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1 **Aquaculture of marine ornamental fish: overview of the production trends**
2 **and the role of academia in research progress**

3

4 **Running head: Role of academia in ornamental fish aquaculture**

5

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7

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18 **Abstract:**

19 The marine ornamental fish trade is expanding and still largely relies on wild fish from
20 tropical coral reef ecosystems. There are unknowns in the wild harvest so that the
21 sustainability of marine ornamental fish trade can therefore be questioned with aquaculture
22 being perceived as a responsible alternative for the procurement of these ornamental marine
23 fish. However, there are still many technical constraints that hinder its development. These
24 blocks require additional coordination with the outcome being an accelerated development of
25 ornamental marine fish production. The main objective of this review is to better identify,
26 understand and discuss the role and the impacts of academic research in the production of
27 marine ornamental fish through qualitative and quantitative approaches. To do so, 222
28 selected scientific publications (including peer-reviewed articles, conferences articles, thesis
29 and reports) from the literature available to date were analyzed and outcomes were framed in
30 perspective of the total number of captive-bred species. Results of the meta-analyses indicate
31 that academic research has led to significant advances in the breeding of some of the more
32 difficult to breed species. While it has a leading role in conservation, its advance of
33 techniques still lags behind private companies and hobbyists. Partnerships promoting
34 synergistic activities between academic research institutes and the private sector (aquaculture
35 farms and public aquariums) are important to optimize future ornamental marine fish
36 production.

37

38 Keywords: Fishkeeping; Sustainable production; Aquaculture; Research and Development;
39 Academic research; Captive breeding

40 **1. Introduction**

41 In 2003, Disney and Pixar released a hit movie, “Finding Nemo” with the two main
42 protagonists being Nemo, a clown anemonefish *Amphiprion ocellaris* and Dory, a Pacific blue
43 tang *Paracanthurus hepatus*. Although the influence of the movie (called the “Nemo Effect”;
44 Militz & Foale 2017) on purchases of wild-caught fish was not rigorously demonstrate
45 (Veríssimo *et al.* in press), some news media papers and pet stores of increasing clownfish
46 sales following the release of this film (Prosek 2010). Notwithstanding, some authors argue
47 that such movies based on an emotive but scientifically incorrect approach, driven by popular
48 media to promote coral reef ecosystems protection can be damaging because it could
49 unintentionally contribute to impulsive purchase of coral marine species by uninformed
50 people (Militz & Foale 2017; Olivotto *et al.* 2017).

51 The threats for coral reefs related to the collection of ornamental fish include the reduction of
52 biodiversity from over-extraction and habitat destruction in some source countries
53 (Dammannagoda 2018). The large number of species in the trade (over 2,500, Rhyne *et al.*
54 2017b) from a large number of countries with many species being collected at number <1,000
55 individuals per year (Rhyne *et al.* 2017b) make any fisheries management plan onerous.
56 Furthermore, destructive methods are still used illegally such as cyanide in Southeast Asia
57 (Vagelli 2011; Cohen *et al.* 2013) although some efforts have been made to adopt friendly
58 collecting methods such as nets and traps (Lecchini *et al.* 2006). Destructive methods are non-
59 selective, causing considerable and long-term damages to coral reefs, risky for collectors and
60 resulted in very high mortality of wild-caught fish. For instance, cyanide fishing has been
61 reported to result in >80% mortality of marine aquarium fish being exported to other
62 countries (Rubec *et al.* 2001). Taking account all the steps from the catches to the final buyer,
63 it is usually estimated that only 30-40% caught marine ornamental fish survive (Wabnitz *et al.*

64 2003). All of these figures demonstrate a high degree of unknowns regarding the
65 sustainability of wild fish collection for the marine ornament market.

66 The marine aquarium trade is a global multimillion industry that started in the 1930s and
67 experienced a significant increase over the last decades (Wabnitz *et al.* 2003; Murray *et al.*
68 2012; Rhyne *et al.* 2012; Leal *et al.* 2015). Thus, marine ornamental fish trade increased from
69 US\$ 24-40 million annually in the 1980s (Wood 1985) to currently exceed US\$ 300 million
70 (Palmtag 2017). Approximately 30 million marine reef fish are commercialized every year
71 worldwide (Wabnitz *et al.* 2003; Rhyne *et al.* 2012; Leal *et al.* 2015). The pressure on wild
72 stocks is increasing, to the point of endangering certain species. One of the famous examples
73 of the direct impacts of fisheries for aquarium trade is the Banggai cardinalfish *Pterapogon*
74 *kauderni* natives to Sulawesi. As described by Rhyne *et al.* (2012), once *P. kauderni* entered
75 the marine aquarium trade it quickly became heavily traded and overexploited. Import prices
76 of *Banggai cardinalfish* dropped as supplies increased and wild population suffered a
77 reduction of population fitness. The Banggai cardinalfish is now included in the IUCN Red
78 List of Threatened Species under the “Endangered” status (IUCN 2018).

79 The captive breeding of marine ornamental fish species (i.e. spawning, hatching, settling and
80 growth to the juvenile or adult stage in enclosed system) is a way to support marine fish
81 aquarium trade (Olivotto *et al.* 2017). However, there are still numerous critical steps to
82 widely produce ornamental marine fish (Moorhead & Zeng 2010; Olivotto *et al.* 2011;
83 Olivotto *et al.* 2017). One of the bottlenecks in marine ornamental fish production is the larval
84 rearing: many species produce larvae virtually impossible to maintain under appropriate
85 conditions, including adequate feeding based on our current knowledge (DiMaggio *et al.*
86 2017; Olivotto *et al.* 2017; Rhyne *et al.* 2017a; Callan *et al.* 2018). Increase the research effort
87 on marine ornamental fish aquaculture is one of the ways to overcome the current brakes to
88 increase the availability of captive-bred (CB) species.

89 Previous literature reviews on this topic have examined the state-of-the-art marine ornamental
90 fish production advances from academic research, at different points of time, including
91 developments in breeding methods as well as larval rearing (see Moorhead & Zeng 2010).
92 The present review is looking at the historical status of marine ornamental fish aquaculture
93 with an emphasis on the advances of academic research. It also provides a qualitative and
94 quantitative analysis on the field of research to highlight, understand and discuss the impacts
95 of academic research in the marine ornamental fish aquaculture. Although this study was
96 focused on ornamental marine aquaculture, most of the issues addressed apply also to
97 invertebrates.

98

99 **2. Methods**

100 2.1. Captive-bred species list

101 2.1.1. Captive-bred species list from the CORAL Magazine

102 The starting point of this study is collection of the data from the annually-updated CORAL
103 Magazine (<https://www.coralmagazine.com>). This magazine is known for reporting all
104 existing captive-bred marine fish species in a list (after called CORAL list) since January
105 2013. More precisely, this list is an annual project, carried out by CORAL Magazine and the
106 Marine Breeding Initiative (MBI), and correspond to an annual accounting of first-time
107 tropical marine fish breeding accomplishments as well as accessibility of CB marine fishes
108 within the marine aquarium hobby and industry (CORAL 2018). This list was drawn from
109 previous inventories such as the Frank Baensch's CB species list established for Reef Culture
110 Technologies (<https://www.frankbaensch.com/marine-aquarium-fish-culture/my-research>) last
111 updated in 2011.

112 To be listed, breeding successes of new species must be supported by documentation to attest
113 to the veracity of the information and/or confirmed by third-party sources (see CORAL 2018

114 for details regarding methodology). The list included species bred in captivity as well as their
115 relative availability in the US market. Thus, listed species can be:

- 116 • Unavailable: Authors and consulted parties were unaware of any availability of these
117 species.
- 118 • Scarce: Only one source or breeder identified for these species, limited number of
119 individuals have been commercially available.
- 120 • Moderate: Limited availability for these species, but several sources identified.
- 121 • Common: Commonly available on the market, easy to find as CB species, and
122 available from several sources.

123 Before the publication of a new list, the authors and editors of the list once again reach out to
124 commercial aquaculturists, public aquarists and academic researchers, in an attempt to
125 compile the most comprehensive list possible (CORAL 2018).

126

127 2.1.2. Checking and updating the CB species list

128 In order to check and update the CORAL list content, all the lists established for the years
129 2012 to 2017, available online (CORAL 2018), have been downloaded and sorted by year. In
130 all cases, species names were verified using the World Register of Marine Species (WoRMS)
131 (Appeltans *et al.* 2012) and FishBase (Froese & Pauly 2018) and corrected when species
132 names were misspelled or species listed under a former synonym. A sorting was then made to
133 remove species mainly raised for human consumption. As a result of this sorting, 20 species
134 from 6 families were removed from the list (Table 1). Although seahorses are used in
135 traditional medicine, Koldewey & Martin-Smith (2010) have shown that sale of live seahorses
136 for aquariums was the dominant market for CB seahorses, and why these species were
137 included in our analysis. Data on each reported breeding success were collected from general
138 online public articles, reports and discussion forums. In order to evaluate the availability of

139 CB species on the world market, availability from e-commerce websites (n=9) from different
140 countries were recorded from September to December 2018 as well as the product list on
141 aquaculture company and wholesaler websites (n=8). In parallel, surveys were sent to the
142 marine ornamental aquaculture stakeholders (consultants and wholesalers, n=4 replies) from
143 Asia and Europe to determine the availability of species recorded in the CORAL list
144 established for 2017 in non-US markets. Global Marine Aquarium Database (GMAD,
145 Wabnitz *et al.* 2003) was one more source of information used to evaluate the availability of
146 CB species in the aquarium trade.

147 The entire data collection process led to the construction of a database (Supplemental data)
148 for the year 2017 where the identified ornamental marine fish species already CB were
149 reported and sorted by family. Accepted scientific names, vernacular name, IUCN Red List
150 status (IUCN 2019) and commercial availability were also provided.

151

152 2.2. Academic literature search

153 Searches were performed individually for each identified captive bred fish species fish (see
154 section 2.1.2) using two commonly used databases: Google Scholar and Web of Science
155 (WOS). In addition, the proceedings from the World Aquaculture Society (WAS) were also
156 considered. Searches included peer-reviewed articles, conferences articles, thesis and
157 scientific reports over the time span from 1950 to present (2018, December 31). Following
158 searches, non-relevant records (i.e. studies that did not address aquaculture and captive
159 breeding) and review articles were removed. The completeness of the results obtained was
160 considered as satisfactory based on (1) comparison with previous reviews (Arvedlund *et al.*
161 2000; Koldewey & Martin-Smith 2010; Moorhead & Zeng 2010; Olivotto *et al.* 2011;
162 Domínguez & Botella 2014; Cohen *et al.* 2017) and (2) using “snowballing” references (i.e.

163 checking citations on reference lists of relevant articles until no further relevant articles could
164 be found; Sayers 2007).

165

166 2.3. Advances in academic research

167 We are aware that improvements made in the cultivation of more suitable live prey such as
168 copepods (e.g. Alajmi *et al.* 2015) were among the most important advances achieved in
169 academic research on marine ornamental fish production. Nevertheless, this review is only
170 focusing on research directly related to fish. From the list of final list of selected papers, each
171 record was then categorised on the basis of the study content and the method used. The
172 different categories are mainly resulting from the key stages of fish biological development
173 (from egg to adult) and main aquaculture production steps. The selected categories are the
174 following:

- 175 • *Broodstock management*: studies addressing basic aspects of maintenance and
176 maturation in captivity of adult fish used as broodstock.
- 177 • *Spawning*: studies reporting spawning in captivity from already CB or wild
178 broodstock, matured or not in captivity.
- 179 • *Egg/Embryonic development*: studies quantifying egg quality from captive spawning
180 and/or describing incubation phase and embryonic development.
- 181 • *Larval rearing*: studies addressing main aspects of larval rearing such the influence of
182 first exogenous food, food enrichment, prey density or/and physical and chemical
183 conditions on zootechnical performances.
- 184 • *Metamorphosis*: studies in which larval rearing has been accomplished until larvae
185 metamorphosis. This category includes both studies reporting complete larval rearing
186 (from hatching to metamorphosis) or partial larval rearing resulting, for example, from
187 purchased hatched larvae.

- 188 • *Juvenile rearing*: studies investigating juvenile rearing from juveniles obtained from
189 larvae or purchased from Aquaculture Company.

190

191 **3. Results**

192 3.1. Captive bred species reported from 2012 to 2017

193 There are currently 338 marine ornamental fish species belonging to 37 families reported as
194 Captive bred (CB) species (Figure 1 and Table 2; excluding species that may be intended for
195 human consumption). Among these species, 134 are commercially available but only 18% of
196 them are common on the market (Table 2). These are mainly species of clownfish
197 (Pomacentridae), dottyback (Pseudochromidae), blenny (Blennidae), and cardinalfish
198 (Apogonidae).

199 Since 2012, when the first CORAL list was published, the number of marine ornamental CB
200 fish species has linearly increased from 225 to 338 in 2017 (Figure 1A). However, the trends
201 observed are not the same depending on the families considered. Among the six most
202 represented families (i.e. 69% of the studied species in 2017; Figure 1A), the number of CB
203 species has been constant since 2012 for Blennidae, Pomacentridae and Pseudochromidae
204 (Figure 1B). Conversely, for the lesser studied species, the number of Gobiidae,
205 Pomacanthidae and Syngnatidae increased over the last 2-3 years (Figure 1C).

206

207 3.2. Academic research effort

208 3.2.1. Summary of scientific database searches

209 From the initial aquaculture-related studies within the bibliographic survey, 222 relevant
210 records were identified (according to the criteria described in the section 2.3). These studies
211 were composed of 184 peer-reviewed research articles, 7 scientific reports, 3 theses, and 28

212 conference abstracts and articles. These indicated that academic research effort focused on
213 117 species from 23 families (Table 3).

214 The bibliometric analysis revealed that academic research effort on reproduction, growth
215 and/or production of marine ornamental fish species increased exponentially from the 1960s
216 until the 2000s with one publication published during the 1960s against 85 publications by the
217 end of the 2000s (Figure 2). After 2009, the research effort continued to increase, with 120
218 publications published between 2010 and December 2018. A similar trend was observed for
219 the number of species considered (Figure 2). Globally, 26 countries contributed, 20 with more
220 than one study (Figure 3). The largest contributor was the USA, represented by 51 studies on
221 46 species, followed by India with 34 studies on 26 species and Australia represented by 23
222 studies on 22 species. The remaining countries were represented by 1 to 15 studies each on 1
223 to 14 species (Figure 3).

224

225 3.2.2. Academic research from a zootechnical point of view

226 In addition to the reports on the studied species, information on the main zootechnical
227 advances led by academic research was collected. For this purpose, the selected publications
228 were analyzed in order to determine which production phases were considered keeping in
229 mind that some studies may investigate more than one phase. Results shows that more than
230 70% of the published academic research was focused on the first production steps (i.e. from
231 the broodstock management to the eggs), whereas only 46% were performed on larval
232 rearing, while 32% carried out experiments until metamorphosis (Figure 4). Furthermore,
233 there was disparity between the families studied (Figure 4). Indeed, the production of species
234 from certain families such as Apogonidae, Blennidae, Gobiidae or Pomacentridae were the
235 focus of research on all life stages. This was also true for other species without free-larval
236 stage such as the Hemiscylliidae, Scyliorhinidae or Syngnathidae. On the other hand, full

237 coverage of each life stage was not researched for other families. This is particularly true for
238 the species of Pomacanthidae family: although academic research effort was important on this
239 family with 18 studies on the breeding of different species from this family (e.g. Olivotto *et*
240 *al.* 2006; Baensch & Tamaru 2009; Callan *et al.* 2014; Rajeswari *et al.* 2017; Figure 3),
241 metamorphosis was almost never achieved. This observation was also true for other less
242 studied families such as Acanthuridae and Chaetodontidae.

243

244 3.3. Total CB species vs. species studied in academic research

245 Sections 3.1 and 3.2.1 revealed that, 338 species from 37 different families were CB and 117
246 species from 23 families studied by research scientists from academia, respectively (Figure 5).
247 The two families most represented were Pomacentridae (with 59 CB and 30 studied species),
248 and Syngnathidae (with 44 CB and 17 studied species). For these families, there were at least
249 2-fold more CB species than species studied at the academic research side. Interestingly,
250 Gobiidae were also among the most CB families with 44 species but their occurrence was
251 limited in scientific literature (8 species, Figure 5). With the exception of Microdesmidae (no
252 recorded as CB but one species studied by academists, Madhu & Madhu 2014), there was
253 always a greater number of CB species than species studied by academic researchers. This
254 trend was particularly true for Gobiidae because they were also among the most studies CB
255 families with 44 species, but their occurrence was limited in scientific literature (8 species,
256 Figure 5).

257

258 **4. Discussion**

259 4.1. Overview of marine ornamental fish aquaculture

260 Based on the CORAL list analysis, to date, 338 species of marine ornamental fish have been
261 successfully captive bred with much of this success driven by private companies and

262 enlightened hobbyists. Although this number has increased by an average percentage rate of
263 8% since 2012, it only represents 19% of the marine ornamental fish species traded for the
264 aquarium hobby (i.e. a minimum of 1,800 species traded annually; Palmtag 2017; Rhyne *et al.*
265 2017b). Moreover, our results shown that only a minor fraction of these CB species (7%) are
266 commonly available on the market such as blenny, clownfish and dottyback (Table 2). Other
267 species have a limited availability on the market (i.e. releases not constant throughout the year
268 and/or in small quantities) such as cardinalfish, goby and some seahorses (Table 2), while
269 others are on the verge of being commercialized with very first releases in the last two years,
270 such as CB surgeonfish (Acanthuridae). This meta-analysis confirms a vast majority of
271 marine ornamental fish are still wild-caught to date. Research in aquaculture of marine
272 ornamental species is therefore crucial to allow a move toward greater sustainability of the
273 marine fishkeeping practice.

274 One of the primary benefits of aquaculture research is that the species' biology is thoroughly
275 investigated. This often leads to improvements of cultivation methods (e.g. broodstock
276 management, larval rearing, and nutrition), which can then be transferred to other species
277 (Tlusty 2002). For now, there are still numerous technical critical factors limiting captive
278 propagation (see Olivotto *et al.* 2017; Rhyne *et al.* 2017a). Nevertheless, the main challenge
279 encountered in marine ornamental production remains the larval rearing: larvae are small and
280 they need very small, living foods for first feeding such as copepods (Olivotto *et al.* 2017;
281 Rhyne *et al.* 2017a). However, mass-scale production of adequate copepod species remains
282 challenging (Dhont *et al.* 2013), and thus, strenghtening research effort on first exogenous
283 feeding of new species'early life-stage is necessary. In addition, one last benefit is that
284 information on the general biology of species can further assist wildlife biologists in the
285 management of the species on their natural environment (Nicosia & Lavalli 1999; Tlusty
286 2002).

287

288 4.2. Current state of the marine ornamental fish academic research

289 Academic research regarding marine ornamental fish aquaculture is most common in North
290 America, Asia and Europe. Three countries (USA, India and in a lesser extent Australia) are
291 responsible for ~50% of the worldwide publications. Among these countries, it is not
292 surprising to find the USA in the foreground of research effort in marine ornamental fish
293 aquaculture since it is the main importer country of coral reef organisms (Rhyne *et al.* 2012,
294 Rhyne *et al.* 2017b). In India, the marine ornamental fish trade has been a more recent
295 development and research is largely focused on hatchery production methods to sustain this
296 trade (Gopakumar *et al.* 2009). The selection of publications for this study only analyzed
297 those written or abstracted in English. We have to thus acknowledge the potential bias in our
298 analyses in academic research on ornamental marine fish. A necessary follow-up would be to
299 address academic marine ornamental research publications from important producer countries
300 (e.g. China, Thailand, Philippines, Czech Republic) that are published in their native
301 language.

302 The evolution of the number of studies published per decade (Figure 2) indicates that the
303 research effort is growing. However, the information published in this research area to date is
304 limited to 117 species, and only 13 were among the top 20 species imported into the US
305 (Rhyne *et al.* 2017b). Nevertheless, we found no relationship between the volume of fish
306 imported and the intensity of academic research (i.e. number of publications).

307 Currently, less than 50% of the studies have been focused on first-exogenous feeding, the
308 most critical phase in marine fish aquaculture. Furthermore, academic research results have
309 been published on all breeding stages (i.e. from the broodstock management to the juvenile
310 rearing) for only 58 species (i.e. 50% of the studied species). These results suggest that
311 advances in the captive breeding of ornamental marine fish are mainly attributable to private

312 companies through their research and development activities and advanced hobbyists. This
313 finding contrasts with the aquaculture of marine fish for human consumption. Indeed, marine
314 food-fish aquaculture developed in the 70-80's, and the bottlenecks regarding captive
315 breeding and nutrition were solved by intense academic research efforts (Nicolaisen 2017).
316 For example, aquaculture of European seabass *Dicentrarchus labrax* and gilthead seabream
317 *Sparus aurata* was initiated on the basis of an important mostly public research effort (UK,
318 France) which started in the 1970s. Then, private entrepreneurship and international
319 cooperation joined the effort and expanded aquaculture all around the Mediterranean Sea
320 (Harache & Paquotte 1996). Some authors suggest that the achievements in marine foodfish
321 culture may be applicable to techniques for marine ornamental fish aquaculture, however,
322 concerted scientific research efforts are lacking (Ostrowski & Laidley 2001). Furthermore, as
323 indicated in the Table 1, some species can be used both for ornamental purpose or as food
324 resource (usually depending on their life-stage). In this case, academic research performed is
325 beneficial to both production sectors (food or ornamental). Batfish (*Platax* sp.) juveniles are
326 attractive for the ornamental market while adults are marketed for human consumption in
327 Asian and South Pacific regions (e.g., Masanet 1995, Barros *et al.* 2011, Leu *et al.* 2018).
328 Interestingly, three of the five most important families on the market: Pomacentridae,
329 Gobiidae and Pomacanthidae are among the most studied families with the highest number of
330 CB species (Table 4). The Pomacentridae largely dominate the aquarium market and 80% of
331 the 10 best-selling species belong to this family (Rhyne *et al.* 2017b). Like Gobiidae,
332 Pomacentridae are generally low value (per individual) species (Biondo 2017; Rhyne *et al.*
333 2017b) unlike Pomacanthidae, which are among the most valuable species (Wood 2001;
334 Balboa 2003). The values of one species has been shown to be closely related to his
335 availability on the market (Green 2003). Considering that, we assume that similarities and

336 differences between the patterns observed for academic research and private sector (Figure 5)
337 can be explained by the following three different strategies:

338 1. Private companies would be focused on mass production of easy-to-trade and easy-to-breed
339 species such as Pomacentridae and dedicate their R&D for very valuable species such as
340 Pomacanthidae.

341 2. Academists would work on a variety of species depending on the need: species easy to
342 breed in order to work on specific research topics in replicated experiments or challenging
343 species to work on a new species (like e.g. Chaetodontidae or Pomacanthidae species).

344 3. Advanced hobbyists would not be interested in the captive breeding of common species,
345 and work on original species that not yet captive bred on a large scale without any economic
346 objective.

347 Academic research and private sectors can be linked. Obviously, the publication of scientific
348 results and extension papers makes information accessible to companies. Other interactions
349 exist between academic research and the private sector such as funding or graduate students
350 working for private companies that may assist in more effective technology transfer than
351 publications. A non negligible part of the academic studies included in this review (approx.
352 10%) were carried out, at least partially, in collaboration with production companies (e.g. da
353 Hora & Joyeux 2009; Leis *et al.* 2011) or public aquaria (e.g. Tlusty *et al.* 2013, Doi *et al.*
354 2015a; Doi *et al.* 2015b, Tlusty *et al.* 2017). This can be explained by the availability of
355 infrastructures better adapted to maintain some species with special needs (e.g. pelagic
356 spawners such as Acanthuridae and Pomacanthidae; Leu *et al.* 2009; Leu *et al.* 2010;
357 Cassiano *et al.* 2015; Leu *et al.* 2015) or large specimens such as sharks (Harahush *et al.*
358 2007; Hövel *et al.* 2010; Payne 2012). Furthermore, public aquaria are also involved in the
359 conservation programs of some species in collaboration with academists (Maitland 1995;
360 Tlusty *et al.* 2013).

361 Some species can be challenging to captive bred due to their specific requirements, the
362 investment in time and money needed and/or their high production costs, which are
363 inconsistent with profitability objectives from private companies. In this context, academic
364 research can lead to significant advances. For instance, some species of Acanthuridae and
365 Chaetodontidae required many years of intensive research and for which the first successes of
366 breeding in captivity up to the production of juveniles were recently published by academic
367 teams (DiMaggio *et al.* 2017; Callan *et al.* 2018; Ohs *et al.* 2018). Although survival rates
368 (<1%) are still incompatible with large-scale commercial production, this research has
369 unlocked certain barriers in the production of pelagic spawner species (Olivotto *et al.* 2017)
370 such as the Pacific blue tang *Paracanthurus hepatus*, reef butterflyfish *Chaetodon sedentarius*
371 and yellow tang *Zebrasoma flavescens*. These success stories illustrate the benefits of
372 interactions between research institutes and private sector in the production of marine
373 ornamental fish.

374

375 4.3. Drivers of marine ornamental fish aquaculture research

376 To understand how the dynamic of marine ornamental fish aquaculture research is influenced,
377 it is important to consider all the potential drivers. The trade of marine ornamental organisms
378 is the main obvious one. Indeed, as a consequence of the growing demand for marine
379 ornamental fish, the pressure on wild stocks is increasing. Although, most of the species
380 currently traded are abundant and occur over wide geographic areas and are generally not
381 endemic or “rare” (Rhyne *et al.* 2012), current knowledge regarding the real status of wild
382 populations is limited. Indeed, we found in our analysis, that among the 338 CB species, 37%
383 were not evaluated by IUCN (Table 2). Furthermore, the negative impacts of fisheries for
384 aquarium trade have been demonstrated for some species. One of the most striking example is
385 the Banggai cardinalfish, an endemic species of the Banggai Islands (Central Sulawesi,

386 Indonesia). Indeed, several subpopulations of this species were strongly affected by the
387 aquarium fishery and exhibited dramatic declines (Yahya *et al.* 2012; Talbot *et al.* 2013;
388 Conant 2015). Therefore, another driver that could be identified is policy: restricting or
389 banning the harvest of some marine ornamental fish from the wild to supply the marine
390 aquarium trade is becoming a growing option when advocating reef conservation (Dee *et al.*
391 2014). In the near future, the collection of several banned species in the trade will be severely
392 restricted, or even prohibited (Calado 2017). In this context, academic research plays also
393 important role in marine fish conservation as evidenced by the 8 threatened species that have
394 been studied by academics (seven Syngnathidae et one Apogonidae, see Table 3). An
395 increasing demand on the market combined with increasingly constrained wild-catches are
396 factors that may favor research on marine ornamental fish aquaculture, whether academic,
397 conducted by private companies or by hobbyists. Nevertheless, there are other limiting factors
398 that restrain the research done on marine ornamental fish in addition to the zootechnical
399 brakes well detailed in literature (e.g. Olivotto *et al.* 2017) that may eventually be overcome.
400 One of the aims of this research is to be able to supply the market with marine ornamental fish
401 produced through closed-cycle aquaculture. Despite significant progress, production of CB
402 fish is unfortunately not cost-effective yet compared to their wild-caught counterparts. The
403 selling prices of CB fish, can be at least 25% higher than those of their wild equivalents
404 (Fotedar & Phillips 2011). For example, aquaculture of mandarin dragonets *Synchiropus* sp. is
405 feasible but faces a large supply of cheaper wild fish (25 USD per wild fish vs. 60 USD per
406 CB fish; Rhyne *et al.* 2017a). Thus, the marketplace need to appreciate fully the advantages of
407 cultured species over wild-caught species to accept the higher prices charged (Corbin *et al.*
408 2003).

409 In this context, successful large-scale production of ornamental marine CB fish is mainly
410 dependent on consumer (i.e. hobbyist) choice and thus the risk on the market is the non-

411 sustainability of the demand in the long run. The bright side for future of farming of
412 ornamental fish is that the current fishkeepers are becoming more and more sensitive to the
413 sustainability of ornamental fish production and price does not seem to be the determining
414 factor in their purchase (Militz *et al.* 2017). The context for the marine fish aquaculture is thus
415 positive, which could consequently stimulate the future research undertaken in this field.
416 Moreover, it should be emphasized that the role of hobbyists is and will remain predominant
417 because they can act on both the trade, by favoring CB fish, as well as through their own
418 research, often freely shared, mainly motivated by the challenge of successful reproduction of
419 difficult to captive-bred species.

420

421 **5. Conclusion**

422 This review highlighted that, regarding advances in captive breeding of marine ornamental
423 fish, academic research is only the tip of the iceberg. Many advances have come through
424 private companies and enlightened hobbyists. However, academic research plays a key role
425 for developing captive reproductive success of certain species requiring many years of
426 development, and for marine species conservation especially in the current context where
427 more and more drastic measures are being taken by the governments concerned to protect
428 coral ecosystems (Dee *et al.* 2014). Unfortunately, from a realistic point of view and despite
429 all the progress made, the research effort in this domain remains to date very expensive and
430 time consuming. It is unlikely that in the near future the majority of marine ornamental fish
431 will be CB as seen freshwater ornamental fish, of which an increasing number of species are
432 now domesticated (Teletcha 2016). In this context, it is crucial to first act in favor of
433 sustainable fishing methods (i.e. with proper stock management and avoiding habitat
434 destruction), then to promote CB fish production. Consumer awareness is a necessary

435 component to drive the development of alternatives to ornamental fish collected from the
436 wild.

437

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445

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640 **Captions to figures**

641

642 Figure 1. (A) Overview of CB marine ornamental fish species listed from 2012 to 2017. The
643 proportions (in number of species) for the 6-main CB families are indicated in the table, (B)
644 Stagnation of the number of species CB in 3 of the main families: Blennidae, Pomacentridae
645 and Pseudochromidae over the period 2012-2017 and (C) Increase in species produced in the
646 Gobiidae, Pomacanthidae and Syngnathidae in the period 2012-2017. For a baseline, the
647 number of CB species reared in 2000 from Frank Baench's list is provided.

648

649 Figure 2. Historical trends in the academic research performed on reproduction and rearing of
650 marine ornamental fish expressed as number of published works and number of species
651 studied since the 1960s to present.

652

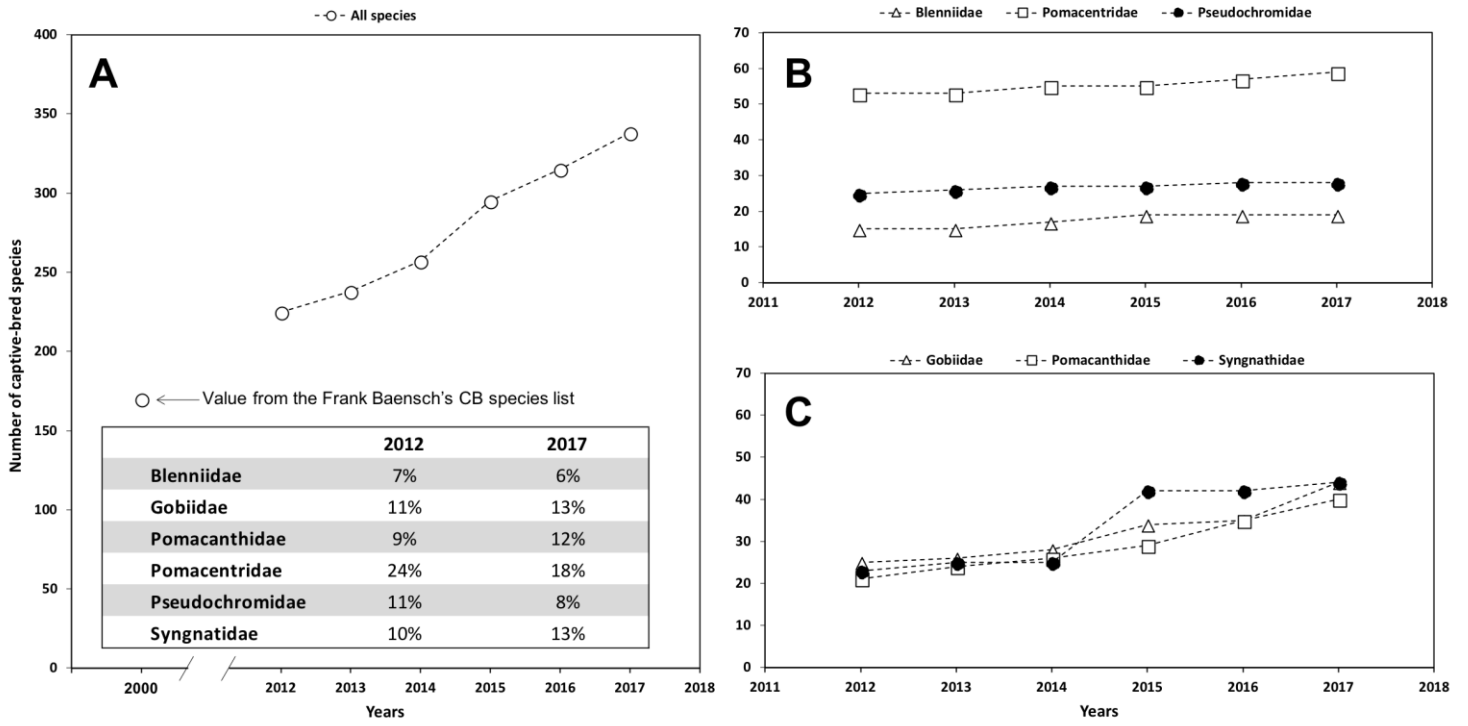
653 Figure 3. Overview of research on reproduction and rearing of marine ornamental fish by
654 country expressed by total number of published studies and species studied from 1960s to
655 present.

656

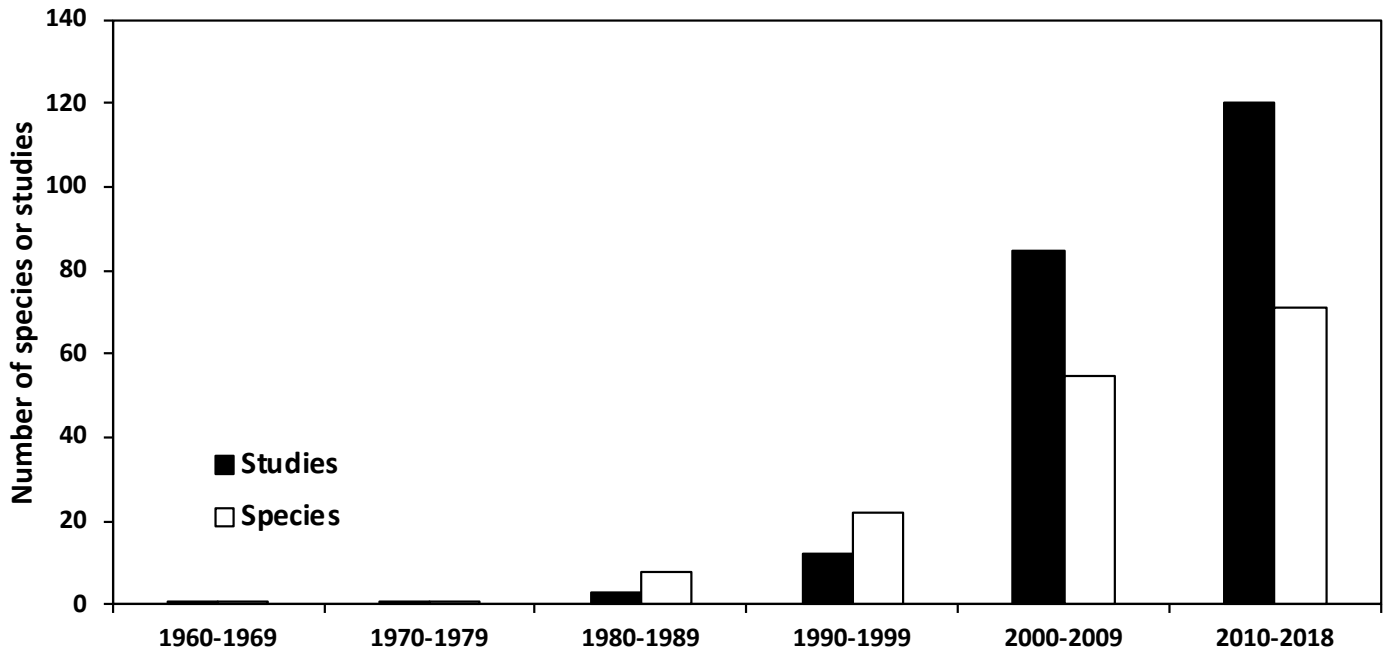
657 Figure 4. Advances in academic research for the different families studied. For each family,
658 the proportion of published studies that have reached a given breeding stage (i.e. broodstock
659 management, spawning, egg/embryonic development, larval rearing, metamorphosis and
660 juvenile rearing) is indicated. The number of studies per family is indicated in brackets. A:
661 broodstock management, B: Spawning, C: Egg/Embryonic development, D: Larval rearing, E:
662 Metamorphosis, F: Juvenile rearing.

663

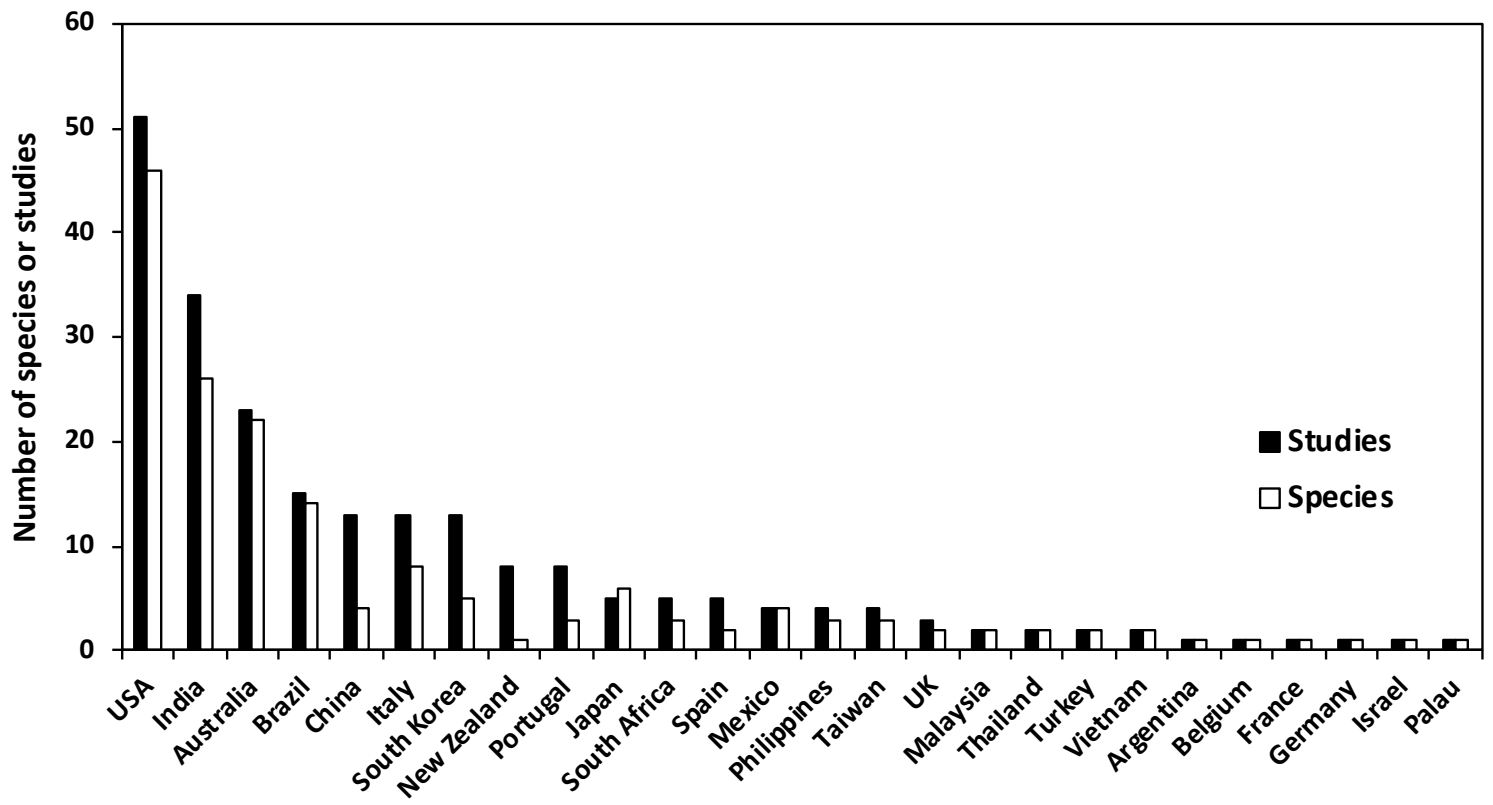
664 Figure 5. (A) Number of marine ornamental fish species studied in academic research and (B)
665 CB species.



666 Figure 1



667 Figure 2



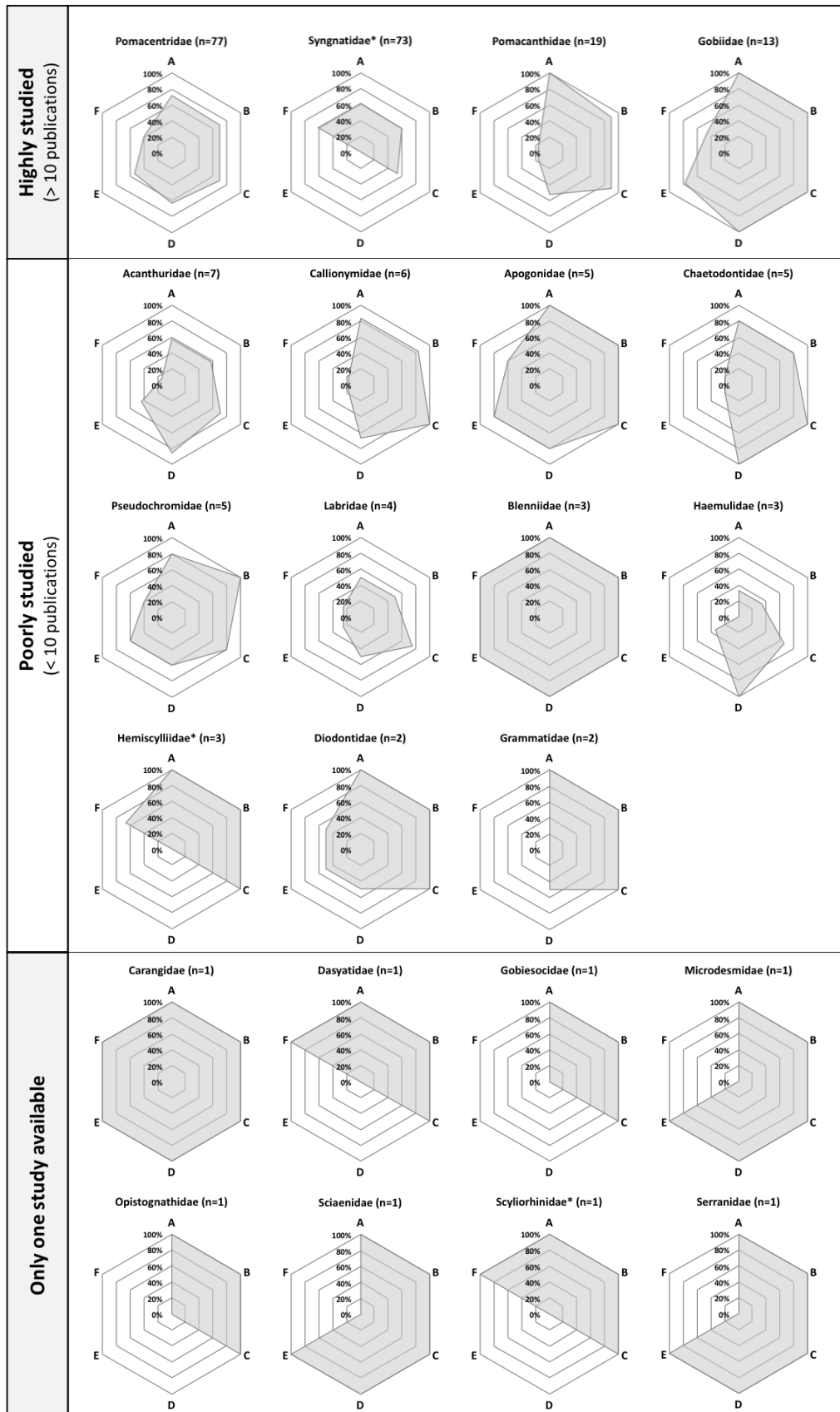
668 Figure 3

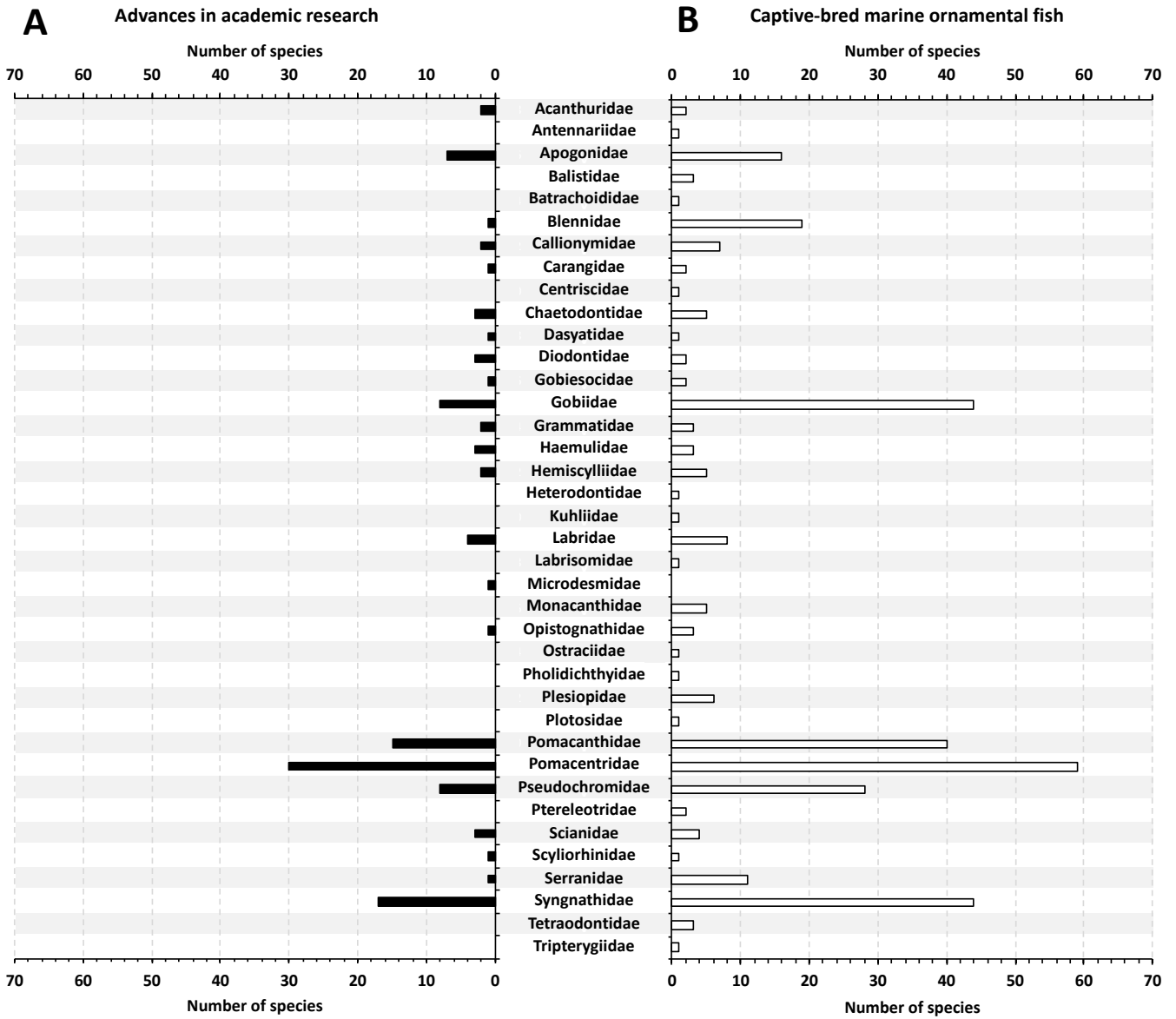
NUMBER OF PUBLICATIONS

+ → -

RESEARCH EFFORT INTENSITY

- ← +





670 Figure 5

671 Table 1. List of the CB marine fish species for human consumption and fishkeeping that have
 672 been excluded from our analysis.

Family	Scientific name	Vernacular name
Batrachoididae	<i>Opsanus tau</i>	Oyster toadfish
Ephippidae	<i>Chaetodipterus faber</i>	Atlantic spadefish
	<i>Platax batavianus</i>	Humpback batfish
	<i>Platax orbicularis</i>	Orbicular batfish
	<i>Platax pinnatus</i>	Dusky batfish
Lutjanidae	<i>Lutjanus sebae</i>	Emperor red snapper
Serranidae	<i>Cromileptes altivelis</i>	Humpback grouper
	<i>Plectropomus leopardus</i>	Leopard coralgroup
	<i>Epinephelus lanceolatus</i>	Giant grouper
	<i>Epinephelus marginatus</i>	Dusky grouper
	<i>Plectropomus areolatus</i>	Squaretail coralgroup
	<i>Plectropomus leopardus</i>	Leopard coralgroup
	<i>Plectropomus leopardus</i>	Leopard coralgroup
Siganidae	<i>Siganus canaliculatus</i>	White-spotted spinefoot
	<i>Siganus fuscescens</i>	Mottled spinefoot
	<i>Siganus guttatus</i>	Orange-spotted spinefoot
	<i>Siganus lineatus</i>	Golden-lined spinefoot
	<i>Siganus rivulatus</i>	Marbled spinefoot
	<i>Siganus vermiculatus</i>	Vermiculated spinefoot
Tetraodontidae	<i>Sphoeroides annulatus</i>	Bullseye puffer
	<i>Sphoeroides maculatus</i>	Northern puffer

673

674 Table 2. Summary of the CB species reported at the end of 2017. For the IUCN status: NE =
 675 Not Evaluated, DD = Data Deficient, LC = Least Concern, NT = Near Threatened, VU =
 676 Vulnerable and EN = Endangered.

Family	Number of species	Availability on the market (%)				IUCN status (%)					
		Unavailable	Scarce	Moderate	Common	NE	DD	LC	NT	VU	EN
Acanthuridae	2	50	50					100			
Antennariidae	1	100				100					
Apogonidae	16	38	38	12	12	75		19			6
Balistidae	3	67	33			34		33	34		
Batrachoididae	1	100				100					
Blennidae	19	47	16	21	16			100			
Callionymidae	7	43	14	43		86		14			
Carangidae	2			100				100			
Centriscidae	1	100					100				
Chaetodontidae	5	80	20					100			
Dasyatidae	1	100							100		
Diodontidae	2	100						100			
Gobiesocidae	2	50		50				100			
Gobiidae	44	57	23	20		38	2	55		5	
Grammatidae	3	67	33					100			
Haemulidae	3	33	67					100			
Hemiscylliidae	5	40	20	40				20	60	20	
Heterodontidae	1		100					100			
Kuhliidae	1	100						100			
Labridae	8	100				12		75			13
Labrisomidae	1	100						100			
Monacanthidae	5	40	20		40	20		60		20	
Opistognathidae	3	100						100			
Ostraciidae	1	100						100			
Pholidichthyidae	1	100				100					
Plesiopidae	6	17	33	50		100					
Plotosidae	1	100				100					
Pomacanthidae	40	53	47			3	2	93		3	
Pomacentridae	59	53	20	8	19	90		10			
Pseudochromidae	28	61	18	7	14	64	4	32			
Ptereleotridae	2	100				50		50			
Scianidae	4	75	25					100			
Scyliorhinidae	1	100							100		
Serranidae	11	91	9					100			
Syngnathidae	44	77	9	9	5	9	36	25	5	23	2
Tetraodontidae	3	100						67		33	
Tripterygiidae	1	100						100			
TOTAL (% total species)	338 (100)	204 (60)	73 (22)	37 (11)	24 (7)	125 (37)	21 (6)	165 (49)	8 (2)	16 (5)	3 (1)

678 Table 3. Summary of the marine ornamental fish species studied in academic research. For the
679 IUCN status: NE = Not Evaluated, DD = Data Deficient, LC = Least Concern, NT = Near
680 Threatened, VU = Vulnerable and EN = Endangered.

Family	Number of studies	Number of species	IUCN status (%)						Captive-bred (%)
			NE	DD	LC	NT	VU	EN	
Acanthuridae	7	2			100				100
Apogonidae	5	7	72		14			14	71
Blenniidae	3	1			100				100
Callionymidae	6	2	100						100
Carangidae	1	1			100				100
Chaetodontidae	5	3			100			33	77
Dasyatidae	1	1				100			100
Diodontidae	2	3	67	33					
Gobiesocidae	1	1			100				100
Gobiidae	13	8	14		86				57
Grammatidae	2	2	50		50				50
Haemulidae	3	3			100				100
Hemiscylliidae	3	2			50	50			100
Labridae	4	4			100				
Microdesmidae	1	1			100				100
Opistognathidae	1	1			100				
Pomacanthidae	19	15	7		93				86
Pomacentridae	75	30	93		7				90
Pseudochromidae	5	8	88		12				100
Sciaenidae	1	3			100				100
Scyliorhinidae	1	1				100			100
Serranidae	1	1	100						
Syngnathidae	73	17	6	53			35	6	94
TOTAL (% total species)	222	117	49 (42)	10 (9)	46 (39)	3 (3)	6 (5)	2 (2)	96 (80)

682 Table 4. Top 5 families of marine ornamental fish in terms of (A) volume of fish imported on
 683 the world, the USA and the Switzerland markets, (B) number of species studied by academia
 684 and (C) number of species captive bred by private companies and hobbyists.

Rank	World	A - Markets		B - Academic research	C - Private companies and hobbyists
		USA	Switzerland		
1	Pomacentridae	Pomacentridae	Pomacentridae	Pomacentridae	Pomacentridae
2	Labridae	Labridae	Labridae	Syngnatidae	Syngnatidae
3	Gobiidae	Pomacanthidae	Gobiidae	Pomacanthidae	Gobiidae
4	Pomacanthidae	Gobiidae	Acanthuridae	Gobiidae	Pomacanthidae
5	Acanthuridae	Acanthuridae	Pomacanthidae	Pseudochromidae	Pseudochromidae

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