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1 **Mapping diversity of species in global aquaculture**

2
3 **Running head title:** One fish, two fish, red fish: farmed fish

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28 **Abstract**

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

50

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

53

54 **1. Introduction**

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

70 Diversification is often presented as an option for achieving sustainable development
71 for future aquaculture (e.g., FAO 2016, Simard *et al.* 2008, Teletchea and Fontaine,
72 2014). Diversification in aquaculture can be approached in many ways including
73 production systems, markets and reared species. Species diversification can be
74 addressed at different spatial levels (local, district, country, region) through several
75 main approaches (1) increasing the number of species being farmed, (2) increasing the
76 evenness of farmed species and (3) increasing the diversity within currently farmed
77 species by developing new strains (FAO 2016). International institutions such as the

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

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

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

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

103

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

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

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

123 In term of production, the total volume of farmed aquatic organisms that has been
124 specified at the species level represented 545,511 tonnes in 1950 (92,946 tonnes for
125 nei, 15% of the total production) and 74,157,491 tonnes in 2017 (37,789,132 tonnes
126 for nei, 34% of the total production). Figure 1B shows the proportion of volume for

127 each major grouping of species that has been identified at the species level. The
128 situation is contrasted among the major groups: the relative proportion of fish
129 specified to the species level was constant (average \pm SD of $83.1 \pm 2.6\%$ for the last
130 67 years) whereas the relative volume of crustacean specified at the species level
131 increased from 1950 to 2006 (from 18.1% to 94.8%), and then remained fairly
132 constant, with a proportion of $94.9 \pm 1.0\%$ of the volume specified at the species
133 levels for the last 10 years (Figure 1B). This trend is opposite for molluscs and
134 aquatic plants: whereby the good estimates at the species level have changed with the
135 increase in volume produced (FAO 2019b) and with the number of species (Table 1),
136 resulting in that the species-volume-based ratio decreasing for both groupings to
137 roughly 50%.

138 To the best of our knowledge, no study exists to date that has examined details of the
139 spatial distribution and associated number of species (or species diversity) in
140 aquaculture. Figure 2 shows the spatial distribution of production for 1980, 2000, and
141 2017 (FAO 2019b).

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

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

146 where p_i is the proportion of production for a given species (i) in a given country and
147 year; n is the total number of species in a given country and year. This index has
148 theoretically no upper limit and its relative interpretation (in time or space) can be

149 informative. Nevertheless, H' is minimal (= 0) when all individuals produced a given
150 year in a given country belong to one single species, and H' is increasing when
151 production is evenly diversified. The index is presented in Figure 4 for the years
152 1980, 2000, and 2017 based on production estimates provided by FAO (2019b). The
153 nei groups were included in the calculation of the index H' . This approach avoided
154 any underestimation of the H' values due to the non-inclusion of unidentified new
155 species included in the nei. The countries with the top 10 diversity indices and the
156 related number of species cultivated by country and year are presented in Table 2 (full
157 results are available in the supplementary material #3).

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

166 China has the highest production, highest number of species, and also the highest
167 Shannon Diversity Index (i.e. 3.32 in 2017). Indeed, Figures 2 to 4 indicate that the
168 importance of China in the aquaculture sector is not limited to having the highest
169 production quantity, its major role in the global market (Villasante *et al.* 2013) or high
170 mean trophic level (Tacon *et al.* 2010), but also in terms of its high diversity index.
171 This high diversity resulted from a combination of factors such as the long history of
172 aquaculture, the natural abundance of indigenous species and sites available for

173 aquaculture, as well as the active role of the Chinese Government to facilitate a
174 diverse aquaculture development (Hishamunda and Subashinge 2003; NBSO 2010).

175 In comparison with other food production system, aquaculture has a relatively high
176 diversity of aquaculture production at the species level. Indeed, as indicated by Troell
177 *et al.* (2014), today 95% of human energy needs originates from ~30 crop species, of
178 which only four (rice, wheat, maize, and potatoes) makeup around two-thirds of total
179 needs. The meat sector is comprised of around 20 terrestrial animal species, of which
180 only a handful is dominant (e.g., cattle, poultry, swine, goat) (Troell *et al.* 2014).
181 Aquaculture production, by contrast, currently involves 462 identified species and
182 145 nei groups listed over the last decades but the production of fish and shellfish is
183 currently dominated by only ca. 20 species that together account for 70% of the total
184 global volume (FAO 2019b). In comparison, the current global crop production
185 originates from ~160 species, and only five of these, namely sugar cane, maize,
186 wheat, rice and potatoes (FAO 2019a) make up more than 50% of production totals.
187 Only a handful of animal species are cultivated for food, but genetic diversity is
188 instead provided by about 7,600 different breeds (Troell *et al.* 2014). The direct
189 comparison indicates that, at least at the species level, aquaculture is more diverse
190 than agriculture even with under-evaluation due to the nei dilemma highlighted earlier
191 (supplementary material #2).

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

198 Liao (2000). Enhancing genetic diversity within species is somehow in opposition to
199 increasing the number of species. Currently, in aquaculture, global datasets on
200 genetically-improved species or strains is scarce. Some successful applications of
201 combined selection for the improvement of fish in developing countries can be found
202 (e.g. GIFT; Eknath *et al.* 1998) or jointly listed (Ponzoni *et al.* 2009). This tracking is,
203 however, typically not performed at a global scale. Today, it is estimated that about
204 10% of the global production is based on genetically improved individuals (Gjedrem
205 2012, Gjedrem and Robinson 2014, Gjedrem and Rye 2018, Olesen *et al.* 2015). In
206 the context of the development of new strains and aquaculture expansion,
207 improvements in the documentation on cultured and wild fish genetic resources is
208 increasingly important (Lind *et al.* 2012).

209

210 **3. The theory: diversity improves resilience**

211 Enhanced diversification in aquaculture could result in improved capacity to adapt to
212 changes – i.e. towards building resilience¹. A more diverse production at different
213 scales (farms to global production) is recognized as beneficial (Lin 2011; Troell *et al.*
214 2014) as diversity is a critical aspect of resilience of a system's performance (Holling
215 1973). According to Downing *et al.* (2012), diverse systems *sensus lato* are generally
216 considered more constant, reliable, predictable and less prone to change than simple
217 systems. However, diversity can never fully prevent a system from collapse but a
218 resilient system may more quickly recover from a disturbance. Although Downing *et*
219 *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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220 advantages related to resilience capacity may also be obtained in more diverse
221 cultivation systems. The application of “resilience thinking²” on production
222 ecosystems has been discussed, mainly in agriculture (Naylor 2008, Lengnick 2014)
223 but also in other production systems (Rist *et al.* 2014, Troell *et al.* 2014). In this case,
224 the resilience of the production system (so called “coerced resilience”; Rist *et al.*
225 2014) is largely determined by technological human inputs (e.g. fertilizers, feed,
226 energy, etc.) that for example increasingly replace natural processes (e.g. intensive
227 monoculture systems). The coerced resilience implies that the system can after a
228 disturbance regain its production if available human capacities are in place (economy,
229 social, knowledge, material, etc.). Fostering coerced resilience may in the long run
230 result in that a stressor that has been successfully shut out generating a bigger impact
231 on the system compared to if more natural dynamics (including disturbances) would
232 have been allowed (e.g. like controlled forest fires, Drever *et al.* 2006).

233 Aquaculture, like all agriculture sectors, is vulnerable to exogenous shocks that affect
234 production. Generally, when production is distributed more evenly between species
235 from different groups (e.g. fish, crustaceans, molluscs and aquatic plants), one would
236 expect that it reduces the risks related to production failure from, for example,
237 diseases or weakening markets, at least at a national level (Elmqvist *et al.* 2003;
238 Gephart *et al.* 2017). Thus, a diversified production should be more resilient to future
239 perturbations, although it depends on the type, severity and duration of disturbance
240 (Walker *et al.* 2004). It has been proposed that culturing more species provides a form
241 of insurance and offers better adaptation possibilities under different climate change
242 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>

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

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

259 Often one type of particular farming practice in combination with one species of
260 interest dominates (e.g. cage farming of Atlantic salmon in Norway and Chile, pond
261 farming of *Pangassius* sp. in Vietnam, etc.). Indeed, organizations or institutions are
262 still advocating single-species farming practice, but from past experience we have
263 learnt that such methods tend to increase vulnerability of the sector and may
264 eventually lead to a social-ecological trap (from Steneck *et al.* 2011; salmon farming
265 industry in Chile, Bustos-Gallardo 2013) especially if they are not able to adapt and
266 transform the production system for farming other species. In addition, it is
267 noteworthy to mention that commercial diversification and competitiveness can,

268 theoretically, also drive species diversification of the industry. Therefore, social,
269 environmental and economic aspects should be in line with the political willingness
270 (Fontaine *et al.* 2009) to facilitate diversification.

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

285

286 **4. The practice: few species dominate production**

287 FAO indicated a trend towards a higher diversity of farmed species (i.e. through
288 increasing number of farmed species; FAO 2016) and this is also confirmed by our
289 results of the Shannon Diversity Index that has globally increased from 1990 to 210
290 (Figure 4). However, Teletchea and Fontaine (2014) highlighted two important facts:
291 1) 28 % of 313 species produced in 1950 were no longer being produced in 2009, 2)

292 18 % produced in negligible quantities (< 100 tonnes). The reasons explaining that a
293 large proportion of species were reared only for a short period of time are currently
294 unknown and would require further extensive investigations (see the Appendix S2
295 from Teletchea and Fontaine (2014) for details). Moreover, it is now well established
296 that global aquaculture production is still dominated by just a few key species (see
297 Troell *et al.* 2014) and recent statistics confirm this: 20 species represent 70% of the
298 global production in 2016 (fish, crustaceans and molluscs; FAO, 2019b). As a likely
299 explanation, we assume that a focus on one or a limited number of species allows
300 rapid innovation and improvement of techniques and efficiency. Thus, in the short run
301 a focus on developing a few species may prove more economically favorable
302 compared than working with a larger number of species. Among the various success
303 stories in aquaculture (previously mentioned in section 2), the development of
304 Atlantic salmon aquaculture is a good example of the advantage of focused
305 development. Improvements to Atlantic salmon species tolerance and production
306 systems made over the last thirty years have been beneficial from social, economic,
307 and ecological perspectives. Tacon *et al.* (2010) noted that salmon growth has
308 increased, and production costs and feed conversion ratios have been reduced, as a
309 result of feed technology advancements and the persistent effort of the industry.

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

316 due to lack of biological and technical knowledge and adequate information about
317 economic feasibility (Jobling 2010).

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

329

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

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

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

348 According to Liao (2000), the exploitation of new native species and introduction of
349 exotic species are two means for aquaculture diversification. Using non-native species
350 can, however, lead to harmful environmental impact that are difficult to reverse or
351 mitigate. For example, Atlantic salmon *S. salar* in Chile, where escape of salmon
352 from farms can have significant ecological consequences on native biota and
353 ecosystems and is considered one of the key environmental risks associated with
354 salmon aquaculture in this country (Quiñones *et al.* 2019). Similar adverse effects
355 have been reported for the aquaculture of African catfish *Clarias gariepinus* and
356 tilapia in Asia (De Silva *et al.* 2009). The transfer of non-native species constitutes a
357 risk for wild populations (e.g. Naylor *et al.* 2001, De Silva *et al.* 2006, Laikre *et al.*
358 2010) resulting in that FAO and other international organizations recommends
359 diversifying aquaculture through the use of indigenous species (Bartley and Casal,
360 1998; De Silva *et al.* 2006).

361 Knowledge about present species diversity within the aquaculture sector, and how this
362 has changed through time, are important for guiding its future development. This paper
363 identifies challenges for accurate quantification of diversity and also discusses
364 benefits and trade-offs for different diversity management. Global aquaculture

365 production is dominated by a few dozen species, something that may erode resilience
366 against future challenges such as diseases and climate change.

367

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377

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540 **Table 1.** Details of number of species globally produced in aquaculture and sorted by
 541 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

542

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

Country name	Shannon diversity			Number of species (nei included)		
	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

544

545 **Captions to figures**

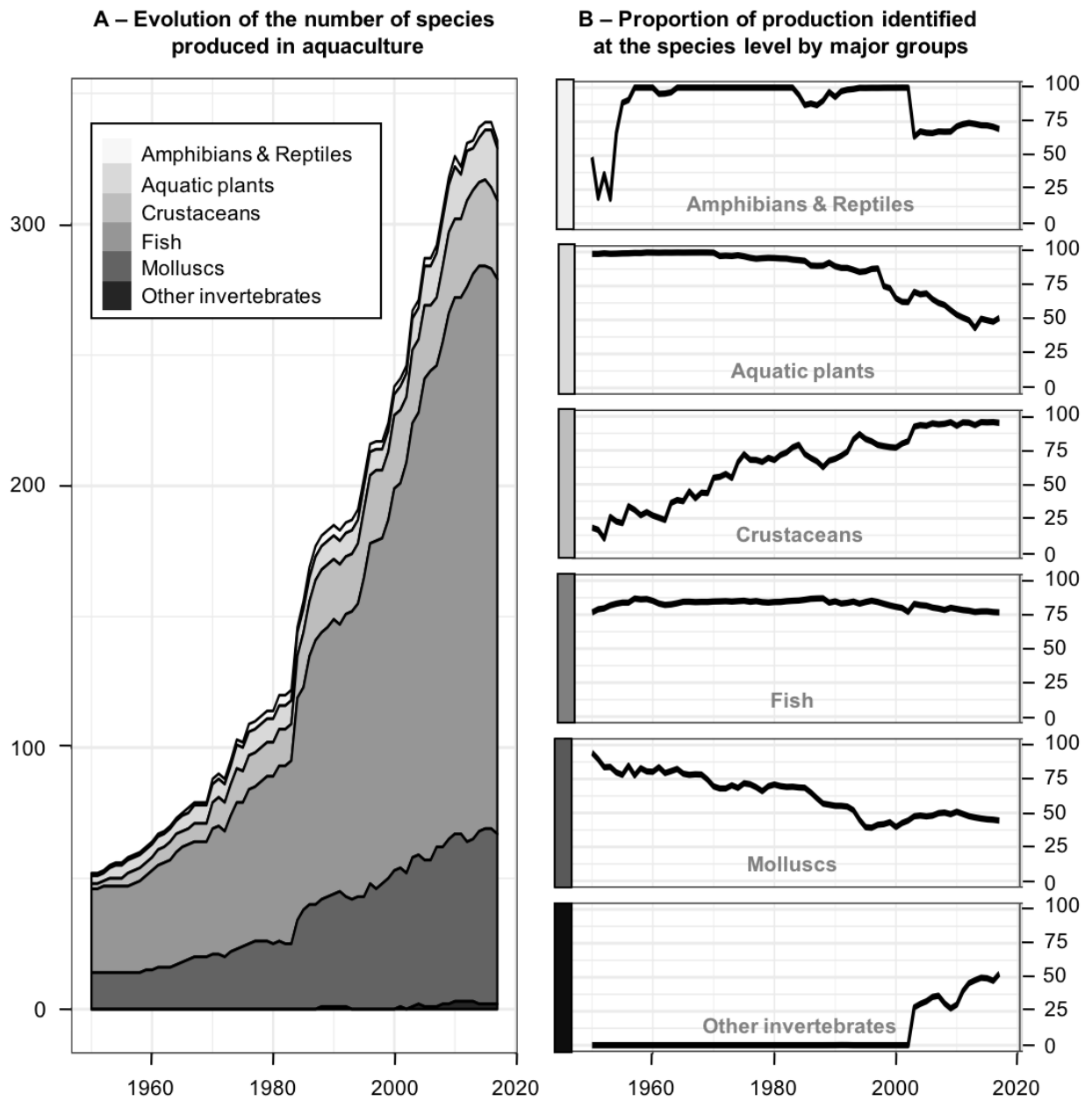
546

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

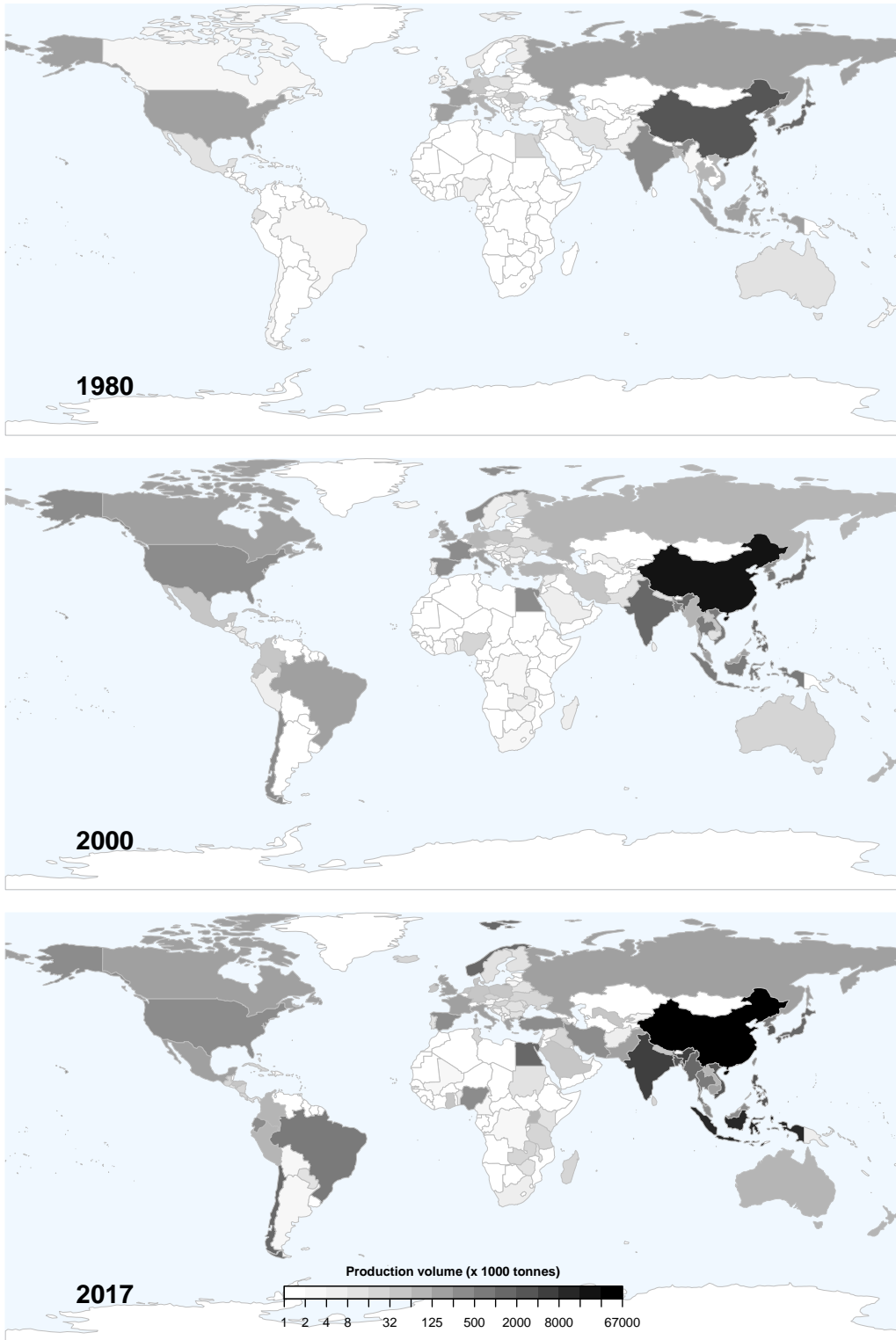
550 **Figure 2.** Aquaculture production represented at the national level in 1980 (top
551 figure), 2000 (middle figure), and 2017 (bottom figure) based on production estimates
552 from FAO (2019b). The production is in t/year and indicated on the legend (notice
553 that the scale is not linear).

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

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

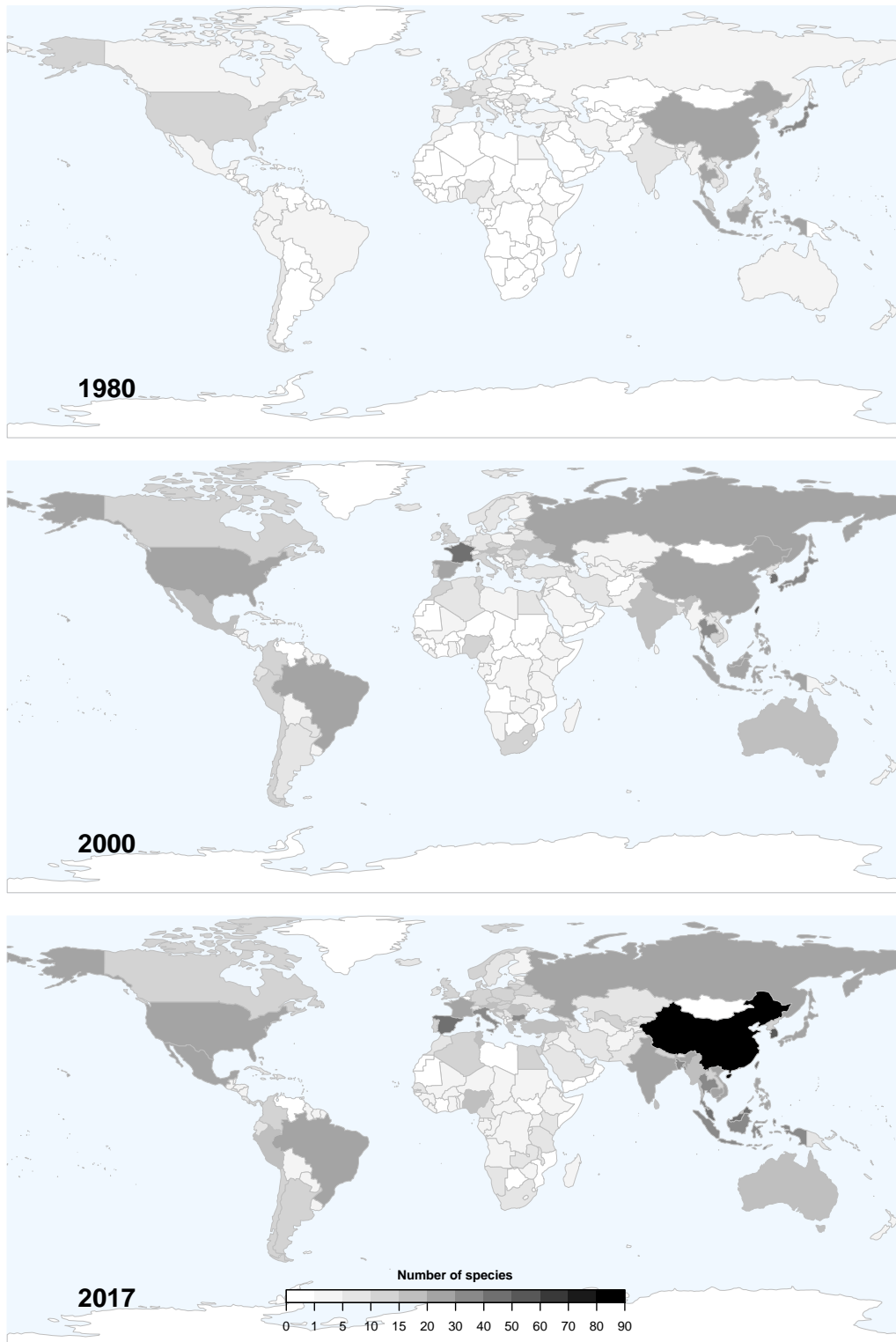


561 **Figure 1**



562

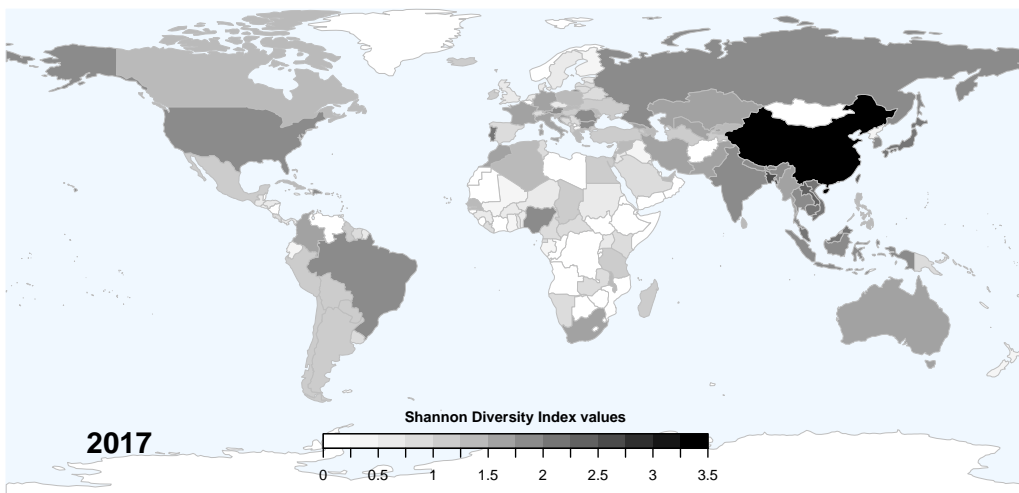
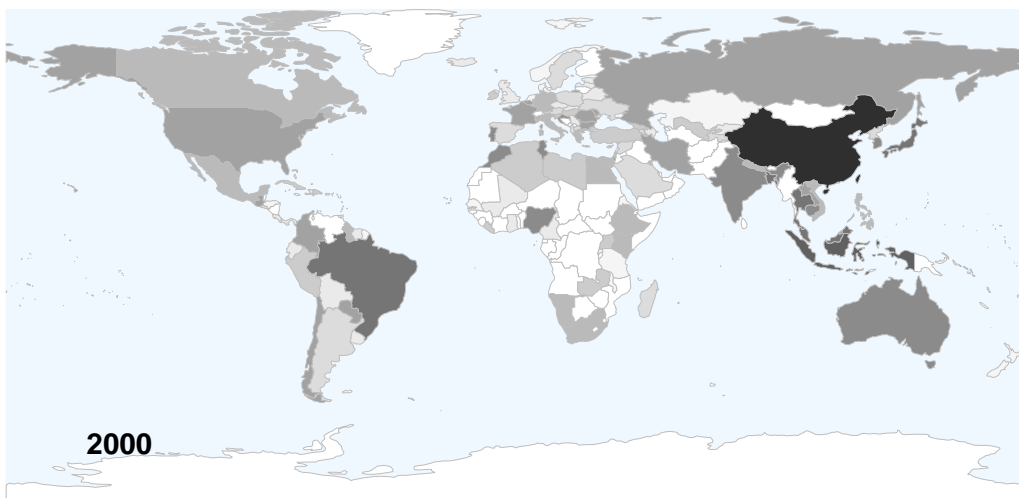
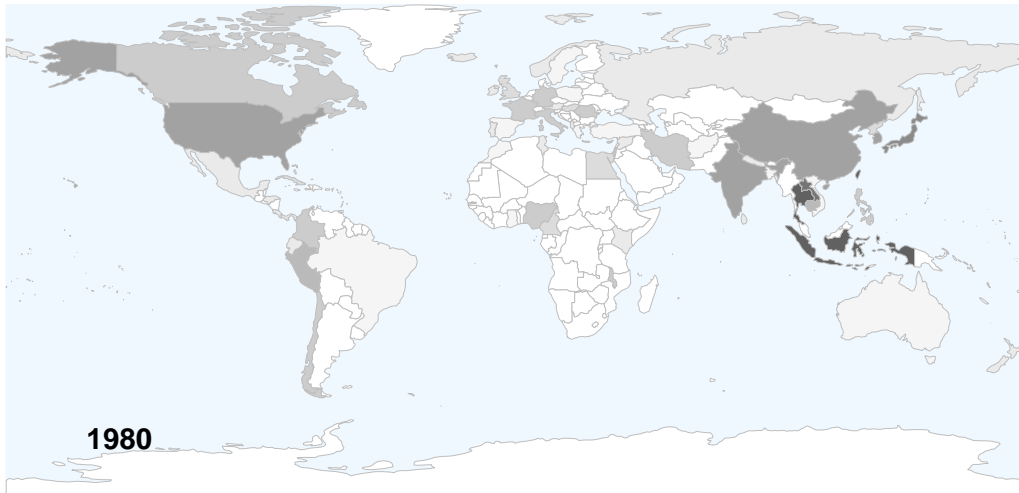
563 **Figure 2**



564

565 **Figure 3**

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Figure 4