Mapping diversity of species in global aquaculture

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Running head title: One fish, two fish, red fish: farmed fish

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Abstract

Aquaculture is the world's most diverse farming practice in terms of number of species, farming methods and environments used. While various organization and institutions have promoted species diversification, overall species diversity within the aquaculture industry is likely not promoted nor sufficiently well quantified. Using the most extensive dataset available (FAO-statistics) and an approach based on the Shannon Diversity index, this paper provides a method for quantifying and mapping global aquaculture species diversity. Although preliminary analyses showed that a large part of the species forming production is still qualified as undetermined species (i.e. "not elsewhere included"), results indicate that usually high species diversity for a country is associated with a higher production but there are considerable differences between countries. Nine of the top 10 countries ranked highest by Shannon Diversity index in 2010 are from Asia with China producing the most diverse collection of species. Since species diversity is not the only level of diversity in production, other types of diversity are also briefly discussed. Diversifying aquatic farmed species can be of importance for long-term performance and viability of the sector with respect to sustaining food production under (sometimes abrupt) changing conditions. This can be true both at the global and regional level. In contrast, selection and focus on only a limited number of species can lead to rapid improvements in terms of production (towards sustainability or not) and profitability. Therefore, benefits and shortcomings of diversity are discussed from both economical and social-ecological perspectives that concurrently are shaping the expanding aquaculture industry.

Keywords: Aqua-farming, Diversification, Resilience, Profitability, Sustainability, Production characteristics

1. Introduction

Early aquaculture dates back at least 2000 years BC (Rabanal 1988) but it was in the last half of the 20th century that a rapid and systematic worldwide expansion occurred (FAO 2018). The growth of aquaculture during this period can be attributed not only to advances in technology and development, but also widespread exchange of information at the national and international levels and need for reliable source of protein food for human consumption (Jones 1987). The real breakthrough in aquaculture appeared in the 1970s with the development of seed production (induced spawning) for the highest-produced groups such as Asian carps, tilapias, and Peneid shrimps (Gjedrem and Branski 2009). The 1970s and 1980s were an important turning point for global aquaculture during which the industry continued to expand greatly both in area and in volume (FAO 2018). This has involved the farming of a large number of species and it has been mainly driven by the increasing demand for fish and shellfish resulting from various factors such as increased global per capita food–fish supplies, urbanization, increasing wealth, capture fisheries stagnation and population growth (Worm *et al*. 2006; Halpern *et al.* 2008; Godfray *et al.* 2010).

Diversification is often presented as an option for achieving sustainable development for future aquaculture (e.g., FAO 2016, Simard *et al.* 2008, Teletchea and Fontaine, 2014). Diversification in aquaculture can be approached in many ways including production systems, markets and reared species. Species diversification can be addressed at different spatial levels (local, district, country, region) through several main approaches (1) increasing the number of species being farmed, (2) increasing the evenness of farmed species and (3) increasing the diversity within currently farmed species by developing new strains (FAO 2016). International institutions such as the

Food and Agriculture Organization of the United Nations (FAO) have recently advocated for stronger aquaculture diversification in regards to species (FAO 2016). To adequately increase species diversity in aquaculture, it is necessary first to have a solid understanding of current diversity.

An accurate assessment of the total number of farmed species and to what extent they are being farmed is a complex undertaking; reports that include such statistics are often scant and unreliable. Therefore, national or global quantification of species farmed still remains an approximation (FAO 2018). Variations from this approximation are likely resulting from a misreporting of countries to FAO (see supplementary material #1 for more details) and these could be due, for example to aggregation of species to genus (or nei) or to the farming of aquatic species without being registered individually to national statistics (e.g. backyard farming or other small-scale production for local markets).

It is nevertheless important to obtain reliable information on the temporal and spatial diversity in order to establish a baseline on aquaculture diversification at the global level. This will permit that accurate information is available to resource managers businesspeople and policymakers to assess the evolution of the industry and therefore plan future businesses. It will be important to understand how the aquaculture industry may become impacted from e.g. climate change and the role diversity can play to help the industry adapt in order to sustaining seafood production.

This study maps and quantifies present the present species diversity in aquaculture and also identifies trends observed since 1980. The work is based on a standard diversity method from ecology that has been adapted to national statistics collected by FAO. The advantages and disadvantages for quantifying species diversification as well as what the factors that shape it in aquaculture are discussed.

2. Quantification of species diversity: trends, maps, index and obstacles

The number of identified species used in global aquaculture from 1950 to 2017 is shown in Figure 1A (FAO 2019b). The number of fish species increased from 32 species of fish in 1950 to 212 species of fish in 2017 (species APR -annual percentage rate- for 1950 to 2017 = 2.9). In 2017, 332 species were reported being farmed worldwide (Figure 1A and Table 1). Among these, 212 were fish species (including 5 hybrids), 65 were molluscs, 30 crustaceans, and 20 aquatic plants, 3 amphibians and reptiles and 3 other invertebrates species. In addition, some other organisms have also been farmed but have not been described at the species level; FAO usually classifies these as "not elsewhere included" (nei; including potentially already known cultured or new species), with the closest link to the species levels when possible. In 2017, there were 92 nei groups (50 fish groups, 15 mollusc groups, 11 crustacean groups, 9 plant groups, and 7 others).

This species aggregation in the “nei” category may limit accurate quantification of species diversity in aquaculture. The “nei” category covers many taxonomic levels: from identified taxa (a multi-species category; e.g. “tilapias nei”) to a larger aggregate level (a more generic category without species information; e.g. “freshwater fishes nei” and “marine fishes nei”). Further details on the “nei dilemma” can be found in the supplementary material #2.

In term of production, the total volume of farmed aquatic organisms that has been specified at the species level represented 545,511 tonnes in 1950 (92,946 tonnes for nei, 15% of the total production) and 74,157,491 tonnes in 2017 (37,789,132 tonnes for nei, 34% of the total production). Figure 1B shows the proportion of volume for each major grouping of species that has been identified at the species level. The situation is contrasted among the major groups: the relative proportion of fish specified to the species level was constant (average ± SD of 83.1 ± 2.6% for the last 67 years) whereas the relative volume of crustacean specified at the species level increased from 1950 to 2006 (from 18.1% to 94.8%), and then remained fairly constant, with a proportion of 94.9 ± 1.0% of the volume specified at the species levels for the last 10 years (Figure 1B). This trend is opposite for molluscs and aquatic plants: whereby the good estimates at the species level have changed with the increase in volume produced (FAO 2019b) and with the number of species (Table 1), resulting in that the species-volume-based ratio decreasing for both groupings to roughly 50%.

To the best of our knowledge, no study exists to date that has examined details of the spatial distribution and associated number of species (or species diversity) in aquaculture. Figure 2 shows the spatial distribution of production for 1980, 2000, and 2017 (FAO 2019b).

The Shannon Diversity Index (*H'*) is a commonly-used measure of species diversity (i.e. the condition of having or being composed of different species) and evenness (i.e. how evenly spread the population is across the species in an area) combined. *H'* is calculated as (Shannon 1948):

$$H' = -\sum_{i=1}^{n} p_i \ln p_i$$

where p_i is the proportion of production for a given species (*i*) in a given country and year; *n* is the total number of species in a given country and year. This index has theoretically no upper limit and its relative interpretation (in time or space) can be informative. Nevertheless, *H'* is minimal (= 0) when all individuals produced a given year in a given country belong to one single species, and *H'* is increasing when production is evenly diversified. The index is presented in Figure 4 for the years 1980, 2000, and 2017 based on production estimates provided by FAO (2019b). The nei groups were included in the calculation of the index *H'*. This approach avoided any underestimation of the *H'* values due to the non-inclusion of unidentified new species included in the nei. The countries with the top 10 diversity indices and the related number of species cultivated by country and year are presented in Table 2 (full results are available in the supplementary material #3).

Combined, Figure 3 and 4 illustrate that there are considerable differences in the number of species used for aquaculture among different countries and the *H'* values. A high *H'* value is generally associated with elevated production of a large number of species, but there can be considerable differences between countries. As an example, Norway cultivated in 2010 13 species and had a diversity index of 0.23 while Nepal cultivated 11 species and had a diversity index of 1.98. This example shows that the distribution of production across the aquaculture-reared species could be completely different between two countries even when they present similar numbers of species.

China has the highest production, highest number of species, and also the highest Shannon Diversity Index (i.e. 3.32 in 2017). Indeed, Figures 2 to 4 indicate that the importance of China in the aquaculture sector is not limited to having the highest production quantity, its major role in the global market (Villasante *et al*. 2013) or high mean trophic level (Tacon *et al.* 2010), but also in terms of its high diversity index. This high diversity resulted from a combination of factors such as the long history of aquaculture, the natural abundance of indigenous species and sites available for aquaculture, as well as the active role of the Chinese Government to facilitate a diverse aquaculture development (Hishamunda and Subashinge 2003; NBSO 2010).

In comparison with other food production system, aquaculture has a relatively high diversity of aquaculture production at the species level. Indeed, as indicated by Troell *et al.* (2014), today 95% of human energy needs originates from ~30 crop species, of which only four (rice, wheat, maize, and potatoes) makeup around two-thirds of total needs. The meat sector is comprised of around 20 terrestrial animal species, of which only a handful is dominant (e.g., cattle, poultry, swine, goat) (Troell *et al.* 2014). Aquaculture production, by contrast, currently involves 462 identified species and 145 nei groups listed over the last decades but the production of fish and shellfish is currently dominated by only ca. 20 species that together account for 70% of the total global volume (FAO 2019b). In comparison, the current global crop production originates from ~160 species, and only five of these, namely sugar cane, maize, wheat, rice and potatoes (FAO 2019a) make up more than 50% of production totals. Only a handful of animal species are cultivated for food, but genetic diversity is instead provided by about 7,600 different breeds (Troell *et al.* 2014). The direct comparison indicates that, at least at the species level, aquaculture is more diverse than agriculture even with under-evaluation due to the nei dilemma highlighted earlier (supplementary material #2).

Obtaining information on the different variants and breeds of farmed aquaculture species that would permit a more direct comparison to terrestrial plant and animal production is difficult given the paucity of global data sets on genetic diversity in aquaculture below the level of species. For instance, new organisms that originate from a species propagated from hybridization and chromosome manipulation (such as triploid) should also be also reflected in the diversity of production, as suggested by

Liao (2000). Enhancing genetic diversity within species is somehow in opposition to increasing the number of species. Currently, in aquaculture, global datasets on genetically-improved species or strains is scarce. Some successful applications of combined selection for the improvement of fish in developing countries can be found (e.g. GIFT; Eknath *et al.* 1998) or jointly listed (Ponzoni *et al.* 2009). This tracking is, however, typically not performed at a global scale. Today, it is estimated that about 10% of the global production is based on genetically improved individuals (Gjedrem 2012, Gjedrem and Robinson 2014, Gjedrem and Rye 2018, Olesen *et al.* 2015). In the context of the development of new strains and aquaculture expansion, improvements in the documentation on cultured and wild fish genetic resources is increasingly important (Lind *et al.* 2012).

3. The theory: diversity improves resilience

Enhanced diversification in aquaculture could result in improved capacity to adapt to changes – i.e. towards building resilience[1]. A more diverse production at different scales (farms to global production) is recognized as beneficial (Lin 2011; Troell *et al.* 2014) as diversity is a critical aspect of resilience of a system's performance (Holling 1973). According to Downing *et al.* (2012), diverse systems *sensus latto* are generally considered more constant, reliable, predictable and less prone to change than simple systems. However, diversity can never fully prevent a system from collapse but a resilient system may more quickly recover from a disturbance. Although Downing *et al.* (2012) mentioned diversity in the context of "wild" systems, some of the

[1] Resilience is the capacity to persist in the face of change, to continue to develop with ever changing environments (Folke 2016):
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advantages related to resilience capacity may also be obtained in more diverse cultivation systems. The application of "resilience thinking [2] " on production ecosystems has been discussed, mainly in agriculture (Naylor 2008, Lengnick 2014) but also in other production systems (Rist *et al.* 2014, Troell *et al.* 2014). In this case, the resilience of the production system (so called "coerced resilience"; Rist *et al.* 2014) is largely determined by technological human inputs (e.g. fertilizers, feed, energy, etc.) that for example increasingly replace natural processes (e.g. intensive monoculture systems). The coerced resilience implies that the system can after a disturbance regain its production if available human capacities are in place (economy, social, knowledge, material, etc.). Fostering coerced resilience may in the long run result in that a stressor that has been successfully shut out generating a bigger impact on the system compared to if more natural dynamics (including disturbances) would have been allowed (e.g. like controlled forest fires, Drever *et al.* 2006).

Aquaculture, like all agriculture sectors, is vulnerable to exogenous shocks that affect production. Generally, when production is distributed more evenly between species from different groups (e.g. fish, crustaceans, molluscs and aquatic plants), one would expect that it reduces the risks related to production failure from, for example, diseases or weakening markets, at least at a national level (Elmqvist *et al.* 2003; Gephart *et al.* 2017). Thus, a diversified production should be more resilient to future perturbations, although it depends on the type, severity and duration of disturbance (Walker *et al.* 2004). It has been proposed that culturing more species provides a form of insurance and offers better adaptation possibilities under different climate change scenarios, especially unexpected events such as diseases or market issues (Cochrane

[2] See the following link for more information on this concept http://stockholmresilience.org/download/18.10119fc11455d3c557d6928/1459560241272/SRC+Applying+Resilience+final.pdf

et al. 2009, FAO 2016). Building resilience may involve building preparedness for general disturbances (general resilience) or for a specific disturbance (specific resilience; Folke 2016). In aquaculture production, widespread outbreaks (such as the infectious salmon anemia in Chile; Bustos-Gallardo 2013), a global drop of a specific commodity demand (where the system is heavily depending on a single species as *Pangassius* spp. in Vietnam; Trifković, 2014), or an intense competition at global markets levels could for example put a single species production country into crisis. This can become then a larger problem (of social and economic impacts) if a region or a country is highly depended to the affected production (Gephart *et al.* 2017).

Building resilience within the aquaculture sector would imply increasing the species diversity. This could be facilitated by a set of policies (principles, rules, and guidelines) formulated or adopted by countries or organization to reach this long-term goal. Past and current aquaculture policies indicate a willingness to push for species diversity at different spatial scales. FAO (2011) highlighted, for example, the existence of this global political willingness: "incentivizing efforts on research and development and promoting aquaculture diversification programs".

Often one type of particular farming practice in combination with one species of interest dominates (e.g. cage farming of Atlantic salmon in Norway and Chile, pond farming of *Pangassius* sp. in Vietnam, etc.). Indeed, organizations or institutions are still advocating single-species farming practice, but from past experience we have learnt that such methods tend to increase vulnerability of the sector and may eventually lead to a social-ecological trap (from Steneck *et al.* 2011; salmon farming industry in Chile, Bustos-Gallardo 2013) especially if they are not able to adapt and transform the production system for farming other species. In addition, it is noteworthy to mention that commercial diversification and competiveness can, theoretically, also drive species diversification of the industry. Therefore, social, environmental and economic aspects should be in line with the political willingness (Fontaine *et al.* 2009) to facilitate diversification.

Diversification also requires successful development and transfer of technologies to practitioners as well as educating consumers and providing them with adequate information about new species and products. National and global policies can facilitate aquaculture diversification while strengthening the consolidated species (i.e. species well established in aquaculture; Cochrane *et al*. 2009). In the context of government policy, Pingali and Rosegrant (1995) detailed the key elements of a long-term strategy to facilitate commercialization and economy-wide diversification as: (1) research and extension in order to generate productivity and income-enhancing technologies; (2) economic liberalization, including trade and macroeconomic reform and deregulation of agriculture; (3) development and liberalization of rural financial and general capital markets; (4) establishment of secure rights to scarce resources, including land and water, and development of markets in these rights; (5) investment in rural infrastructure and markets; and (6) development of support services, particularly health and nutrition programs.

4. The practice: few species dominate production

FAO indicated a trend towards a higher diversity of farmed species (i.e. through increasing number of farmed species; FAO 2016) and this is also confirmed by our results of the Shannon Diversity Index that has globally increased from 1990 to 210 (Figure 4). However, Teletchea and Fontaine (2014) highlighted two important facts: 1) 28 % of 313 species produced in 1950 were no longer being produced in 2009, 2)

18 % produced in negligible quantities (< 100 tonnes). The reasons explaining that a large proportion of species were reared only for a short period of time are currently unknown and would require further extensive investigations (see the Appendix S2 from Teletchea and Fontaine (2014) for details). Moreover, it is now well established that global aquaculture production is still dominated by just a few key species (see Troell *et al.* 2014) and recent statistics confirm this: 20 species represent 70% of the global production in 2016 (fish, crustaceans and molluscs; FAO, 2019b). As a likely explanation, we assume that a focus on one or a limited number of species allows rapid innovation and improvement of techniques and efficiency. Thus, in the short run a focus on developing a few species may prove more economically favorable compared than working with a larger number of species. Among the various success stories in aquaculture (previously mentioned in section 2), the development of Atlantic salmon aquaculture is a good example of the advantage of focused development. Improvements to Atlantic salmon species tolerance and production systems made over the last thirty years have been beneficial from social, economic, and ecological perspectives. Tacon *et al.* (2010) noted that salmon growth has increased, and production costs and feed conversion ratios have been reduced, as a result of feed technology advancements and the persistent effort of the industry.

As noticed by Teletchea and Fontaine (2014), the rush for new species does not always lead to success. The history of aquaculture shows that attempts to farm numerous fish species often result in only one or a few years of trials before efforts are abandoned (~25 % of the species reared since 1950 had been produced for 5 years or less, Teletchea and Fontaine 2014). Failures are often due to premature attempts for industrialization and to overly optimistic speculation about market demand rather than due to lack of biological and technical knowledge and adequate information about economic feasibility (Jobling 2010).

Indeed, enhancing success rates of a "new species" and its viability require time and market demand considerations (Muir *et al*. 1996; Paquotte *et al.* 1996, Muir and Young 1998). Extensive zootechnical research into new species is necessary before being to be able to farm "new species" at a large-scale and at low cost. According to Paquotte *et al.* (1996), the best options for success in aquaculture are both (1) fast-growing species at low costs and (2) products acceptable to consumers. In practical terms, aquaculture output is likely to remain based on a limited number of key species and market changes stimulated to expand demand of these core species rather than to develop demand for other species (i.e. occupying other market niches; Muir and Young 1998). There might be occasionally some exceptions but this seems to be marginal when we look at the biggest aquaculture species produced.

5. A concluding perspective: the right balance to strike?

Overall, aquaculture is expanding in terms of new areas and species as well as intensifying and diversifying the product range of species and product forms to respond to consumer demands and needs (FAO 2018). Based on our results, Asian aquaculture and particularly China's aquaculture production is the most diversified. This is not surprising considering that diversification of cultured species has been a major goal of China's aquaculture development program (Liu and Li 2010) as well as for some surrounding countries such as Viet Nam (Luu 2011) or India (Sathiadhas *et al.* 2006). Increased demand for seafood and expected far-reaching climate change impacts have also been suggested as main drivers of aquaculture diversification in

Asia (FAO 2016). In this continent, diversity of species created local social benefits to small-scale farmers, offering both biological and economic benefits in aquaculture (Liao 2000). However, aquaculture production in many countries outside Asia is mainly driven by a handful of species - reflecting market demand at national and international levels. A broad and diverse aquaculture portfolio of a country can mitigate potential shocks from rapid changes in markets or environmental conditions (Troell *et al.* 2014). Diversification will depend on political willingness and also close-partnership between research and the aquaculture industry.

According to Liao (2000), the exploitation of new native species and introduction of exotic species are two means for aquaculture diversification. Using non-native species can, however, lead to harmful environmental impact that are difficult to reverse or mitigate. For example, Atlantic salmon *S. salar* in Chile, where escape of salmon from farms can have significant ecological consequences on native biota and ecosystems and is considered one of the key environmental risks associated with salmon aquaculture in this country (Quiñones *et al.* 2019). Similar adverse effects have been reported for the aquaculture of African catfish *Clarias gariepinus* and tilapia in Asia (De Silva *et al.* 2009). The transfer of non-native species constitutes a risk for wild populations (e.g. Naylor *et al.* 2001, De Silva *et al.* 2006, Laikre *et al.* 2010) resulting in that FAO and other international organizations recommends diversifying aquaculture through the use of indigenous species (Bartley and Casal, 1998; De Silva *et al.* 2006).

Knowledge about present species diversity within the aquaculture sector, and how this has changed trough time, are important for guiding its future development. This paper identifies challenges for accurate quantification of diversity and also discusses benefits and trade-offs for different diversity management. Global aquaculture production is dominated by a few dozen species, something that may erode resilience against future challenges such as diseases and climate change.

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Table 1. Details of number of species globally produced in aquaculture and sorted by major groups (nei group excluded; FAO 2019b).

	1980	2000	2017
Fish	64	146	212
Crustaceans	13	28	30
Molluscs	25	53	65
Amphibians and Reptiles	3	3	3
Other invertebrates	0	0	2
Aquatic plants	9	8	20
Total	114	238	332

Table 2. Top 10 countries ranked by highest Shannon diversity index for 2017.

	Shannon diversity			Number of species (nei included)		
Country name	1980	2000	2017	1980	2000	2017
China	1.72	2.81	3.32	22	30	86
Bangladesh	0.37	2.04	2.54	3	10	31
Taiwan, Province of China	2.44	2.75	2.41	28	51	44
Singapore	0.68	1.57	2.38	8	9	14
Lao People’s Democratic Republic	2.08	1.63	2.37	8	9	14
Japan	1.95	2.14	2.17	31	31	27
China, Hong Kong SAR	2.16	2.51	2.13	15	19	18
Cambodia	1.48	1.80	2.08	6	12	25
Malaysia	0.20	2.25	2.06	14	26	47
Portugal	0.70	1.82	2.03	6	14	15

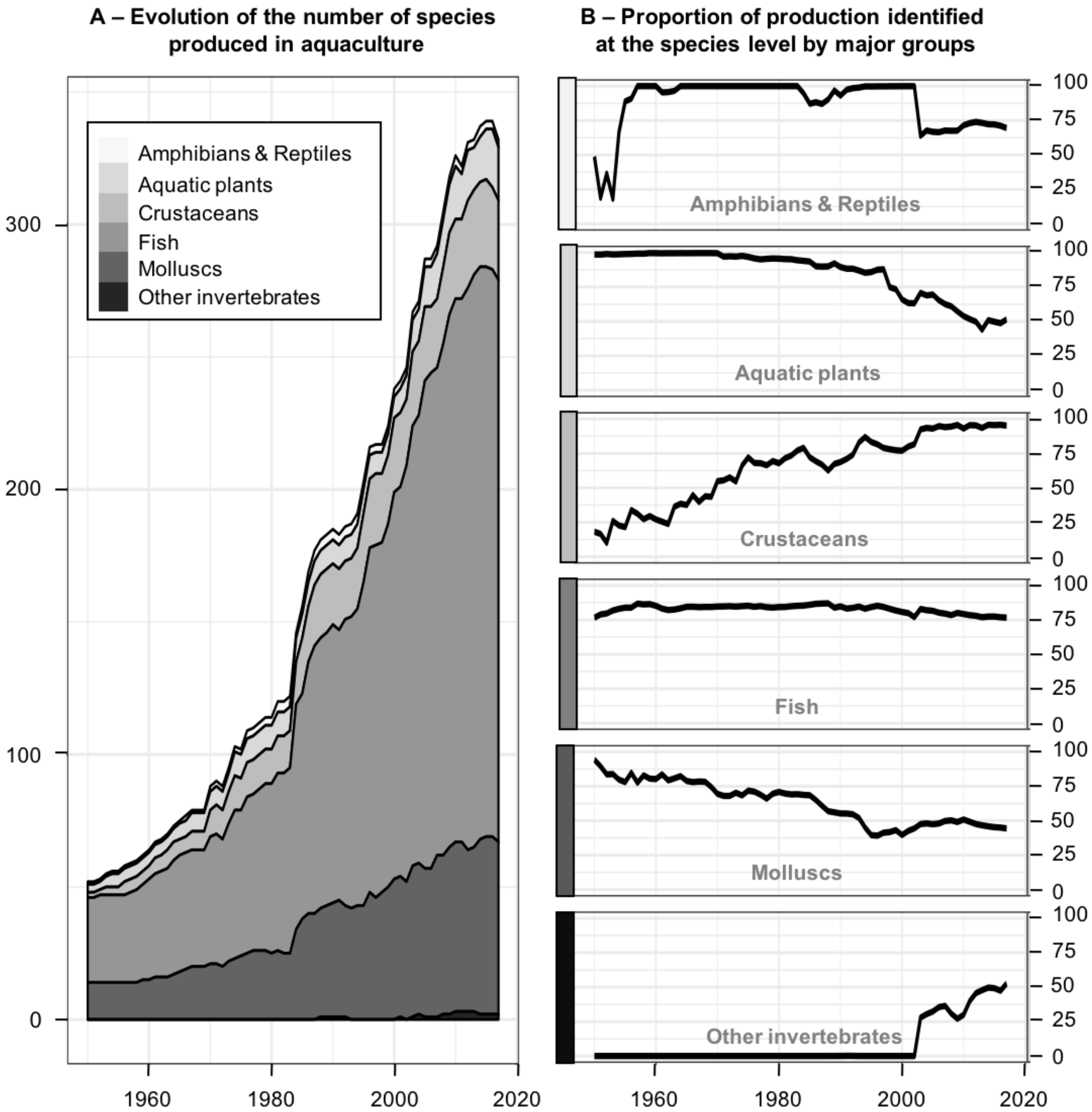
Captions to figures

Figure 1. Global trends of (A) number of species globally produced in aquaculture sorted by major groups (nei group excluded) and (B) proportion (%) of these species for each major group (FAO 2019b).

Figure 2. Aquaculture production represented at the national level in 1980 (top figure), 2000 (middle figure), and 2017 (bottom figure) based on production estimates from FAO (2019b). The production is in t/year and indicated on the legend (notice that the scale is not linear).

Figure 3. Number of species cultivated by country i in 1980 (top figure), 2000 (middle figure), and 2017 (bottom figure) based on estimates from FAO (2019b). Notice that the legend is not linear, but provides more resolution for low values.

Figure 4. Shannon diversity index expresses combined evenness and diversity by country in 1980 (top figure), 2000 (middle figure), and 2017 (bottom figure) based on estimates from FAO (2019b). The legend is not linear, and darker colors indicate higher diversity.


A – Evolution of the number of species produced in aquaculture
Amphibians & Reptiles
Aquatic plants
Crustaceans
Fish
Molluscs
Other invertebrates
300
200
100
0
1960
1980
2000
2020
B – Proportion of production identified at the species level by major groups
Amphibians & Reptiles
Aquatic plants
Crustaceans
Fish
Molluscs
Other invertebrates
100
75
50
25
0
1960
1980
2000
2020

561 **Figure 1**

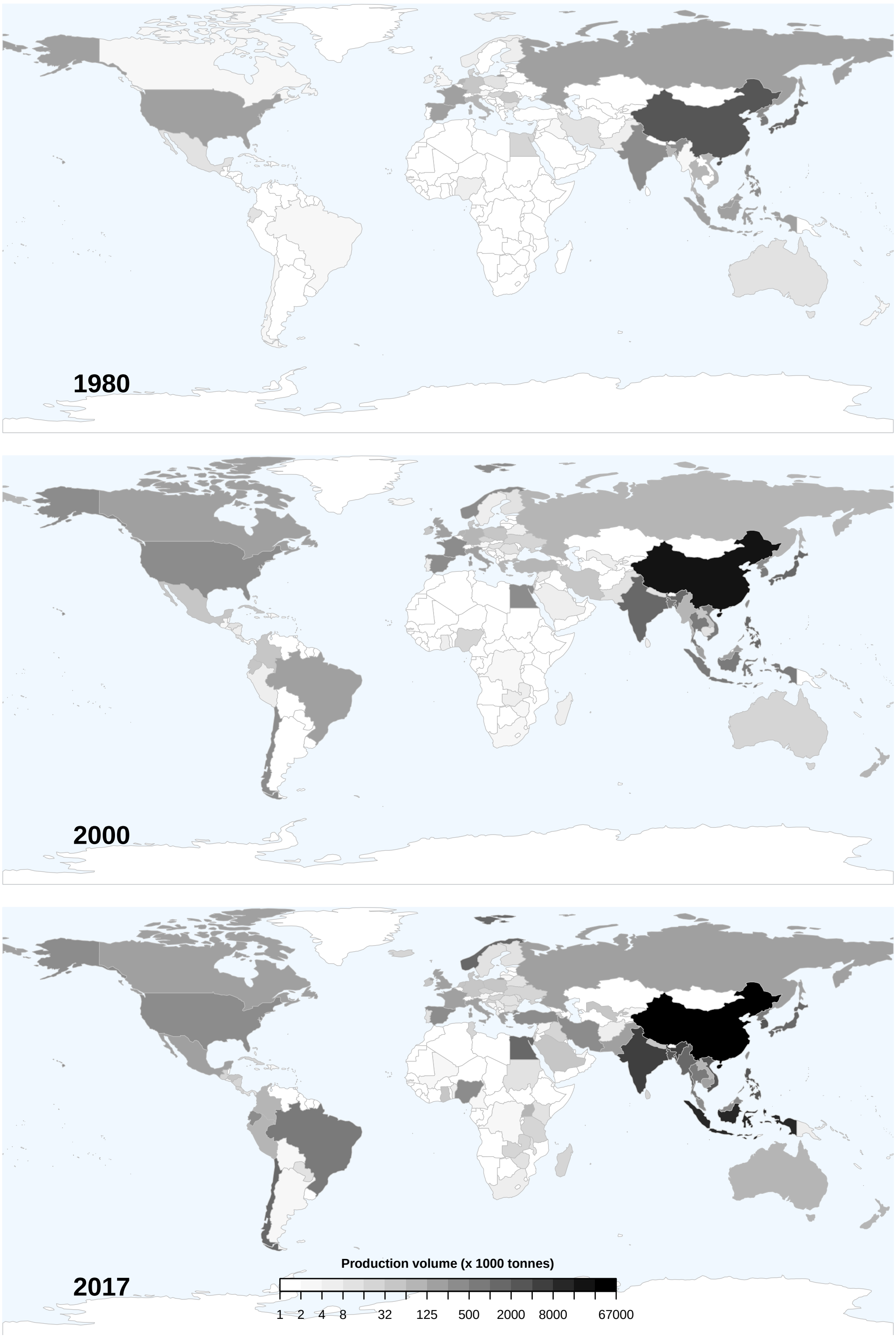

1980
2000
2017
Production volume (x 1000 tonnes)
1 2 4 8 32 125 500 2000 8000 67000

Figure 2

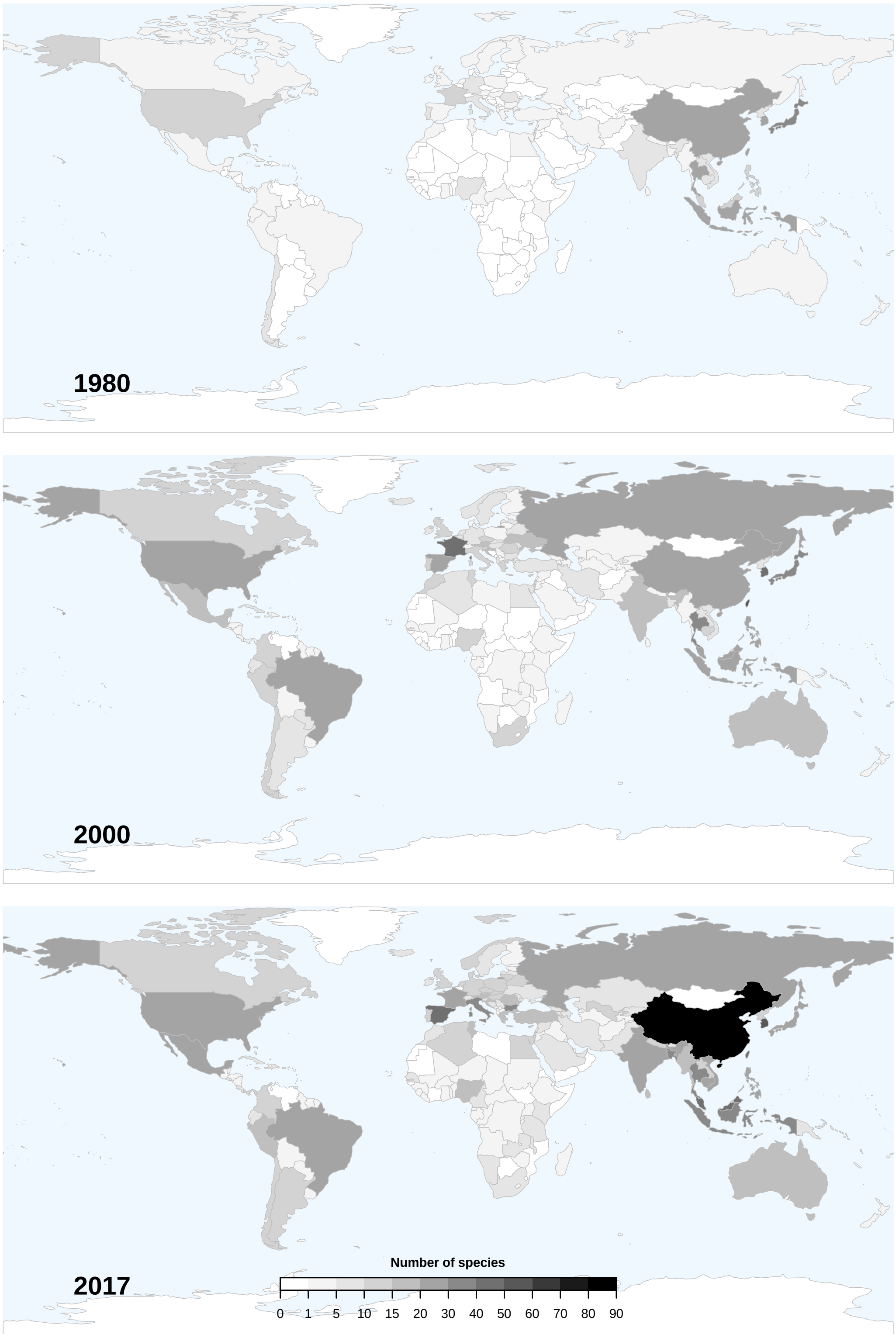

1980
2000
2017
Number of species
0 1 5 10 15 20 30 40 50 60 70 80 90

Figure 3

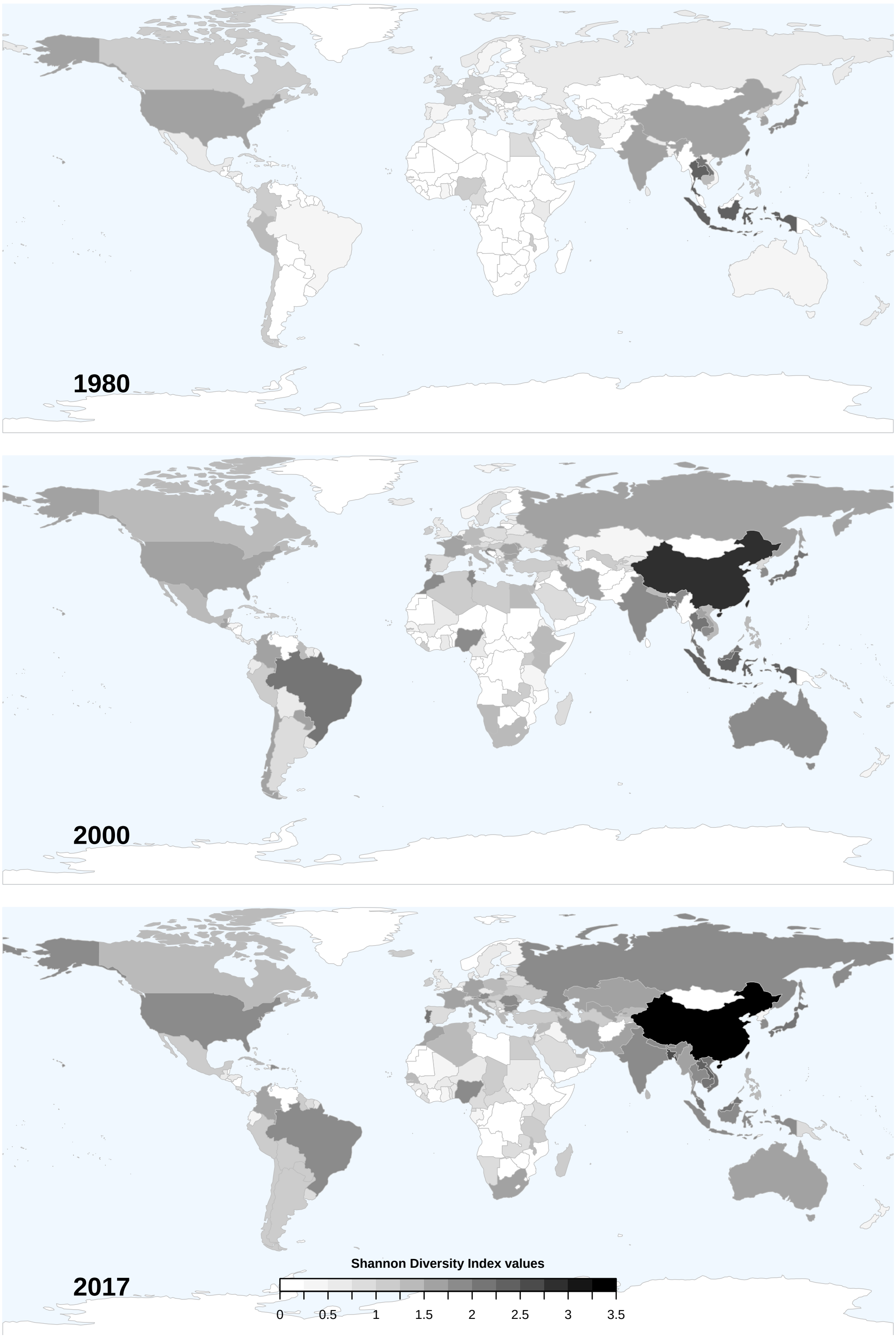

1980
2000
2017
Shannon Diversity Index values
0
0.5
1
1.5
2
2.5
3
3.5

Figure 4