}{6000}\right) + \frac{300}{6000} \times \ln\left(\frac{300}{6000}\right) + \frac{100}{6000} \times \ln\left(\frac{100}{6000}\right)\right]} = 1.33 \qquad \text{(A.1)}$$

TABLE A1

Estimation or projection of benchmark ENS and expected ENS

Variable or indicator	Baseline at time *t*	Projection at time *T*	
		Scenario I: same BSDI	Scenario II: higher BSDI
Information needed for estimation or projection			
Population (thousand; coefficient = 0.1117)[1]	10 000	12 000	12 000
Per capita GDP (PPP international dollar; coefficient = 0.0934)[1]	14 000	20 000	20 000
Urban ratio (%; coefficient = –0.2796)[1]	60	70	70
Aquaculture production (tonnes; coefficient = 0.0245)[1]	6 000	30 000	30 000
Species #1	5 600	10 000	10 000
Species #2	300	8 000	8 000
Species #3	100	7 000	7 000
Species #4	–	3 900	3 900
Species #5	–	1 100	1 100
Actual or target effective number of species (ENS)[2]	1.33	4.24	4.24
Benchmarking species diversification index (BSDI)[3]	0.50	0.50	1.50
Estimation or projection			
Benchmark ENS[4]	2.69	2.83	2.83
Expected ENS[5]	1.34	1.41	4.24

Notes: 1. The coefficients of the four explanatory variables are obtained from Table 5 in the main text. 2. The actual ENS at baseline time *t* and the target ENS at future time *T* are calculated by equation (1) in the main text based on species composition at the two times. 3. The BSDI here are arbitrarily specified, whereas estimated BSDI for individual countries are available in Appendix II. 4. Benchmark ENS are estimated by equation (4) in the main text. 5. Expected ENS are calculated by equation (6) in the main text. PPP = purchasing power parity.

According to the baseline information presented in Table A1, the benchmark ENS of country *i* can be estimated by equation (4) in the main text as

$$\overline{ENS}_{it} = e^{\sum_k \beta_k \ln(x_{it,\,k})} = e^{0.1117\times\ln(10000)+0.0934\times\ln(14000)+(-0.2796)\times\ln(60)+0.0245\times\ln(6000)} = 2.69 \quad \text{(A.2)}$$

As indicated in equation (A.2), the estimated benchmark ENS (2.69) is equal to the sum of the mean effects of the four explanatory variables on ENS, and the mean effect of each variable is quantified by the corresponding coefficient. As these coefficients are estimated according to the experiences of all countries, the benchmark ENS represents a global average ENS given country *i*'s aquaculture production, population, per capita GDP and urban ratio.

As indicated in equation (3) in the main text, the deviation of country *i*'s actual ENS from its benchmark ENS is determined by two factors. One is the benchmarking species diversification index (BSDI) that captures the effect of unspecified structural factors (e.g. geolocation, climate conditions, resource endowments, dietary habits, long-term government policies or business strategies, among others) on ENS.

Country *i*'s current BSDI is arbitrarily set as 0.5 (Table A1), which indicates that country *i*'s ENS is expected to be only 50 percent of its benchmark ENS due to structural factors, i.e.

$$\mathrm{E}(ENS_{it}) = \overline{ENS}_{it} \times BSDI_i = 2.69 \times 0.5 = 1.34 \qquad \text{(A.3)}$$

A comparison of equations (A.1) and (A.3) indicates that country *i*'s actual ENS at time *t* (1.33) is slightly lower than its expected ENS (1.34). The difference is due to the last term in equation (3) in the main text, which is an error term that captures the impact of random shocks. The error term is a random variable with zero mean. This means that country *i*'s actual ENS tends to fluctuate around its expected ENS. While country *i*'s actual ENS is lower than its expected ENS at time *t*, it could be higher at another time during the examined period.

Utilization of the benchmarking system

Based on resource availability and technical feasibility, country *i* plans to increase its aquaculture production from 6 000 tonnes at time *t* to 30 000 tonnes at time *T* through species diversification. The strategy is expected to increase its total number of species from three to five with more even species composition (Table A1). Similar to equation (A.1), the corresponding ENS at time *T* can be calculated as

$$\mathrm{ENS}_{iT} = e^{-\left[\frac{10000}{30000} \times \ln\left(\frac{10000}{30000}\right) + \frac{8000}{30000} \times \ln\left(\frac{8000}{30000}\right) + \frac{7000}{30000} \times \ln\left(\frac{7000}{30000}\right) + \frac{3900}{30000} \times \ln\left(\frac{3900}{30000}\right) + \frac{1100}{30000} \times \ln\left(\frac{1100}{30000}\right)\right]} = 4.24 \qquad \text{(A.4)}$$

The resulting ENS at time T (4.24) essentially represents country *i*'s target ENS implied by the species composition of its 30 000 tonnes of aquaculture production target at time *T*. The benchmarking system can be used to evaluate this aquaculture development plan.

According to the target production (30 000 tonnes) and the expected value of the other three explanatory variables (Table A1), country *i*'s benchmark ENS at time *T* can be estimated, similar to equation (A.2), as

$$\overline{ENS}_{iT} = e^{\sum_k \beta_k \ln(x_{iT,k})} = e^{0.1117 \times \ln(12000) + 0.0934 \times \ln(20000) + (-0.2796) \times \ln(70) + 0.0245 \times \ln(30000)} = 2.83 \qquad \text{(A.5)}$$

The result indicates that despite the fivefold increase in aquaculture production, together with expected changes in the other three explanatory variables, country *i*'s benchmark ENS would only increase slightly from 2.69 at time *t* to 2.83 at time *T*.

If the country's BSDI remains unchanged at 0.5 (scenario I in Table A1), then its expected ENS at time *T* can be calculated, similar to equation (A.3), as

$$\mathrm{E}(ENS_{iT_{scenario\,I}}) = \overline{ENS}_{iT} \times BSDI_{i_{scenario\,I}} = 2.83 \times 0.5 = 1.41 \qquad \text{(A.6)}$$

The resulting 1.41 of expected ENS at time *T* is much lower than country's 4.24 of target ENS at time *T*.

If country *i* could increase its BSDI to 1.5 (scenario II in Table A1), then its expected ENS at time *T* would be

$$\mathrm{E}(ENS_{iT_{scenario\ II}}) = \overline{ENS}_{iT} \times BSDI_{i_{scenario\ II}} = 2.83 \times 1.5 = 4.24 \qquad \text{(A.7)}$$

This result implies that given the magnitude and species composition of its target aquaculture production at time *T*, only if country *i* increase its BSDI to 1.5 would its expected ENS at time *T* be at par with its target ENS.

In order to facilitate the species diversification aquaculture development strategy, country *i* needs to (i) assess underlying factors that make its expected ENS only 50 percent of its benchmark ENS (i.e. the current BSDI being 0.5); and (ii) explore policy measures to increase its BSDI to 1.5. The country should examine the feasibility of the species diversification strategy through both supply-side (e.g. resource endowment, technical capacity and supply chain logistics) and demand-side (e.g. market capacity) perspectives. It could also learn from aquaculture development experiences in countries with an ENS equal or greater than 4.24 and those with a BSDI equal or higher than 1.5, particularly the status and trends of aquaculture species composition in these countries.

The assessment and exploration may indicate that (i) despite resource availability and technical feasibility, some constraints (e.g. inadequate market capacity) tend to hinder the realization of the 30 000 tonnes of production target; and (ii) the constraints are difficult to overcome within the planning time frame. Under this situation, country *i* may need to adjust the magnitude and/or species composition of the production target to make it more achievable.

Technical notes

In practice, data and parameters needed to project benchmark ENS and expected ENS in the future may be obtained in the following ways.

- Similar to the above example, the projection of aquaculture production may be specified according to production targets in an aquaculture development plan.
- The projected value of population could be obtained from the United Nations World Population Prospects. https://population.un.org/wpp
- The projected value of per capita GDP (measured in international dollar adjusted for purchasing power parity, or PPP) could be obtained from the International Monetary Fund World Economic Outlook (WEO) Database. https://www.imf.org/en/Publications/SPROLLs/world-economic-outlook-databases#sort=%40imfdate%20descending
- The projected value of urban ratio could be obtained from the United Nations World Urbanization Prospects. https://population.un.org/wup
- The coefficients for the four explanatory variables can be obtained from Table 5 in the main text.
- The value of BSDI can be obtained from Table A2 in Appendix II.

Data used to project benchmark ENS and expected ENS in the future should be in the same units as those used to estimate the coefficients of the four explanatory variables (Table A1). For example, as urban ratio is measured by percentage, a 50 percent urban ratio should be inputted as 50 but not as 0.5.

ENS is no less than 1 by definition. Therefore, in case the projected benchmark ENS or expected ENS is less than 1, the projected value should be set to 1.

Appendix II – Benchmarking species diversification in global aquaculture: comprehensive results

TABLE A2

Benchmarking species diversification in global aquaculture: comprehensive results

Region	Country/ territory (ranked alphabetically)	Four explanatory variables				Aquaculture species diversification benchmarking system			
		Population (2018, thousand)	Per capita GDP (measured in purchasing power parity, 2018, international dollar)	Ratio of urban population in total population (2018, %)	Aquaculture production (2018, tonnes)	Total number of species (2018)	Effective number of species (ENS; 2018)	Benchmark ENS (2018)	Benchmarking species diversification index (BSDI; 2008–2018)
Asia	Afghanistan	37 172	1 954	25	7 950	2	1.04	3.31	0.36
Europe	Albania	2 883	13 307	60	6 258	4	3.77	2.33	1.56
Africa	Algeria	42 228	15 569	73	5 100	14	4.44	3.01	1.53
Africa	Angola	30 810	6 469	66	1 752	1	1.00	2.69	0.44
Americas	Antigua and Barbuda	96	26 795	25	10	1	1.00	1.86	0.55
Americas	Argentina	44 361	20 629	92	3 205	12	3.29	2.88	1.16
Asia	Armenia	2 952	10 313	63	17 000	7	2.76	2.31	1.50
Oceania	Australia	24 898	52 942	86	96 799	19	4.21	3.26	1.62
Europe	Austria	8 891	52 098	58	3 991	18	6.81	2.99	1.81
Asia	Azerbaijan	9 950	18 058	56	478	6	4.61	2.64	1.44
Americas	Bahamas	386	32 699	83	7	1	1.00	1.56	0.77
Asia	Bangladesh	161 377	4 720	37	2 405 416	31	13.39	4.41	2.79
Americas	Barbados	287	18 525	31	26	2	1.10	1.95	0.68
Europe	Belarus	9 453	20 014	79	11 581	11	2.54	2.60	0.90
Europe	Belgium	11 482	47 944	98	111	1	1.00	2.42	0.64
Americas	Belize	383	8 797	46	563	3	1.45	1.82	0.72
Africa	Benin	11 485	2 414	47	5 114	3	2.00	2.47	0.82
Asia	Bhutan	754	10 326	41	224	7	6.48	2.01	3.17
Americas	Bolivia (Plurinational State of)	11 353	7 408	69	3 500	5	3.43	2.43	1.56
Europe	Bosnia and Herzegovina	3 324	14 221	48	3 639	9	2.37	2.50	1.08
Africa	Botswana	2 254	18 606	69	15	1	1.00	1.94	0.52
Americas	Brazil	209 469	16 066	87	605 730	29	5.35	3.87	1.86
Asia	Brunei Darussalam	429	80 543	78	1 116	12	3.14	1.99	1.42
Europe	Bulgaria	7 052	23 019	75	16 342	35	6.24	2.61	2.50
Africa	Burkina Faso	19 751	1 967	29	548	5	3.18	2.78	1.01
Africa	Burundi	11 175	734	13	1 550	3	1.29	3.06	0.40
Asia	Cambodia	16 250	4 335	23	254 050	25	7.91	3.63	2.31
Africa	Cameroon	25 216	3 778	56	2 340	7	2.19	2.62	1.11

TABLE A2 (Continued)

Region	Country/ territory (ranked alphabetically)	Four explanatory variables				Aquaculture species diversification benchmarking system			
		Population (2018, thousand)	Per capita GDP (measured in purchasing power parity, 2018, international dollar)	Ratio of urban population in total population (2018, %)	Aquaculture production (2018, tonnes)	Total number of species (2018)	Effective number of species (ENS; 2018)	Benchmark ENS (2018)	Benchmarking species diversification index (BSDI; 2008–2018)
Americas	Canada	37 075	49 544	81	191 323	13	3.48	3.50	1.03
Africa	Central African Republic	4 666	776	41	190	5	3.44	1.92	1.66
Africa	Chad	15 478	1 949	23	450	4	3.23	2.88	0.72
Americas	Chile	18 729	25 722	88	1 287 233	17	3.47	3.13	1.30
Asia	China	1 427 648	17 700	59	66 135 059	85	27.67	6.04	4.73
Asia	China, Hong Kong SAR	7 372	65 180	100	4 133	16	7.62	2.58	3.58
Americas	Colombia	49 661	14 996	81	132 756	11	4.62	3.21	1.55
Africa	Congo	5 244	5 778	67	95	2	1.23	2.02	0.57
Americas	Costa Rica	4 999	17 646	79	20 820	7	2.61	2.42	0.93
Africa	Côte d’Ivoire	25 069	4 267	51	4 500	5	2.49	2.77	1.09
Europe	Croatia	4 156	25 842	57	18 067	22	5.64	2.69	2.49
Asia	Cyprus	1 189	29 052	67	7 347	6	2.00	2.21	0.96
Europe	Czechia	10 666	37 116	74	21 751	14	2.10	2.89	0.69
Africa	Democratic Republic of the Congo	84 068	867	44	3 200	2	1.03	2.82	0.37
Europe	Denmark	5 752	52 384	88	36 453	13	1.99	2.69	0.65
Americas	Dominican Republic	10 627	17 807	81	2 500	11	6.96	2.49	2.20
Americas	Ecuador	17 084	11 676	64	539 755	9	1.28	3.08	0.49
Africa	Egypt	98 424	13 171	43	1 561 457	12	3.20	4.35	0.79
Americas	El Salvador	6 421	8 317	72	8 600	8	1.52	2.34	0.69
Africa	Equatorial Guinea	1 309	22 796	72	15	3	2.69	1.84	1.32
Europe	Estonia	1 323	33 985	69	944	4	1.62	2.14	0.95
Africa	Eswatini	1 136	10 675	24	100	1	1.00	2.41	0.42
Africa	Ethiopia	109 224	2 010	21	165	3	1.84	3.61	0.50
Oceania	Fiji	883	10 311	56	795	5	2.13	1.93	1.07
Europe	Finland	5 523	46 438	85	14 164	3	1.33	2.60	0.53
Europe	France	64 991	45 588	80	185 650	28	5.12	3.71	1.46
Africa	Gabon	2 119	17 917	89	45	2	1.42	1.84	0.75
Africa	Gambia	2 280	2 658	61	35	4	2.59	1.71	1.43
Asia	Georgia	4 003	10 645	59	2 382	8	3.28	2.33	1.82
Europe	Germany	83 124	52 408	77	34 196	15	4.92	3.75	1.26
Africa	Ghana	29 767	6 406	56	76 630	5	1.39	3.06	0.44
Europe	Greece	10 522	29 714	79	132 392	17	3.60	2.90	1.21
Americas	Grenada	111	15 702	36	20	1	1.00	1.65	0.62
Americas	Guatemala	17 248	8 444	51	28 317	4	2.00	2.96	0.61
Africa	Guinea	12 414	2 474	36	687	4	2.81	2.56	1.03
Africa	Guinea-Bissau	1 874	1 798	43	40	1	1.00	1.78	0.57
Americas	Guyana	779	8 549	27	307	4	2.82	2.25	1.63

TABLE A2 (Continued)

Region	Country/ territory (ranked alphabetically)	Four explanatory variables				Aquaculture species diversification benchmarking system			
		Population (2018, thousand)	Per capita GDP (measured in purchasing power parity, 2018, international dollar)	Ratio of urban population in total population (2018, %)	Aquaculture production (2018, tonnes)	Total number of species (2018)	Effective number of species (ENS; 2018)	Benchmark ENS (2018)	Benchmarking species diversification index (BSDI; 2008–2018)
Americas	Haiti	11 123	1 864	55	1 400	5	1.49	2.23	0.68
Americas	Honduras	9 588	5 127	57	65 000	2	2.00	2.62	0.77
Europe	Hungary	9 707	32 134	71	17 852	11	3.17	2.83	1.15
Europe	Iceland	337	57 853	94	19 185	6	2.18	1.91	1.65
Asia	India	1 352 642	7 766	34	7 071 302	21	6.53	6.14	1.03
Asia	Indonesia	267 671	13 056	55	14 772 104	38	4.62	4.78	1.13
Asia	Iran (Islamic Republic of)	81 800	19 690	75	439 718	12	5.32	3.67	1.23
Asia	Iraq	38 434	17 517	70	25 737	3	1.72	3.16	0.57
Europe	Ireland	4 819	80 074	63	36 896	7	3.33	3.01	1.13
Asia	Israel	8 382	40 235	92	17 000	13	4.98	2.64	2.15
Europe	Italy	60 627	39 543	70	143 338	33	4.45	3.74	1.26
Americas	Jamaica	2 935	9 207	56	1 616	4	1.78	2.23	0.58
Asia	Japan	127 202	43 981	92	1 032 675	28	8.69	4.01	2.05
Asia	Jordan	9 965	9 376	91	900	2	1.89	2.20	0.88
Asia	Kazakhstan	18 320	27 765	57	1 600	8	5.73	3.01	1.60
Africa	Kenya	51 393	3 450	27	15 524	6	2.15	3.62	0.62
Oceania	Kiribati	116	2 072	54	3 652	2	1.01	1.39	0.73
Asia	Kuwait	4 137	74 067	100	198	2	1.23	2.27	0.53
Asia	Kyrgyzstan	6 304	3 891	36	2 559	5	3.91	2.55	1.51
Asia	Lao People's Democratic Republic	7 062	7 605	35	108 200	14	10.47	3.05	3.54
Europe	Latvia	1 928	29 993	68	830	8	3.26	2.21	1.19
Asia	Lebanon	6 859	13 045	89	1 031	5	1.17	2.20	0.59
Africa	Lesotho	2 108	3 277	28	2 500	2	1.00	2.39	0.44
Africa	Liberia	4 819	1 314	51	240	5	1.43	1.92	0.80
Africa	Libya	6 679	11 184	80	10	1	1.00	1.98	0.63
Europe	Lithuania	2 801	34 631	68	3 750	12	2.64	2.43	0.78
Africa	Madagascar	26 262	1 634	37	12 758	6	2.98	2.85	1.04
Africa	Malawi	18 143	1 304	17	9 014	7	3.57	3.31	1.16
Asia	Malaysia	31 528	31 699	76	391 977	47	8.67	3.42	2.32
Africa	Mali	19 078	2 317	42	3 926	3	1.41	2.67	0.72
Europe	Malta	439	48 492	95	10 022	4	1.77	1.90	1.31
Oceania	Marshall Islands	58	3 595	77	2	1	1.00	1.02	0.99
Africa	Mauritius	1 267	23 667	41	2 070	8	1.34	2.43	0.79
Americas	Mexico	126 191	20 364	80	247 222	22	3.26	3.73	0.84
Europe	Montenegro	628	18 939	67	1 097	5	2.67	1.89	1.57
Africa	Morocco	36 029	8 732	62	1 267	7	5.52	2.83	1.91
Africa	Mozambique	29 496	1 328	36	127	1	1.00	2.56	0.59
Asia	Myanmar	53 708	6 405	31	1 131 706	22	5.64	4.14	1.21
Africa	Namibia	2 448	11 073	50	472	9	2.81	2.22	1.39

TABLE A2 (Continued)

Region	Country/ territory (ranked alphabetically)	Four explanatory variables				Aquaculture species diversification benchmarking system			
		Population (2018, thousand)	Per capita GDP (measured in purchasing power parity, 2018, international dollar)	Ratio of urban population in total population (2018, %)	Aquaculture production (2018, tonnes)	Total number of species (2018)	Effective number of species (ENS; 2018)	Benchmark ENS (2018)	Benchmarking species diversification index (BSDI; 2008–2018)
Asia	Nepal	28 096	3 063	20	59 000	11	7.24	3.78	1.77
Europe	Netherlands	17 060	56 814	91	52 285	11	1.69	3.05	0.65
Oceania	New Zealand	4 743	41 709	87	104 549	4	1.70	2.65	0.61
Americas	Nicaragua	6 466	5 526	59	29 468	2	1.00	2.46	0.45
Africa	Niger	22 443	1 048	16	350	2	1.90	3.10	0.60
Africa	Nigeria	195 875	5 966	50	291 323	16	5.54	4.00	1.49
Europe	North Macedonia	2 083	15 665	58	1 359	3	1.78	2.22	0.84
Europe	Norway	5 338	74 161	82	1 355 117	13	1.26	3.06	0.45
Asia	Oman	4 829	41 100	85	451	2	1.70	2.34	0.55
Asia	Pakistan	212 228	5 378	37	159 083	10	5.63	4.30	1.33
Oceania	Palau	18	15 636	80	23	7	2.90	1.08	2.01
Americas	Panama	4 177	25 565	68	10 445	11	2.92	2.53	0.81
Oceania	Papua New Guinea	8 606	3 586	13	6 001	6	2.27	3.56	0.75
Americas	Paraguay	6 956	13 582	62	11 536	5	3.18	2.60	0.89
Americas	Peru	31 989	14 301	78	103 598	16	3.33	3.06	1.13
Asia	Philippines	106 651	8 932	47	2 304 361	27	3.89	4.16	0.93
Europe	Poland	37 922	31 985	60	43 361	14	3.65	3.54	0.96
Europe	Portugal	10 256	32 102	65	11 814	20	8.16	2.89	2.41
Americas	Puerto Rico	3 040	42 710	94	20	4	2.81	2.01	1.27
Asia	Qatar	2 782	127 534	99	10	1	1.00	2.13	0.47
Asia	Republic of Korea	51 172	41 748	81	2 278 850	62	7.14	3.80	2.01
Europe	Republic of Moldova	4 052	6 390	43	12 530	7	4.03	2.53	1.77
Europe	Romania	19 506	26 471	54	12 298	17	5.60	3.22	1.91
Europe	Russian Federation	145 734	28 912	74	204 032	28	7.58	3.98	1.61
Africa	Rwanda	12 302	2 228	17	5 128	4	1.56	3.27	0.43
Americas	Saint Kitts and Nevis	52	31 845	31	1	1	1.00	1.57	0.76
Americas	Saint Lucia	182	13 965	19	29	3	2.78	2.09	1.10
Americas	Saint Vincent and the Grenadines	110	11 977	52	2	1	1.00	1.37	0.74
Oceania	Samoa	196	5 965	18	13	2	1.12	1.92	0.56
Asia	Saudi Arabia	33 703	55 115	84	72 000	10	2.21	3.39	0.86
Africa	Senegal	15 854	3 754	47	1 108	7	4.61	2.57	1.43
Europe	Serbia	8 803	13 946	56	7 339	6	2.55	2.71	0.87
Africa	Sierra Leone	7 650	1 604	42	85	2	1.25	2.12	0.61
Asia	Singapore	5 757	98 274	100	5 702	44	10.45	2.63	3.63
Europe	Slovakia	5 453	35 067	54	2 224	12	3.11	2.76	1.04
Europe	Slovenia	2 078	36 567	55	1 919	8	3.76	2.46	1.61

TABLE A2 (Continued)

Region	Country/ territory (ranked alphabetically)	Four explanatory variables				Aquaculture species diversification benchmarking system			
		Population (2018, thousand)	Per capita GDP (measured in purchasing power parity, 2018, international dollar)	Ratio of urban population in total population (2018, %)	Aquaculture production (2018, tonnes)	Total number of species (2018)	Effective number of species (ENS; 2018)	Benchmark ENS (2018)	Benchmarking species diversification index (BSDI; 2008–2018)
Oceania	Solomon Islands	653	2 160	24	5 520	2	1.00	2.15	0.46
Africa	South Africa	57 793	13 660	66	7 868	9	5.35	3.19	1.73
Africa	South Sudan	10 976	1 776	20	20	1	1.00	2.66	0.37
Europe	Spain	46 693	39 929	80	347 825	43	2.28	3.59	0.75
Asia	Sri Lanka	21 229	13 687	18	30 921	21	4.68	4.22	1.19
Africa	Sudan	41 802	4 251	35	10 000	2	1.65	3.33	0.55
Americas	Suriname	576	15 504	66	110	3	2.13	1.74	0.93
Europe	Sweden	9 972	54 358	87	11 672	4	1.66	2.79	0.76
Europe	Switzerland	8 526	64 333	74	1 743	7	2.30	2.79	0.68
Asia	Taiwan Province of China	23 726	52 747	78	283 891	45	11.13	3.42	3.34
Asia	Tajikistan	9 101	3 418	27	480	5	3.12	2.74	1.28
Asia	Thailand	69 428	19 018	50	890 864	34	6.79	4.09	1.74
Asia	Timor-Leste	1 268	5 245	31	1 610	5	1.35	2.28	0.55
Africa	Togo	7 889	1 768	42	290	3	1.30	2.22	0.93
Oceania	Tonga	103	6 008	23	20	1	1.00	1.69	0.60
Americas	Trinidad and Tobago	1 390	31 917	53	7	2	1.79	2.04	1.01
Africa	Tunisia	11 565	12 472	69	21 826	16	1.88	2.68	1.30
Asia	Turkey	82 340	27 842	75	311 681	18	3.26	3.75	0.85
Asia	Turkmenistan	5 851	19 257	52	70	4	3.86	2.44	1.22
Africa	Uganda	42 729	2 269	24	103 737	3	1.90	3.71	0.53
Europe	Ukraine	44 246	8 822	69	18 595	6	2.96	3.00	0.83
Asia	United Arab Emirates	9 631	75 141	87	3 350	10	3.92	2.79	0.97
Europe	United Kingdom of Great Britain and Northern Ireland	67 142	45 244	83	197 618	15	1.86	3.69	0.56
Africa	United Republic of Tanzania	56 313	3 122	34	120 086	9	1.75	3.58	0.41
Americas	United States of America	327 096	62 654	82	468 185	28	6.42	4.65	1.43
Americas	Uruguay	3 449	23 657	95	102	5	3.07	1.99	1.06
Asia	Uzbekistan	32 476	7 708	50	57 384	14	4.97	3.22	1.37
Oceania	Vanuatu	293	2 802	25	6	3	1.14	1.68	1.05
Asia	Viet Nam	95 546	7 434	36	4 153 323	22	7.40	4.42	1.61
Africa	Zambia	17 352	4 203	44	24 300	7	2.70	2.89	1.07
Africa	Zimbabwe	14 439	2 947	32	10 585	3	1.05	2.92	0.38

With ever-growing concerns over climate change, disease outbreaks, market fluctuations and other uncertainties, species diversification has become an increasingly prominent strategy for sustainable aquaculture development. Policy and planning on species diversification require a holistic, sector-wide perspective to assess the overall prospect of individually promising species that may not be entirely successful when competing for limited resources and markets. This paper examines the status and trends of species diversification in global aquaculture and establishes a benchmarking system to facilitate the comparison of species diversification patterns across countries. The benchmarking results based on the experiences of around 200 countries for three decades can provide points of reference to facilitate evidence-based policy and planning in sustainable aquaculture development. Additionally, the benchmarking system can be used in foresight analyses to help design or refine future production targets in policy and planning for aquaculture development. Indicating the usefulness of global experiences in guiding policy and planning in individual countries may motivate more efforts in strengthening global data on aquaculture. Improved global data would not only enhance the quality of information generated from the benchmarking system but also could expand the system to include more indicators.

ISBN 978-92-5-135642-5 ISSN 2070-7010

9 789251 356425

CB8335EN/1/01.22