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9 **Rapid change of Yangtze fisheries and its implications for global freshwater ecosystem**  
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12

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28 **Abstract:** Freshwater capture fisheries are globally essential for food security and aquatic  
29 biodiversity conservation. The Yangtze River Basin is the third longest, and one of the most  
30 human-influenced drainage basins worldwide. Since the founding of P. R. China in 1949, this  
31 large river system has suffered increasing human perturbation and its sustainable development  
32 is now severely challenged. Meta-analysis showed that Yangtze River fisheries have  
33 experienced an extraordinary process of utilization-overexploitation-protection during the past  
34 70 years, to the extent that other globally important rivers may never have encountered. Its  
35 fisheries appear to have collapsed over the past four decades, with yield decreasing to only 25%  
36 of an historic peak of 400,000 metric tonnes in the late 1950s. Endemic, migratory and rare  
37 fishes have been highly threatened with obvious changes in fish community structure and  
38 aquatic biodiversity. Anthropogenic activities, including impoundment of water in dams,  
39 discharge of pollutants, and riverine modification for vessel navigation, have caused large  
40 decreases in fisheries yields. Projections from surplus production modelling showed potential  
41 for improvement under fishing ban scenarios, but without any prospect for full recovery to  
42 historical stock status. This study revealed that the change in fisheries resources was  
43 dominated by the social-ecological watershed system, and an integrated approach to river  
44 basin management is warranted. Better management of freshwater ecosystems to integrate  
45 food security with biodiversity conservation is urgently needed throughout the world, and the  
46 changes evident in the Yangtze River fish populations can serve as an informative global

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47 reference.

48 **Key words:** biodiversity conservation, China, fishing ban, food security, human impact,  
49 inland fishery

50 **Table of contents**

51 **1 INTRODUCTION**

52 **2 MATERIALS AND METHODS**

53 **2.1 Study area**

54 **2.2 Data on fisheries yields and fish communities**

55 **2.3 Environmental factors and their impacts**

56 **2.4 Biomass estimation and future projections**

57 2.4.1 Surplus production model

58 2.4.2 Scenario settings

59 **2.5 Synthesizing fishing and biodiversity threats in global rivers**

60 **3 RESULTS**

61 **3.1 Fisheries yields in time and space**

62 **3.2 Structural changes in fish community**

63 **3.3 Environmental factors and their impacts on capture yields**

64 **3.4 Biomass projection in the future**

65 **3.5 Fishing and biodiversity threats in global large rivers**

66 **4 DISCUSSION**

67 **4.1 Limitations of methods**

68 **4.2 Fisheries utilization and protection in the Yangtze**

69 **4.3 Challenges for Yangtze aquatic biodiversity**

70 **4.4 Fishing pressure and biodiversity threat of global rivers**

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71 **4.5 Future management implications**

72 **ACKNOWLEDGEMENTS**

73 **DATA AVAILABILITY STATEMENT**

74 **REFERENCES**

75

76

77 **1 INTRODUCTION**

78 Freshwater capture fisheries are essential for food security and biodiversity conservation  
79 worldwide (Food and Agriculture Organization of the United Nations [FAO], 2016; Funge-  
80 Smith & Bennett, 2019; Lynch et al., 2017; McIntyre, Reidy Liermann, & Revenga, 2016;  
81 Welcomme, Valbo-Jorgensen, & Halls, 2014; Youn et al., 2014). Global production from  
82 inland capture fisheries was approximately 11.9 million metric tonnes in 2014, accounting for  
83 7.1% of the total global production according to a report by FAO (2016). Freshwater capture  
84 fisheries provide a source of animal protein which is equivalent to the total requirements of  
85 approximately 119.1 million people, based on 36 countries where protein consumption data  
86 were available (Fluet-Chouinard, Funge-Smith, & McIntyre, 2018); moreover, these fisheries  
87 account for up to 81% of the nutrient supply to low-income countries where other protein  
88 sources are too expensive (McIntyre et al., 2016). In addition to sustaining target species  
89 production for human needs, conserving freshwater fish diversity is critically important for  
90 maintaining ecosystem function and provision of ecosystem services (Harrison et al., 2014).  
91 Freshwater areas represent less than 1% of the entire surface area of the Earth, yet contain 40%  
92 (i.e. 13,000 strictly freshwater species) of all fish species, whereas saline waters covering 70%  
93 of the Earth's surface, contain the remaining 60% (i.e. 16,000 species) (Lévêque, Oberdorff,  
94 Paugy, Stiassny, & Tedesco, 2008; Tedesco et al., 2017). Freshwater fishes are highly  
95 evolved and specialized with some only able to live in specific local habitats (Tedesco et al.,  
96 2012). In Western Europe and the USA, riverine fish extinction rates are ~112 times higher  
97 than background extinction rates (Dias et al., 2017). Human influences such as fishing

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98 pressure can lead to precarious circumstances for aquatic animals already in low abundance. It  
99 has been predicted that freshwater biodiversity and ecosystem services will be severely  
100 reduced by 2050; thus, a systematic and effective protection framework is urgently needed if  
101 this predicted situation is to be averted (Jenkins, 2003; Nguyen et al., 2016; Vörösmarty et al.,  
102 2010; Zhou et al., 2010).

103  
104 The Yangtze River is the third longest, and third most water-rich river system, yet it is also  
105 one of the most human-impacted large rivers in the world (Liu & Diamond, 2005; Yang, Ma,  
106 & Chang, 2009; Yang, Wen, & Li, 2007; Yang, Zhu, & Jiang, 2011). The Yangtze River has  
107 experienced large perturbations and severe overall stress from anthropogenic activities during  
108 the past 70 years as a consequence of China's economic development and modernization (Liu  
109 & Diamond, 2005; Qiu, 2012; Wu et al., 2004; Xie, Wu, Huang, & Han, 2003). The drainage  
110 basin crosses the western, middle and eastern parts of China, comprising one-fifth of the land  
111 area and traverses 19 provincial administrative units (56% of all units) (Yang et al., 2007,  
112 2009, 2011). The basin is home to more than 0.4 billion people (one-third of the Chinese  
113 population) and generates approximately two-fifths of China's gross domestic product (GDP).  
114 Also, the Yangtze River is the busiest river in the world in terms of inland vessel navigation  
115 with numerous diverse watercraft ranging from bamboo rafts to large cruise ships. It has made  
116 great contributions to China's rapid economic growth both historically and currently. The  
117 river is presently under a new development plan called the "Yangtze River Economic Belt" to  
118 further promote the economic development of China (Central Government of China, 2014;  
119 Yang et al., 2007, 2009, 2011).

120  
121 Fishes in the Yangtze River are very important for both fisheries development and aquatic  
122 biodiversity conservation (Yang et al., 2007, 2009, 2011; Zeng, 1990). Like the Amazon,  
123 Mekong and Niger rivers, the wild capture fishery in the Yangtze River supplies a vital food  
124 source for local residents in a myriad of communities in its catchment (FAO, 2016;  
125 Welcomme et al., 2014; Zeng, 1990). In the 1950s, yields from wild capture fisheries in the

---

126 Yangtze River accounted for approximately 60% of inland fish production in China (Yang et  
127 al., 2007, 2009, 2011). Currently, among the 35 major freshwater aquaculture species in  
128 China, 26 species are distributed in the Yangtze River (Yang et al., 2007). Furthermore, the  
129 quality of the four major Chinese domestic carps (i.e. black carp (*Mylopharyngodon piceus*,  
130 Cyprinidae), grass carp (*Ctenopharyngodon idella*, Cyprinidae), silver carp  
131 (*Hypophthalmichthys molitrix*, Cyprinidae), and bighead carp (*H. nobilis*, Cyprinidae)) are  
132 considered to be the best among all aquatic systems in China. Prior to success in artificial  
133 propagation techniques for the four major Chinese carp species, more than 10 billion fish  
134 larvae and juveniles were caught each year from the middle reaches of the Yangtze River for  
135 aquaculture during the period of 1958–1962, with the highest number of 20 billion reported in  
136 1960 (Hubei Provincial Water Resources and Electric Power Bureau, 1975). Thus the  
137 Yangtze River has been greatly supporting development of China's freshwater culture as well  
138 as capture fisheries. Currently, fisheries production (i.e. wild capture and aquaculture) in the  
139 Yangtze River Basin accounts for 60% of China's total freshwater fisheries production (Yang  
140 et al., 2007, 2009, 2011). There are approximately 416 fish species and subspecies in the  
141 Basin, of which 362 are strictly freshwater species and 178 are endemic (Ye, Li, Liu, Zhang,  
142 & Xie, 2011). In addition, there are some unique aquatic mammals, amphibians and reptiles,  
143 such as Baiji (*Lipotes vexillifer*, Lipotidae), Yangtze finless porpoises (*Neophocaena*  
144 *asiaeorientalis*, Phocoenidae), Chinese giant salamander (*Andrias davidianus*,  
145 Cryptobranchidae), and Chinese alligator (*Alligator sinensis*, Alligatoridae) (Yang et al., 2007,  
146 2009, 2011).

147  
148 Fisheries sustainability and biodiversity conservation in the Yangtze River have both faced  
149 great challenges, in common with most large-river systems throughout the world (Dudgeon,  
150 2010, 2011; Jackson, Loewen, Vinebrooke, & Chimimba, 2016; Vörösmarty et al., 2010;  
151 Youn et al., 2014). With continual socio-economic development associated with the Yangtze  
152 River Basin, various human activities have adversely affected the Yangtze River's aquatic  
153 organisms and their habitats (Chen, Duan, Liu, & Shi, 2003; Chen, Xiong, Wang, & Chang,  
154 2009; Lu et al., 2016; Yang et al., 2007, 2009, 2011; Zhang et al., 2017). The major

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155 threatening elements include damming (Cheng, Li, Castello, Murphy, & Xie, 2015; Liu, Qin,  
156 Xu, Ouyang, & Wu, 2019; Wang, Li, Duan, Chen, et al., 2014; Wang, Li, Duan, Luo, et al.,  
157 2014), legal overfishing and illegal fishing (Ma et al., 2018; Zhu & Chang, 2008), water  
158 pollution (Müller et al., 2008), reclamation of lakes for farmland, isolation of lakes from  
159 rivers (Cheng et al., 2014; Fang et al., 2006), waterway channel construction, and vessel  
160 navigation (Huang & Li, 2016; Xie, 2017a, 2017b). To date, wild capture fisheries production  
161 has already decreased to less than 100 thousand tonnes, falling well short of the maximum  
162 production of 427 thousand tonnes in 1954 (Zeng, 1990). The quantity of newly produced  
163 eggs and larvae of the four major Chinese carp species (i.e. the dominant commercial species  
164 in the Yangtze River) was approximately 1.11 billion in 2015, accounting for only 1% of  
165 historic production (118.4 billion) estimated for 1964–1965 (Yi, Yu, & Liang, 1988; Zhang et  
166 al., 2017). Sixty-five Yangtze River fish species (15.6% of total) were registered in various  
167 threatened categories of the China Species Red List (Ye et al., 2011). The Baiji (Turvey et al.,  
168 2007), Chinese paddlefish (*Psephurus gladius*, Polyodontidae) (Zhang et al., 2020), and  
169 Reeves shad (*Tenualosa reevesii*, Clupeidae) are thought to be functionally extinct because no  
170 living specimens of these species have been found for over 15 years (Yang et al., 2007, 2009,  
171 2011). The Yangtze finless porpoise and Chinese sturgeon (*Acipenser sinensis*, Acipenseridae)  
172 are highly endangered (Mei et al., 2014; Wu et al., 2015). In particular, the natural spawning  
173 activity of Chinese sturgeon has been interrupted several times in the year of 2017–2019 (Wei  
174 et al., unpublished data), which may be due to the decline of its breeding population and the  
175 degeneration of its spawning habitat, which have led to a strong signal of a near-extinction  
176 status (Huang & Wang, 2018; Wu et al., 2015).

177

178 Currently, ecological issues in the Yangtze River, especially fisheries sustainability and  
179 aquatic biodiversity conservation, have received considerable attention, which is  
180 unprecedented for this system as the emphasis in the past was on how to greater utilize  
181 fisheries resources (Bryan et al., 2018; Yang et al., 2007, 2009, 2011). The new principle for  
182 more ecologically sustainable development of the Yangtze River is “Go together for  
183 conservation, No excessive development”. In response to this shift in policy, a systematic and

---

184 ambitious fisheries adjustment plan, involving 278.3 thousand fishermen and 113.3 fishing  
185 boats, has been proposed, and some of the planned actions are already being implemented (Yi  
186 & Yu, 2018). Other comprehensive protection plans for the river, which directly or indirectly  
187 benefit particular aquatic organisms and their habitats or the entire aquatic ecosystem, have  
188 also been implemented, with others to be conducted in the near future (Bryan et al., 2018;  
189 Yang et al., 2007, 2009, 2011). This new policy is critical for recovering depleted fisheries  
190 resources and halting declines in aquatic biodiversity as further delay will limit the extent to  
191 which the Yangtze River ecosystem and the services it provides can be restored.

192

193 The Yangtze River has experienced an extraordinary process of  
194 utilization-overexploitation-protection in the past 70 years, and this process is one that many  
195 other large river systems may have never encountered, or at least not to the same extent.  
196 Globally, although each river basin has its own unique characteristics among its social  
197 (population, diet habits, etc.), economic (GDP, agriculture, industry, etc.), and natural  
198 (climate, hydrology, topography, biology, etc.) dimensions, most will nevertheless experience  
199 a similar sequence of utilization, overexploitation, and rehabilitation at some stage. The  
200 Yangtze River Basin can therefore serve as an informative example from which riverine  
201 managers in other countries can learn. In this study of the socio-ecological watershed system  
202 of the Yangtze River (Figure 1), first changes in wild capture fisheries production and fish  
203 community composition were reviewed from the inception of the People's Republic of China  
204 in 1949 until 2016. Second, to determine the impacts of human activities the influence of  
205 environmental factors (e.g. run-off, water impoundment, water pollution and navigation) on  
206 fisheries resources between 1997 and 2016 were investigated, and their impacts on fisheries  
207 yields were examined. Third, fish biomass under three different fishing regulation scenarios  
208 up to 2030 was predicted. Finally, fishing pressure and biodiversity threats faced by the 30  
209 largest river systems in the world were reviewed. The objective of this study was to explore  
210 changes in Yangtze River fisheries including their interactions with human activities in such a  
211 highly human-dominated ecosystem over the past 80 years, and ultimately to provide  
212 meaningful management guidance for large river systems worldwide.

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213

## 214 2 MATERIALS AND METHODS

### 215 2.1 Study area

216 The Yangtze River stretches from Tibet to Shanghai (24°30'–35°45' N, 90°33'–122°25' E)  
217 where it finally flows into the East China Sea (Figure 2) (Yang et al., 2007, 2009, 2011). The  
218 mainstream is more than 6,300 km long within a catchment area of  $1.8 \times 10^6$  km<sup>2</sup>. Most areas  
219 of the basin have a subtropical monsoon climate. The total annual flow and sediment  
220 discharge at Datong station averaged  $8.93 \times 10^{12}$  m<sup>3</sup> (1950–2015) and  $3.68 \times 10^9$  t (1951–2015),  
221 respectively (Changjiang Water Resources Commission of the Ministry of Water Resources,  
222 P. R. China, 2017). The elevation difference from the headwater to the estuary is  
223 approximately 5,400 m, with riverbed gradients ranging from  $54 \times 10^{-4}$  to  $0.097 \times 10^{-4}$  (Yu &  
224 Lu, 2005). The basin has more than 10,000 tributaries; among them 437 have catchment areas  
225 larger than 1,000 km<sup>2</sup>, and 22 have catchment areas larger than 10,000 km<sup>2</sup> (Yu & Lu, 2005).  
226 Approximately 4,000 lakes are included in the basin area, 27 of which are larger than 100 km<sup>2</sup>,  
227 and 5 are larger than 1,000 km<sup>2</sup> (Zeng, 1990). In particular, Dongting Lake (2,625 km<sup>2</sup>) and  
228 Poyang Lake (3,750 km<sup>2</sup>), located in the middle reach, are the two largest freshwater lakes in  
229 China (Yu & Lu, 2005).

230

231 In the Yangtze River, historically 361–370 species and subspecies have been reported (Chen  
232 et al., 2003; Fu, Wu, Chen, Wu, & Lei, 2003; Fu, Wu, Wang, Lei, & Chen, 2004), but the  
233 latest research identified approximately 416 fish species and subspecies, 362 of which are  
234 strictly freshwater species (Ye et al., 2011). The number of endemic fish species is 178  
235 (42.8%), out of which 65 are on the China Species Red List (Ye et al., 2011). The most  
236 species-rich phylogenetic orders in the river are Cypriniformes (280 species), Perciformes (50  
237 species), and Siluriformes (40 species). The Yangtze River mainstream can be divided into  
238 five sections (Figure 2): riverhead (above Batang), upper reach (Batang–Yichang), middle  
239 reach (Yichang–Hukou), lower reach (below Hukou), and estuary. The number of fish species  
240 (endemic species) in each section is 14 (8), 279 (147), 227 (70), 158 (23), and 142 (10),  
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241 respectively (Ye et al., 2011). The number of species registered in various threatened  
242 categories of the China Species Red List is 4, 48, 20, 9 and 12, for the five sections  
243 respectively (Ye et al., 2011).

244

245 The Yangtze River Basin is one of the most exploited regions in China (Liu & Diamond,  
246 2005; Yang et al., 2007, 2009, 2011). For example, the river has tens of thousands of dams on  
247 its mainstream and tributaries. The Gezhouba Dam at the end of the upper reach was closed in  
248 1981 and is currently the lowermost dam on the Yangtze mainstream (Zhang et al., 2017).  
249 There is no fish passage on the dam, although a nation-wide debate has been triggered over  
250 this situation. The Three Gorges Dam, which supports the largest power station in the world,  
251 was completed in 2002, and a trial operation began in 2003 before becoming fully operational  
252 in 2009; this dam is located approximately 40 km upstream from the Gezhouba Dam.  
253 Accordingly, the enormous dam created a reservoir which is 600 km in length and has greatly  
254 changed the fluvial environment and aquatic ecosystem (Liu, Wang, & Cao, 2012; Wu et al.,  
255 2004; Wu, Huang, Han, Xie, & Gao, 2003; Yang, Gao, Li, Ma, & Liu, 2012). A number of  
256 issues, such as isolation of lakes from the river and reclamation of some of them for farmland,  
257 have been controversial. To date, only two large lakes remain connected to the Yangtze  
258 mainstream (Huang, Wu, & Li, 2013; Xie, 2017a, 2017b). Furthermore, other human  
259 activities, including overfishing, water pollution, waterway construction and vessel navigation,  
260 river channelization, port construction, and sand and gravel extraction, have seriously affected  
261 the aquatic ecosystem of the Yangtze River (Yang et al., 2007, 2009, 2011).

262

## 263 **2.2 Data on fisheries yields and fish communities**

264 To explore for changes in fisheries resources and fish community composition in the Yangtze  
265 River, we extensively investigated the literature regarding wild fisheries production (no  
266 previous estimates of fish population or stock biomass were available), fish community  
267 structure and aquatic biodiversity in the river since the 1970s (Chen et al., 2009; Fish  
268 Laboratory, Institute of Hydrobiology, Hubei Province, 1976; Liu & Gao, 2012; Zeng, 1990).

---

269 Relevant data from a large body of publicly available literature were transcribed and utilized  
270 in our analyses. The data on fisheries yields in the Yangtze River were mainly obtained from  
271 Zeng (1990) and a series of the *Bulletin on the Ecological and Environmental Monitoring*  
272 *Results of the Three Gorges Project* (Abbreviation: *Bulletin of the Three Gorges Project*)  
273 from 1997 to 2017. During 1949–1995, the yield data were based on provincial areas (Chen et  
274 al., 2003; Zeng, 1990), and since 1996, they have been based on four major yield producing  
275 areas (Liu & Gao, 2012; Lu et al., 2016; Table S1): Three Gorges Reservoir, middle reach of  
276 Yangtze, Dongting Lake and Poyang Lake. The data on fisheries production (wild capture and  
277 aquaculture) were obtained from a series of the *China Fisheries Statistical Yearbook* from  
278 1979 to 2017. Data on fish community structure were compiled chiefly from Zeng (1990),  
279 Yang et al. (2007, 2009, 2011), Ye et al. (2011), Liu and Gao (2012), and a series of the  
280 *Bulletin of the Three Gorges Project* from 1997 to 2017, which included special reports. The  
281 list of references is provided in Table S1.

282

### 283 **2.3 Environmental factors and their impacts**

284 To understand the impacts of anthropogenic activities on fisheries resources, four categories  
285 (12 factors) of environmental variables were selected based on present knowledge (Yang et al.,  
286 2007, 2009, 2011; Zeng, 1990). These categories included i) river runoff (i.e. total discharge  
287 and mean sediment concentration at three representative sites: Yichang, Hankou and Datong;  
288 locations in Figure 2); ii) water impoundment (i.e. number of reservoirs and total reservoir  
289 capacity); iii) water pollution (i.e. the total volume of waste water emissions and ratio of low  
290 water quality reach, that is, the ratio of river reach with water quality belonging to Categories  
291 IV, V, and above, according to *Environmental Quality Standards for Surface Water* (GB  
292 3838-2002) issued by China); and iv) vessel navigation (i.e. ship cargo volume and total  
293 passenger traffic). Because the total biomass of fish in the Yangtze River is difficult to  
294 estimate, we used wild capture fisheries yields, which are highly correlated with biomass.  
295 Data on key environmental factors were mainly obtained from a series of the *Changjiang*  
296 *Sediment Bulletin* from 2000 to 2016 and the *Yangtze River Yearbook* from 1998 to 2017. To  
297 understand the relationships between wild capture fisheries yields and environmental factors,  
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298 as well as the interconnections among the environmental factors themselves, the Spearman  
299 correlation analysis was used. To exclude co-correlations of factors and identify key  
300 environmental factors, a stepwise regression analysis in the PASW Statistics 18 (IBM, USA)  
301 was performed.

302

## 303 **2.4 Biomass estimation and future projections**

### 304 2.4.1 Surplus production model

305 The middle reach of the Yangtze and the two largest lakes (Dongting and Poyang lakes) have  
306 been the major fishing areas since 1990s (Figure 2). Since a number of large lakes in the  
307 lower Yangtze (i.e. in Jiangsu and Anhui provinces) have become isolated from the Yangtze  
308 main stream by sluice and were used for aquaculture these can no longer be treated as natural  
309 resources. Despite rich biodiversity in its headwaters, commercial fisheries production in the  
310 Yangtze's upper reaches is relatively low and so is not an important fishing area. A surplus  
311 production model was selected to estimate fish biomass in the three major fishing areas. This  
312 model was selected because it only requires catch and effort data (Hoggarth et al., 2006). It  
313 was considered to be the most suitable model for the Yangtze River due to a general lack of  
314 biological information which would be needed as inputs and parameters for more complex  
315 models. The fundamental concept of this model is that fish populations follow a depletion  
316 curve with population size decreasing as more fish in the population are caught than are  
317 replaced through recruitment. Assuming that fishing success is related to abundance, changes  
318 in fish populations can be reflected in trends in catch per unit effort (CPUE), which will  
319 decrease in proportion to decreasing exploitable biomass (Hilborn & Walters, 1992). The  
320 biomass estimation was conducted using the CEDA 3.0.1 package (MRAG Ltd, UK), which  
321 is based on the standard dynamics of surplus production models but uses non-equilibrium  
322 fitting methods and three different error models (Hoggarth et al., 2006). After test running, the  
323 Schaefer and Fox production models were used to conduct the estimation (Equations 1–3):

$$324 \quad B_{t+1} = B_t + f(B_t) - C_t \quad (1)$$

---

325 Schaefer:  $f(B_t) = rB_t(1 - B_t/K)$ ,  $MSY = rK/4$  (2)

326 Fox:  $f(B_t) = rB_t \ln(K/B_t)$ ,  $MSY = rKe^{-1}$  (3)

327 where  $B$  is the fish stock biomass,  $t$  is the time (year),  $C$  is the catch,  $r$  is the intrinsic rate of  
328 growth,  $K$  is the carrying capacity of the population, and  $MSY$  is the maximum sustainable  
329 yield.

330

331 For conducting sensitivity analysis, the Schaefer and Fox production models, including two  
332 error assumptions (LSQ, least squares; and Log, log transform) and an initial proportion (IP)  
333 from 0.1 to 1.0, were used. In each area, the model and parameter combinations produced 40  
334 estimates of biomass and population characteristics. The goodness-of-fit was determined  
335 using plots of residuals, coefficients of determination, and reasonable projections. The CPUE  
336 data in the three areas were calculated from the *Bulletin of the Three Gorges Project* from  
337 1997 to 2017, which included special reports.

338

#### 339 2.4.2 Scenario settings

340 Three scenarios were set with different catches and fishing effort in the three areas. The  
341 projection period was from 2017 to 2030 based on the following considerations: 1) the latest  
342 available data were in 2016, and since 2017 the fishing ban policy was implemented in some  
343 tributaries and protected areas with variability in implementation among areas complicating  
344 the situation, so for simplicity the projection period was set to start in 2017; and 2) because  
345 confidence intervals widen as the projection period increases, a limitation on model prediction  
346 of 10 years was deemed suitable, so the projection period ended in 2030.

#### 347 *Scenario one: maintaining current fishing pressure*

348 It was assumed that there was no change in fisheries management policy. The annual catch  
349 during 2017–2030 was the same as the average yield since the trial operation of the Three  
350 Gorges Project (2003) to 2016.

---

351 *Scenario two: fishing ban in protected areas*

352 It was assumed that there was no fishing in all aquatic protected areas since the Chinese  
353 government announced a ban on any kind of fishing in the 332 aquatic protected areas in the  
354 Yangtze River as of 2018 (Yi & Yu, 2018). The protected areas include 53 natural protected  
355 areas and 279 aquatic germplasm protected areas (for protecting species with potential  
356 commercial benefit) at national, provincial and municipal levels. The proportion of the  
357 combined total of these two kinds of protected areas to the entire water area was estimated.  
358 This ratio was then used to predict the extent to which fishing pressure (i.e. so-called catch  
359 weight) would decrease in the 2017–2030 period.

360 *Scenario three: fishing ban in the entire Yangtze River*

361 It was assumed that any fishing activity was prohibited and that no fish were caught from the  
362 entire Yangtze River during the period 2017–2030.

363

## 364 **2.5 Synthesizing fishing and biodiversity threats in global rivers**

365 Pressure from fishing and biodiversity threats from other anthropogenic activities have been  
366 quantitatively evaluated on a global scale by Vörösmarty et al. (2010). The spatial distribution  
367 status of fishing pressure and biodiversity threats throughout the world was described in the  
368 form of a raster (using 30' latitude/longitude grids). In contrast, we chose to use a raster  
369 comprising river basin spatial units in accordance with Tedesco et al. (2017), as we consider  
370 that river basin/watershed units are more appropriate as an integral part of river ecosystems  
371 and more meaningful for riverine fisheries management. To make the river basins comparable,  
372 we chose only the 30 largest river basins which have their watershed areas proximal to the  
373 Yangtze River. The spatial analysis was conducted using ArcGIS (ESRI, USA).

374

## 375 **3 RESULTS**

### 376 **3.1 Fisheries yields in time and space**

---

377 Fisheries yields in the Yangtze River showed declining trends during 1949–2016 (Figure 3).  
378 The average decadal yields from 1950s to 2010s were 324.65, 252.77, 166.96, 242.33, 149.85,  
379 64.35, and 58.37 thousand tonnes, respectively. The maximum yield of 427.22 thousand  
380 tonnes was reported in 1954, and the minimum yield of 46.50 thousand tonnes in 2011. The  
381 trend of gradual decline in wild fisheries production was expressed as (assumed  $x=1$ ):  $y =$   
382  $393.08e^{-0.027x}$ ,  $R^2 = 0.71$ . The ratios of the yields from fisheries in the Yangtze River to the  
383 total fisheries production in China presented an obvious declining trend. The maximum ratio  
384 of the yield from the Yangtze River to the freshwater capture yield in China was 67.40%; that  
385 to the freshwater capture and aquaculture in China was 44.39%; and that to the total fishery  
386 production in China was 31.63%. However, in 2016, the above three ratios were 2.86%,  
387 0.19%, and 0.10%, respectively, indicating that the contribution of the capture fishery in the  
388 Yangtze River to food security in China was extremely low at that point in time.

389

390 In Dongting Lake, wild capture production was  $24.22 \pm 8.96$  (10.37–55.00) thousand tonnes  
391 during 1950–2016, with a coefficient of variation (CV) of 37.0% (Figure 3). In Poyang Lake,  
392 the production was  $25.55 \pm 10.83$  (10.02–71.90) thousand tonnes during 1949–2016, with a CV  
393 of 42.4%. It is noteworthy that yield from the Three Gorges Reservoir increased, whereas in  
394 the middle Yangtze it clearly decreased. The spatio-temporal pattern of yields associated with  
395 the provincial area had no obvious change; however, there was clearly observable annual  
396 variation in each area (Figures 3 and 4). The spatial distribution of average yield density  
397 (1949–1985) among seven provinces declined from the estuary to the upstream region (Figure  
398 4). Until 1985, the latest available data, the areas near the estuary, such as Shanghai and  
399 Jiangsu, had the highest yield densities (1,125.21 and 949.30 kg/km<sup>2</sup>, respectively). The areas  
400 in the middle and lower reaches, such as Hubei and Anhui, had the second highest yield  
401 densities, and those in the two large-lake provinces (i.e. Dongting Lake in Hunan and Poyang  
402 Lake in Jiangxi) had the third highest yield densities. Finally, the upper reach (Sichuan) had  
403 the lowest yield density (only 15.14 kg/km<sup>2</sup>).

404

---

### 405 3.2 Structural changes in fish community

406 The community structure of fishes, such as the proportions of endemic and migratory species,  
407 and the number of rare and endangered species have been considerably altered during the  
408 fisheries development process (Figure 5). During 1997–2016, the percentage of endemic fish  
409 species among all fishes in the upper Yangtze reach was  $22.8 \pm 2.9\%$  (18.6–30.8%), showing a  
410 declining trend with a slope of  $-0.32$  (Figure 5a). In Mudong (i.e. at the tail of the Three  
411 Gorges Reservoir) (Figure 2), a decreasing trend with a slope of  $-0.60$  was clearly observed.  
412 It could reasonably be assumed that the aquatic habitat was highly affected by the operation  
413 of the dam, accordingly endemic fishes decreased because most of them being rheophilic  
414 required flowing water. From the 1950s to the 2010s, the biomass percentages of the four  
415 major Chinese carp species (i.e. the most commercially important migratory fishes in the  
416 Yangtze River; the biomass percentage is based on their proportion of total catch weight) in  
417 Dongting and Poyang lakes were  $12.8 \pm 5.0\%$  (6.7–21.0%) and  $8.4 \pm 2.8\%$  (5.9–12.5%),  
418 respectively (Figure 5b). Both showed decreasing trends, with the trend in Dongting Lake was  
419 more obvious than that in Poyang Lake. It was concluded that either physically disconnected  
420 (sluice) or biologically disconnected (streamflow is unimpeded, but fish migration behavior is  
421 changed due to hydrological alteration) would have effects on species composition in the  
422 lakes. Those such as Dongting Lake and Poyang Lake, although still physically connected  
423 nevertheless showed changes in species composition. In addition, fishing activities also  
424 altered fish composition due to their selectivity of specific fish species.

425

426 Owing to the Gezhouba Dam impeding the river since 1981, the number of rare and  
427 endangered fishes diminished rapidly (Figure 5c and 5d). The number of mature Chinese  
428 sturgeons below the Gezhouba Dam was estimated to be approximately 2,500 individuals in  
429 the early 1980s but declined to approximately 50 by 2014–2016 (Figure 5c). Bycatch numbers  
430 of Chinese paddlefish and Yangtze sturgeon (*Acipenser dabryanus*, Acipenseridae) peaked in  
431 1985 and then dropped dramatically (Figure 5d). These two fishes are migratory species that  
432 were widely distributed in the upper, middle and lower reaches of the Yangtze River,  
433 although their spawning areas were located in the upper reach. As the Gezhouba Dam in the  
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434 middle reach blocked the migration route of these two fishes in 1981, their juveniles of  
435 various age classes (0+ and above) became restricted to the middle and lower reaches of the  
436 Yangtze River. These juveniles gradually matured and swam upstream but were blocked  
437 below the Gezhouba Dam. As the maturation age of Chinese paddlefish is 5–7 years, and 4–6  
438 years for Yangtze sturgeon (Wei et al., 1997), 4–5 years after the dam closed the number  
439 gradually increased to its peak then started to decrease. The decrease implies that their  
440 populations were declining, and the last living specimen of the Chinese paddlefish was found  
441 in 2003 in the upper Yangtze. No Yangtze sturgeon was found below the Gezhouba Dam  
442 during 1995–2000, indicating the rapid decline of its favored habitat. Currently, 70 aquatic  
443 animals in the Yangtze River Basin have been listed as nationally and/or internationally  
444 protected species (Table 1, Table S2), which implies a serious loss in aquatic biodiversity.

445

### 446 **3.3 Environmental factors and their impacts on capture yields**

447 The environmental factors in each of the four categories varied greatly during 1997–2016  
448 (Figure 6, Table 2). The total flow discharged at the three stations varied among years, yet  
449 there was no clear trend, while the mean sediment concentration at the stations has obviously  
450 decreased since 2003 (i.e. the trial operation of the Three Gorges Project). In particular, the  
451 mean sediment concentration at Yichang, which is located just below the Three Gorges Dam,  
452 decreased considerably (Figure 6a). Both the reservoir number and the total reservoir capacity  
453 clearly increased (Figure 6b). The total volumes of wastewater emissions clearly increased,  
454 while the ratio of low water quality has decreased since 2010 (Figure 6c). This result implied  
455 that water pollution prevention work has become more effective than it was before. Ship  
456 cargo volume increased, while total passenger traffic decreased (Figure 6d). This decrease in  
457 passengers might have resulted from diversified transport methods; hence, passengers could  
458 choose other transport methods, such as railways and highways, rather than ships.

459

460 Correlation analysis between wild capture fisheries production and environmental conditions  
461 showed significant associations with many of those factors (Table 2). Significant positive

---

462 correlations were found between production and runoff characteristics, e.g. the total discharge  
463 ( $r=0.50-0.62$ ,  $P<0.05$ ) and the average sediment concentration ( $r=0.57-0.75$ ,  $P<0.05$ ), at the  
464 three stations. Correlations between capture production and water impoundment ( $r=-0.63$ ,  
465  $-0.68$ ,  $P<0.01$ ) as well as between capture production and water pollution ( $r=-0.72$ ,  $-0.72$ ,  
466  $P<0.01$ ) were significantly negative. Ship cargo volume was negatively correlated with  
467 capture production ( $r=-0.69$ ,  $P<0.01$ ), whereas total passenger traffic had a positive  
468 correlation with capture production ( $r=0.80$ ,  $P<0.01$ ). In addition, weak positive correlations  
469 were found between the two runoff variables because they were inherently related. Water  
470 retention in dams showed significant negative correlation with sediment concentration  
471 because of its effects on the runoff process. Note that although some environmental variables  
472 were significantly correlated, they did not have inherent cause and effect relationships with  
473 each other and were more likely to have similarly developing trends with time.

474

475 The stepwise regression method built two effective regression formulae (Table 3). Two  
476 variables (i.e. the sediment concentration (Datong) and the ratio of low water quality reaches),  
477 which were selected from the 12 variables, built the better formula, with  $F(2, 14)=34.283$   
478 ( $P<0.001$ , adjusted  $R^2=0.83$ ). This result implied that sediment concentration and water  
479 pollution had a significant influence on fishing yields with year.

480

### 481 **3.4 Biomass projection in the future**

482 Dongting Lake had the highest average CPUE of  $11.70\pm 4.19$  kg/boat-day, with a drastic range  
483 in the variation of  $5.24-21.34$  kg/boat-day and a CV of 35.8% (Figure 7). The average CPUE  
484 values in the middle reach of the Yangtze River and Poyang Lake were  $7.05\pm 2.54$  (range  
485  $4.70-15.20$ ) kg/boat-day and  $5.84\pm 1.66$  (range  $3.33-8.76$ ) kg/boat-day, respectively and were  
486 relatively close. Overall, the CPUE in Dongting Lake showed a downward trend, while that in  
487 the middle reach and in Poyang Lake had slightly upward trends.

488

---

489 The spatial analysis showed that the 332 aquatic protected areas were distributed in 13  
490 provincial areas of the Yangtze River (Figure 8). The number of protected areas in each  
491 province was highly dependent on the proportion of the area included in the Yangtze River.  
492 For instance, Hubei had the largest number of 83, while Shanghai had the smallest number of  
493 only two. It revealed that these 332 protected areas occupied approximately 1/3 of the entire  
494 water area in the basin. Accordingly, the scenario settings for future biomass estimation are  
495 described in Table 4.

496

497 The surplus production model estimated past and future biomass in three areas (Table 5,  
498 Figure 9). In each area, two of 40 estimates were selected according to the standard of the  
499 goodness-of-fit (Table 5). The two lakes have a larger carrying capacity  
500 (78,054.91–96,321.65 t in Dongting Lake and 92,974.70–135,020.60 t in Poyang Lake) than  
501 that of the middle Yangtze (22,377.51–23,943.21 t). The maximum sustainable yield (MSY)  
502 and the final biomass in the two lakes were higher than those in the middle reach of the  
503 Yangtze. Under the three management scenarios, the three areas showed very similar  
504 variation in biomass (Figure 9). If fishing activity were to continue under the present situation,  
505 then the biomass would not change, remaining at its relatively low current level. If fishing  
506 was banned in the protected areas, then the biomass would slightly increase. If fishing was  
507 completely banned from all areas of the river, then the biomass would rapidly increase and  
508 remain at a relatively high level. However, as indicated by difference in the estimates of the  
509 population growth rate parameter  $r$  (Table 5), the recovery period for fisheries resources in the  
510 two lakes would be much faster (3–5 years) than that for the middle reach (8 years). In  
511 comparison, the sum of the MSY in the three areas was ~76.17 thousand tonnes, which was  
512 still far less (26.1%) than the average yield of 103.06 thousand tonnes reported during  
513 1949–1985 in the corresponding provinces (i.e. Hubei, Jiangxi, and Hunan) (Figure 4).

514

### 515 **3.5 Fishing and biodiversity threats in global large rivers**

516 Based on data from Vörösmarty et al. (2010), evaluations of fishing pressure and biodiversity  
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517 threats on thirty large rivers globally were analyzed (Figure 10, Table S3). The analysis  
518 showed that the Mekong, Ganges, and Yangtze rivers had the first, second, and third highest  
519 fishing pressures, respectively. The Danube, Mississippi, and Shatt al-Arab rivers had the first,  
520 second, and third highest biodiversity threats, respectively, and the Yangtze River ranked in  
521 6th place. By simply summing the two indices of fishing pressure and biodiversity threat, the  
522 Shatt al-Arab, Yangtze, Ganges, Mekong, and Niger rivers occupied the top five positions,  
523 respectively.

524

## 525 **4 DISCUSSION**

### 526 **4.1 Limitations of methods**

527 Systematic and long-term monitoring of the Yangtze aquatic ecosystem has been insufficient  
528 due to the huge spatio-temporal scale and lack of research effort (Chen et al., 2009; Liu &  
529 Gao, 2012). Hydrological monitoring of the Yangtze River, which started in the late 19th  
530 century, is more comprehensive than biological monitoring of its aquatic ecosystem (Yang,  
531 Xu, Milliman, Yang, & Wu, 2015). The commencement of the Three Gorges Project in the  
532 middle 1990s, prompted more extensive monitoring of natural resources and the aquatic  
533 environment of the Yangtze River Basin (Chen et al., 2009; Liu & Gao, 2012). The reason  
534 that the correlation and projection analyses in this study were performed only from the late  
535 1990s was because of limited data availability prior to then. However, to target the entire  
536 Yangtze River, comprehensive fisheries surveys could not be undertaken due to deficiencies  
537 in past investments in data collection, and a lack of systematic organization including data  
538 sharing mechanisms. In this study, the surplus production model seemed to be the only  
539 feasible method which allowed the exploitable biomass to be estimated for such an enormous  
540 study area (Hoggarth et al., 2006). The model assumed that fish migration in the evaluated  
541 area was negligible. In fact, some fishes migrated to the middle reach and the two lakes, yet  
542 their number and biomass were very low (Xie, 2007a, 2007b). Hence, it was reasonable to use  
543 this model in the present study. Further monitoring using direct measurements like acoustic  
544 detection of fishes, could possibly improve the biomass estimation results in this study. Other

---

545 anthropogenic activities directly related to the fishery, such as artificial fish propagation and  
546 release (i.e. stocking), recreational fishing, illegal fishing, and dam ecological operations,  
547 were excluded from this analysis due to limitations in the available data which are not well  
548 elucidated at such large temporal and spatial scales. The prediction is nevertheless worthwhile  
549 and the results meaningful despite the omission of these extrinsic factors that may be  
550 influencing production. Our models predicted trends in fish biomass under three future fishing  
551 scenarios, i) maintaining the current level of fishing pressure, ii) banning fishing in protected  
552 areas, and iii) banning fishing in the entire Yangtze River; results that can provide guidance  
553 for future fisheries management in the Yangtze River. Moreover, it is hoped that future  
554 studies will be able to include more variables (Yang et al., 2007, 2009, 2011).

555

#### 556 **4.2 Fisheries utilization and protection in the Yangtze**

557 The Yangtze River Basin has experienced great changes in the utilization and protection of its  
558 fisheries during the past 70 years (Table 6) (Chen et al., 2003; Lu et al., 2016; Zeng, 1990).  
559 From the 1950s to the 1970s, the main role of the Yangtze River was to provide protein-rich  
560 food (Zeng, 1990). Since the 1970s, after the construction of the Gezhouba Dam, the  
561 protection of migratory fishes (such as the four major Chinese carp species, Chinese sturgeon,  
562 and others) started to receive more attention (Yi et al., 1988; Zhang et al., 2017). However,  
563 the first fisheries law in China was not decreed until 1986, and in the Yangtze River, the first  
564 regulation was issued in 1988. The protection of rare, endangered, and endemic species as  
565 well as their habitats has gradually been recognized as an important issue. In 2002, a tentative  
566 fishing ban policy was trialed in the middle and lower reaches of the Yangtze River (Yi & Yu,  
567 2018). In 2003, the fishing ban policy was officially implemented and became an important  
568 national-level policy for all inland waters of China following on from a marine fishing  
569 moratorium. Since 2006, artificial fish propagation and release (i.e. stocking) projects  
570 involving many species have been conducted after implementing conservation programs on  
571 living aquatic resources (Chen et al., 2009). In general, stocking is for commercial harvesting  
572 or rehabilitation of endangered or endemic species. For instance, stocking of Chinese mitten  
573 crab (*Eriocheir sinensis*, Varunidae), and the four major Chinese domestic carps, within the  
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574 lakes in the middle and lower Yangtze Basin is mainly for harvesting, whereas stocking of  
575 protected species, such as Chinese sturgeon, Yangtze sturgeon and Chinese sucker, etc., is  
576 aimed at rehabilitating wild populations. Since 2015, three rescue action plans on flagship  
577 species in the Yangtze River, such as Chinese sturgeon, Yangtze finless porpoise, and  
578 Yangtze sturgeon, have been successively implemented (Yi & Yu, 2018). Since 2017, a  
579 long-term fishing ban policy was implemented, first in a tributary of the upper Yangtze and  
580 subsequently extended to 332 nature and germplasm protected areas throughout the entire  
581 river basin. To protect wild populations and genetic germplasm resources of three migratory  
582 species including Chinese mitten crab, the issuing of a special fishing permit to fish for them,  
583 which began in 2002, ceased in late 2018. Currently, more integrated and comprehensive  
584 protection plans (a 10-year fishing ban) for the entire Yangtze aquatic ecosystem are being  
585 designed (Ministry of Agriculture and Rural Affairs of China, 2019; Yi & Yu, 2018).

586

#### 587 **4.3 Challenges for Yangtze aquatic biodiversity**

588 Yangtze River aquatic biodiversity is still facing a number of challenges even though the  
589 fishing ban policy has been implemented (Chen et al., 2003, 2009; Huang & Li, 2016; Liu et  
590 al., 2019; Ye et al., 2011). First, habitat fragmentation and its loss due to damming and sluice  
591 construction are difficult to remediate, while some endemic fishes remain exposed to a high  
592 risk of extinction (Cheng et al., 2015; Zhang et al., 2013; Zhang, Gao, Wang, & Cao, 2015).  
593 The Three Gorges Dam and upstream dams without fish passages have directly blocked the  
594 migration of fishes and altered the fluvial river reach into artificial reservoirs (Wu et al., 2003,  
595 2004). This greatly decreased the diversity of endemic fishes as most of them were rheophilic  
596 so required flowing water. Currently, there is a plan to build 27 dams along the 2,290 km of  
597 the Jinsha River (i.e. the upper reach of the Yangtze and the most species-rich area in the  
598 river). Once these dams have been built nearly no river flow will remain (Yang et al., 2007,  
599 2009, 2011). Moreover, a plan to construct a sluice at the confluence of Dongting Lake and  
600 Poyang Lake, which are the only lakes still connected to the mainstream of the river, has been  
601 proposed, although there has been considerable debate about the merits of this project (Huang  
602 et al., 2013; Xie, 2017a, 2017b). In addition, although reclaiming lakes for farmland is now  
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603 strictly forbidden, areas that have already been converted into farmland cannot be reverted to  
604 lakes. Second, habitat alterations and deterioration due to reservoir operations and various  
605 human activities are difficult to remediate. Reservoir operations largely changed hydrological  
606 processes such as flow and sediment transport and deposition (Wu et al., 2004; Yang et al.,  
607 2015), and altered the water temperature regime (Wang, Li, Duan, Chen, et al., 2014; Wang,  
608 Li, Duan, Luo, et al., 2014) which is critical for fishes throughout the entire Yangtze River.  
609 This study revealed that the sediment concentration had important impacts on the yields from  
610 capture fisheries. In addition, issues of water pollution, waterway construction and  
611 channelization, sand and gravel extraction, port construction, and noise and vibration from  
612 vessel navigation are extremely difficult to completely resolve (Yang et al., 2007, 2009, 2011).  
613 Third, the recreational fishery and exotic species should be given more attention. Based on  
614 our experience, the recreational fisheries catch could be very high; thus, effective regulatory  
615 management will be required in the near future (Ma et al., 2018). According to a basin-wide  
616 capture survey during 2017–2018 in the Yangtze River, a total of 25 exotic species have been  
617 recorded, out of which 11 had never been previously observed in the basin, such as several  
618 kinds of tilapia, largemouth bass (*Micropterus salmoides*, Centrarchidae), freshwater  
619 pompano (*Piaractus brachypomus*, Serrasalminidae) (Zhang et al., 2020, unpublished data).  
620 Moreover, the abundance of exotic species gradually increases from the Yangtze estuary to  
621 the headwater, implying that the upstream regions are of greater concern in this regard. In the  
622 past, although exotic fish species were occasionally caught in the Yangtze River, due to  
623 fishing pressure their influence on the aquatic ecosystem was low. However, the fishing ban  
624 policy may be allowing them to flourish, as evidenced by the buildup of an enormous quantity  
625 of red swamp crayfish in Dongting Lake. In 2017, its catch reached 11,300 tonnes, accounting  
626 for nearly 30% of the total capture production (FB-MARA-PRC, NFTECC, & CFA, 2019). If  
627 fishing activities in this lake ceased, then the ecological impacts would be incalculable.  
628 Accordingly, measures for controlling their possible sources should be instigated (Liu,  
629 McGarrity, Bai, Ke, & Li, 2013). Lastly, an integrated and scientifically based strategic  
630 management system for the entire Yangtze River aquatic ecosystem is urgently required  
631 (Chen et al., 2009; Liu and Gao, 2012).

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632

633 It is speculated that the current protection measures can only rehabilitate Yangtze River  
634 fisheries resources to a certain degree. Once a fish community structure is severely disrupted,  
635 it is almost impossible to restore. Functionally extinct species (i.e. Baiji, Chinese paddlefish,  
636 and Reeves shad) (Turvey et al., 2007; Zhang et al., 2020) will become completely extinct if  
637 no further rescue measures are undertaken.

638

#### 639 **4.4 Fishing pressure and biodiversity threat of global rivers**

640 The circumstance of each river is different, not only because it differs in geographic location  
641 and associated environment, but also in economic development, fisheries (especially  
642 aquaculture) development status, and even the various consumptive habits of the local people  
643 (Castello & Macedo, 2016; FAO, 2016; Welcomme et al., 2014). Some rivers face concerns  
644 related to food supply (McIntyre et al., 2016), whilst others are confronted by a need for  
645 biodiversity conservation (Kominoski et al., 2018). Nevertheless, in all drainage areas, human  
646 perturbations have become generally high (Jackson et al., 2016; Vörösmarty et al., 2010) and  
647 human population growth has created increased dependency on their natural resources, which  
648 in turn leads to increased fishing pressure and biodiversity threats.

649

650 The rapid change in fisheries development and biodiversity conservation in the Yangtze River  
651 has many management implications for other large-river systems in the world (Castello &  
652 Macedo, 2016; Jackson et al., 2016; Kominoski et al., 2018), as the river has experienced a  
653 challenging process of utilization-overexploitation-protection of its fisheries during the last 80  
654 years; moreover, other large rivers may have similar issues. Given the similarity in  
655 circumstances between these large rivers and the Yangtze River in terms of fishing pressure  
656 and biodiversity threats (Figure 10, Table S3), ecosystem management initiatives in the  
657 Yangtze River could be informative for other globally large rivers to improve the  
658 management outcomes for their ecosystems.

---

#### 660 4.5 Future management implications

661 In the Yangtze River Basin, five aspects of future management are strongly recommended.  
662 First, the present cascaded dam development plan at the basin scale should be reconsidered  
663 and revised (Cheng et al., 2015; Kominoski et al., 2018; Winemiller et al., 2016). The  
664 cumulative and long-term effects of the dams at the basin scale should be re-evaluated to  
665 develop a more ecologically sustainable plan (Castello & Macedo, 2016; Ziv, Baran, Nam,  
666 Rodríguez-Iturbe, & Levin, 2012). Some tributaries are important for biodiversity  
667 conservation so that the excessive number of small dams located in tributaries should be  
668 removed or modified by adding fish passages. Second, a more natural run-off process should  
669 be created through strategic reservoir operations. Under the increasing impacts of climatic  
670 change and human activities, more components of favorable ecosystems such as water  
671 temperature regimes, flood pulses, and sedimentation processes should be designed based on  
672 the needs of aquatic organisms (Sabo et al., 2017; Wang, Li, Duan, Chen, et al., 2014; Wang,  
673 Li, Duan, Luo, et al., 2014; Yang et al., 2015). Third, the need for appropriate and stringent  
674 fisheries policies, to ensure sustainable wild capture and aquaculture practices, must be  
675 addressed (Kang et al., 2017; Ma et al., 2018; Wang, Cheng, et al., 2015; Wang, Li, &  
676 Waerebeek, 2015), and ecosystem-based fisheries management in light of selective fishing  
677 policies should be implemented (Goulding et al., 2019; Zhou et al., 2010). The lakes  
678 (reservoirs) in the Yangtze River Basin potentially suitable for aquaculture should be  
679 scientifically differentiated, and sustainable fisheries should be ensured by encouraging  
680 responsible well-managed fishing activities compatible with engaging local communities in  
681 generating socio-ecological benefits. Fishing related tourism, incorporating the catering  
682 industry, recreational angling, and cultural activities needs to be encouraged in a balanced  
683 manner to maximize long-term economic and ecological benefits. More importantly,  
684 aquaculture and species conservation in lakes should be integrated with flood control, water  
685 supply, etc., through support from all relevant stakeholders. In addition, recreational angling  
686 in natural waters should be scientifically managed via restrictions that limit equipment,  
687 thereby curtailing the take of particular species, as well as imposing moratoria and temporal

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688 closures where appropriate to protect endangered and threatened species, ecosystems at risk,  
689 and vulnerable habitats (Ma et al., 2018). In addition, aquaculture in the basin should have  
690 effective ways to prevent the introduction of exotic species, with stocking required to use  
691 local species, and not permitting release of hybrids, gene-modified species, and species that  
692 don't meet ecological requirements (Kang et al., 2017; Wang, Cheng, et al., 2015). Fourth, a  
693 scientific-based systematic management system should be implemented at the basin scale  
694 (Chen et al., 2009; Heiner, Higgins, Li, & Baker, 2011; Wang, Gao, Jakovlić, & Liu, 2017).  
695 Finally, public education imparting knowledge and promoting understanding about the critical  
696 roles and importance of the ecosystem of the Yangtze River and ecosystem services it  
697 provides for human well-being is also necessary, including changing the way people interact  
698 with the river system e.g. avoidance of risks from releasing exotic species by ceasing this  
699 practice as a religious activity or irresponsible release of unwanted ornamental fish or fish  
700 pets by the public (Liu et al., 2013). It is noteworthy that recovery of fisheries resources will  
701 not directly result in the rehabilitation of aquatic biodiversity, which requires a much more  
702 sophisticated approach to deal with the complexities of ecological interactions.

703

704 This study demonstrated that overexploited fisheries resources could be recovered by  
705 enforcing a fisheries protection policy including drastic measures such as a complete ban on  
706 fishing in the entire river. However, once aquatic habitats are lost or seriously degraded, it  
707 will be extremely difficult if not impossible for them to be fully restored. The structure of the  
708 fish communities, which is strongly related to biodiversity, is likely to be transformed by  
709 indiscriminate fishing and will be challenging to rehabilitate. Of paramount importance is that  
710 the rare and endangered, endemic and migratory aquatic species of the Yangtze River Basin  
711 require urgent intervention to prevent their extinction.

712

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720

## 721 **DATA AVAILABILITY STATEMENT**

722 The data that supports the findings of this study are available in this published article and its  
723 supporting information.

724

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1086 **Table 1** Protected species in the Yangtze River basin; a detailed list is found in Table S2.

Type of protection list	Category and number	Total
The IUCN Red List of Threatened Species	Critically Endangered, 16;	29
	Endangered, 3;	
	Vulnerable, 1;	
	Near Threatened, 4;	
	Least Concern, 5	

<b>Convention on International Trade in Endangered Species of Wild Fauna and Flora</b>	Appendix I, 5; Appendix II, 3	8
<b>National Protected Wildlife in China</b>	Top Level, 5; Second Level, 9	14
<b>China Species Red List (Fishes)</b>	Extinct, 2; Extinct in the Wild, 2; Critically Endangered, 5; Endangered, 36; Vulnerable, 20	65

1088 **Table 2** Spearman correlations between wild capture fisheries production and environmental factors in the Yangtze River during 1997–2016.

Theme	Mean	SD	Capture production (n=20)	Runoff process (n=17)							Water impoundment projects (n=20)		Water pollution (n=20)		Navigation (n=20)	
				1	2	3	4	5	6	7	8	9	10	11	12	13
Production and factor #			1													
Capture production	1	7.16	2.64	X	0.50*	0.62**	0.61**	0.57*	0.57*	0.75**	-0.63**	-0.68**	-0.72**	-0.72**	-0.69**	0.80**
Summed discharge (Yichang) ( $\times 10^9$ m <sup>3</sup> )	2	406.62	46.77		X	0.64**	0.59*	0.35	0.38	0.50*	-0.13	-0.12	-0.07	-0.36	-0.16	0.21
Summed discharge (Hankou) ( $\times 10^9$ m <sup>3</sup> )	3	684.67	70.98			X	0.93**	0.32	0.33	0.53*	-0.03	-0.04	0.04	-0.56*	-0.10	0.11
Summed discharge (Datong) ( $\times 10^9$ m <sup>3</sup> )	4	868.18	113.06				X	0.17	0.16	0.42	0.13	0.10	0.16	-0.62**	0.03	0.03
Sediment concentration (Yichang) (kg/m <sup>3</sup> )	5	0.201	0.256					X	0.96**	0.93**	-0.81**	-0.87**	-0.83**	0.10	-0.91**	0.78**
Sediment concentration (Hankou) (kg/m <sup>3</sup> )	6	0.195	0.109						X	0.94**	-0.80**	-0.86**	-0.80**	0.07	-0.88**	0.74**
Sediment concentration (Datong) (kg/m <sup>3</sup> )	7	0.190	0.075							X	-0.71**	-0.77**	-0.73**	-0.10	-0.81**	0.73**
Reservoir number ( $\times 10^3$ ind.)	8	55.74	11.33								X	0.95**	0.92**	0.11	0.92**	-0.89**
Total reservoir capacity ( $\times 10^9$ m <sup>3</sup> )	9	335.43	186.37									X	0.97**	0.13	0.98**	-0.94**
Waste water emissions ( $\times 10^9$ t)	10	29.30	5.53										X	0.20	0.96**	-0.97**
Low water quality reach (%)	11	26.01	5.38											X	0.13	-0.26
Ship cargo volume ( $\times 10^6$ t)	12	54.34	37.97												X	-0.94**
Total passenger traffic ( $\times 10^6$ )	13	1.59	1.25													X

1089 \* Correlation is significant at the 0.05 level (2-tailed)

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1090 \*\* Correlation is significant at the 0.01 level (2-tailed)

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1092 **Table 3** Stepwise regression between the capture production (CP) and the environmental  
 1093 factors in the Yangtze River. Two factors were selected from the 12 environmental variables  
 1094 (Table 2).

Model	Variables entered	Regression formula	R	R <sup>2</sup>	Adjusted R <sup>2</sup>	F	Sig.
1	Sediment concentration (Datong) (SC <sub>DT</sub> )	CP = 41.930 + 104.954 × SC <sub>DT</sub>	0.795	0.63	0.61	25.776	<0.001
2	Sediment concentration (Datong) (SC <sub>DT</sub> ), Low water quality reach (R <sub>LWQR</sub> )	CP = 67.695 + 95.749 × SC <sub>DT</sub> - 0.885 × R <sub>LWQR</sub>	0.911	0.83	0.81	34.283	<0.001

1095  
 1096 **Table 4** Scenario settings for catches in three major fishing areas in the Yangtze River.

Area	Middle reach (t)	Dongting Lake (t)	Poyang Lake (t)
Scenario 1 (No fishing ban, assumed catch was the average yield during 2003–2016)	1706	23651	28829
Scenario 2 (Ban fishing in protected areas, which means the catch decreases by 1/3)	1137	15767	19219
Scenario 3 (Ban fishing in all water areas, no catch at all)	0	0	0

1097  
 1098 **Table 5** Parameter estimates for the catch and effort data in the three major fishing areas in  
 1099 the Yangtze River using the Schaefer and Fox production models, including two error  
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1100 assumptions (LSQ, least squares; and Log, log transform). IP, initial proportion; K, carrying  
 1101 capacity of the population; q, catchability coefficient; r, intrinsic rate of growth; MSY,  
 1102 maximum sustainable yield; R. Yield, replacement yield; R<sup>2</sup>, coefficient of determination.

Area	Model	Fit	IP	K (t)	q( $\times 10^{-4}$ )	r	MSY (t)	R. yield (t)	Final biomass (t)	R <sup>2</sup>
Middle reach	Schaefer	LSQ	0.5	22377.51	5.71	0.395	2208.94	1947.48	15038.15	0.156
	Schaefer	Log	0.5	23943.21	5.39	0.367	2194.44	1967.41	15822.29	0.137
Dongting Lake	Fox	LSQ	0.4	78054.91	2.15	1.297	37247.91	28985.09	49863.66	0.686
	Fox	LSQ	0.5	96321.65	1.69	1.116	39530.38	28804.40	64577.12	0.681
Poyang Lake	Fox	LSQ	0.2	92974.70	1.17	1.119	38279.83	27435.70	63008.21	0.907
	Fox	Log	0.3	135020.60	1.05	0.662	32884.25	28016.19	79052.20	0.938

1103  
 1104 **Table 6** Key events affecting Yangtze River fisheries and aquatic biodiversity since the  
 1105 1980s.

Date	Event
Jul 1, 1986	Issued the “Fisheries Law of the People's Republic of China”
Jul 2, 1988	Issued the “Provisional Regulations on the Management of Fishery Resources in the Middle and Lower Reaches of Yangtze River”
Dec 10, 1988	Issued the list of key protected wildlife in China. In the Yangtze River, 5 species were listed at the top protection level and 8 at the second highest level
Sep 28, 1995	Issued the “Yangtze River Fishery Resource Management Regulations”
Apr 4, 2000	Built a national protected area (between Hejiang and Leibo) for protecting rare species in the upper Yangtze. In 2005, this protected area was enlarged and renamed as the Upper Yangtze National Protected Area for Endangered

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and Endemic Fishes, which is the largest protected area ( $3.32 \times 10^4$  ha) for freshwater fishes in China

- Jan 6, 2003 Started the fishing ban policy in the Yangtze River. The fishing ban period was 3 months: Feb-Apr above the Gezhouba Dam and Apr-Jun below the dam
- Feb 14, 2006 Issued the “Program of Action on the Conservation of Living Aquatic Resources of China”, including the Yangtze River as a key area
- Sep 28, 2015 Issued the “Rescue Action Plan for Chinese Sturgeon (2015–2030)”
- Jan 1, 2016 Adjusted and improved the fishing ban policy. The fishing ban area was enlarged to cover the major mainstream, tributaries and lakes, and the period was extended to 4 months (March to June)
- Dec 13, 2016 Issued the “Rescue Action Plan for Yangtze Finless Porpoise (2016–2025)”
- Jan 1, 2017 The full fishing ban was applied in a tributary (Chishui River, 436 km) in the upper reach for ten years (2017–2026) (Liu et al., 2012)
- Nov 23, 2017 The full fishing ban was applied in 332 aquatic protected areas in the Yangtze River, which accounted for 1/3 of the water areas in the entire drainage area
- Mar 22, 2018 Issued the “Key River Basin Aquatic Biodiversity Conservation Program”, which included 7 basins. The first basin was the Yangtze River
- May 15, 2018 Issued the “Rescue Action Plan for Yangtze Sturgeon (2018–2035)”
- Oct 15, 2018 Issued the "Opinions on Strengthening the Protection of Aquatic Organisms in the Yangtze River"
- Dec 28, 2018 Special fishing permit for longjaw grenadier anchovy (*Coilia macrognathos*, Engraulidae), phoenix-tailed anchovy (*Coilia mystus*, Engraulidae), Chinese mitten crab, introduced on Feb 8, 2002, was ceased

1106

1107 **Figure legends:**

1108

1109 **Figure 1** Conceptual framework, logical ideas and research content in the present study.  
1110 Human activities, aquatic organisms, and aquatic environments interact with each other, and  
1111 policies, such as fisheries law, fishing moratorium policy, rescue action plan, biodiversity  
1112 conservation program, etc. are used to regulate these to get the best ecosystem services.  
1113 Figure appears in colour in the online version only.

1114

1115 **Figure 2** The study area that is the Yangtze River Basin, showing cities, dams, rivers and  
1116 lakes. The geographic data are from the National Fundamental Geographic Information  
1117 System of China. Dam information (associated with reservoirs that have a storage capacity  
1118 greater than 0.1 km<sup>3</sup>) in the drainage basin is from the NASA Socioeconomic Data and  
1119 Applications Center (SEDAC) (Lehner et al., 2011a, b). Based on this dam information, a few  
1120 dams on the mainstream have been added that reflect recent developments. Figure appears in  
1121 colour in the online version only.

1122

1123 **Figure 3** Fisheries capture production in the Yangtze River Basin and its percentage of  
1124 China's fisheries production during the period of 1949–2016. Yields in the four major  
1125 production areas of the basin are indicated separately when the data are available. Figure  
1126 appears in colour in the online version only.

1127

1128 **Figure 4** The spatial distribution of fisheries capture production in the Yangtze River during  
1129 the period of 1949–1985 (n = 27–37, Zeng, 1990). Map shows the mean yield density (kg/km<sup>2</sup>)  
1130 in 7 provinces (Chongqing municipality belonged to Sichuan Province at that time). The

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1131 vertical bars in the 7 boxes indicate the capture yields ( $\times 10^3$  t) by year (1949–1985). The  
1132 average yield is seen in the title of the box. TGR-Three Gorges Reservoir, MR-middle reach,  
1133 DTL-Dongting Lake, and PYL-Poyang Lake. Figure appears in colour in the online version  
1134 only.

1135  
1136 **Figure 5** Variations in fish community and number in the Yangtze during capture fisheries  
1137 development. Refer to Figure 2 for the locations. (a) Percentage of endemic species monitored  
1138 in the upper reach and number monitored in Mudong, (b) biomass percentage of  
1139 representative migratory species (the four major Chinese carp species) in the two largest lakes  
1140 in the middle reach, (c) estimated number of adult Chinese sturgeon below the Gezhouba  
1141 Dam since the dam was closed in 1981 (Figure S1), (d) bycatch number of Chinese paddlefish  
1142 in the entire Yangtze, and bycatch number of Yangtze sturgeon below the Gezhouba Dam.  
1143 Figure appears in colour in the online version only.

1144  
1145 **Figure 6** Variations in environmental factors in the Yangtze River. (a) Run-off process, refer  
1146 to Figure 2 for the locations of the monitoring sites; (b) water impoundment; (c) water  
1147 pollution, data from the entire Yangtze River; (d) navigation, data from the Gezhouba Dam  
1148 and the Three Gorges Dam. Figure appears in colour in the online version only.

1149  
1150 **Figure 7** Catch per unit effort (CPUE) in three major fishing areas in the Yangtze River  
1151 during 2001–2016. Figure appears in colour in the online version only.

1152  
1153 **Figure 8** The spatial distributions of the aquatic protected areas in the Yangtze River. The  
1154 numbers before and after the slash represent the quantities of nature and aquatic germplasm  
1155 protected areas, respectively. The green color scale indicates the total number of protected  
1156 areas. Figure appears in colour in the online version only.

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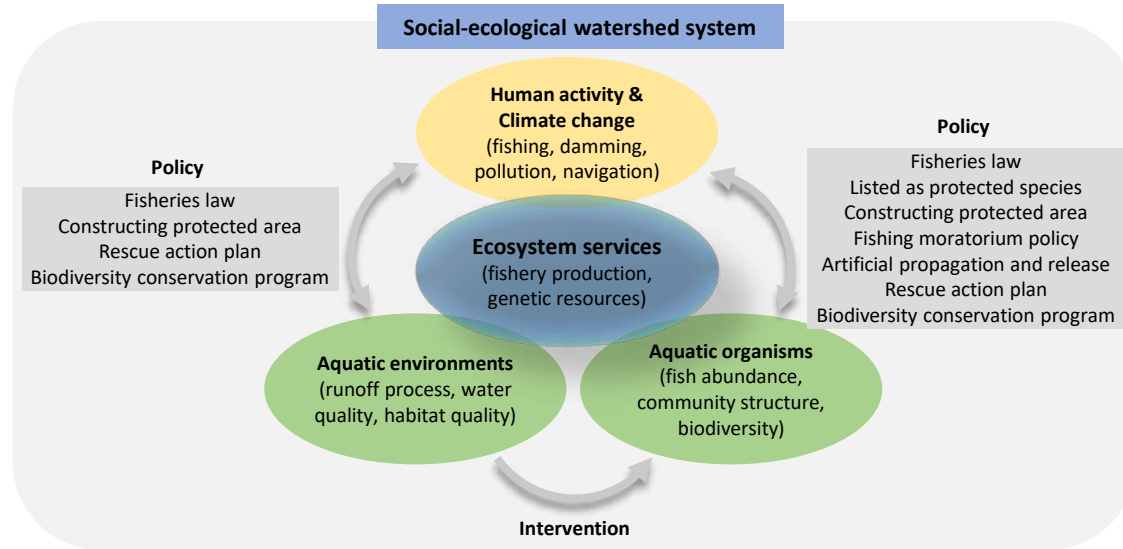
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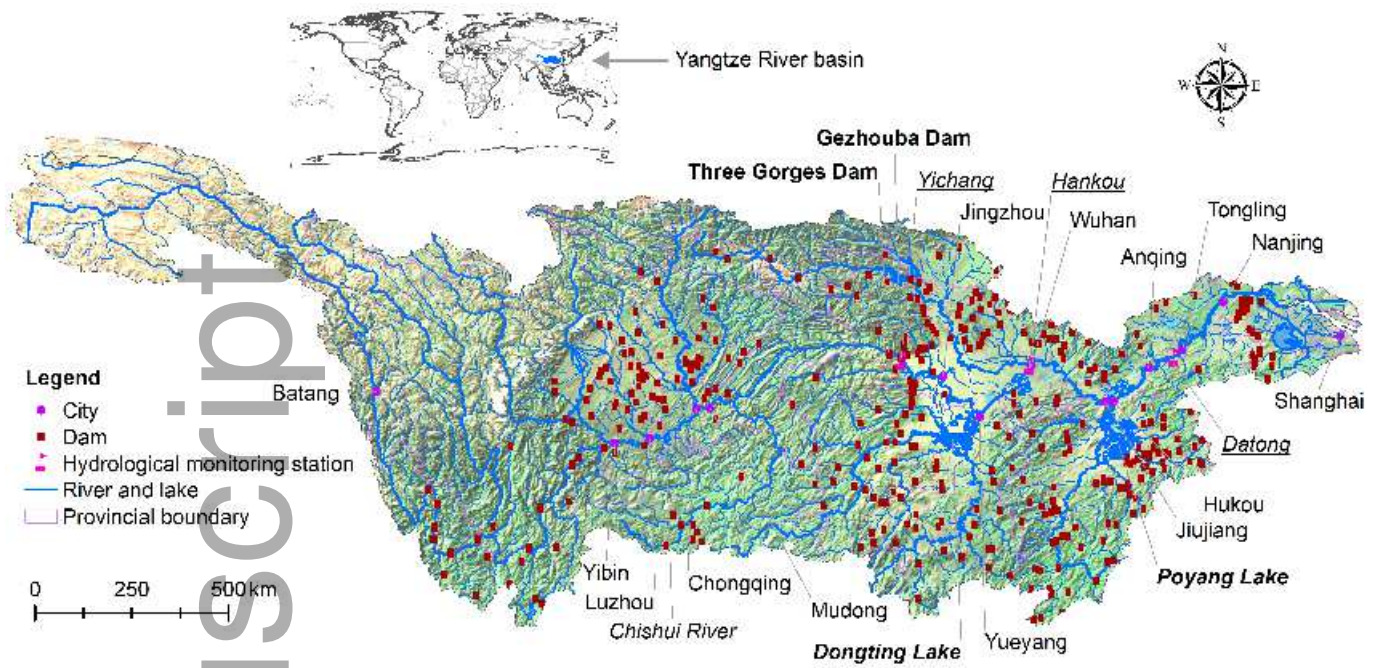
1158 **Figure 9** Future stock biomass in the three major fishing areas in the Yangtze River under  
1159 three different catch scenarios. Refer to Table 4 for scenario settings. Figure appears in colour  
1160 in the online version only.

1161

1162 **Figure 10** Index of fishing pressure and biodiversity threat in the 30 largest global river  
1163 basins. The index is between 0 and 1 (lowest to highest) and is calculated by further analyzing  
1164 data from Vörösmarty et al. (2010) and Tedesco et al. (2017). (a) Fishing pressure, roughly  
1165 estimated based on capture production and net primary productivity; (b) biodiversity threat, a  
1166 combination index based on 23 catchment stressors (factors) including fishing pressure; (c)  
1167 scatter plots. Figure appears in colour in the online version only.

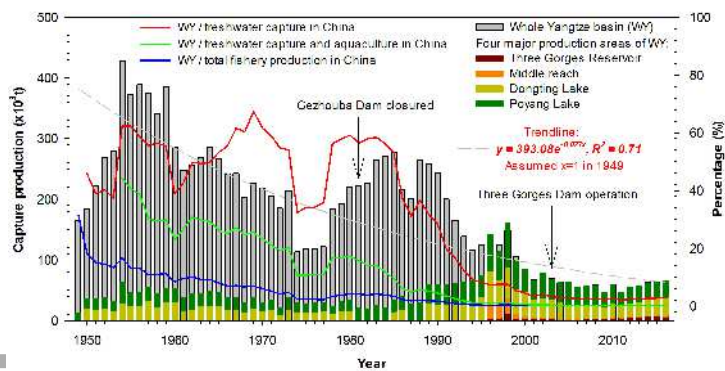
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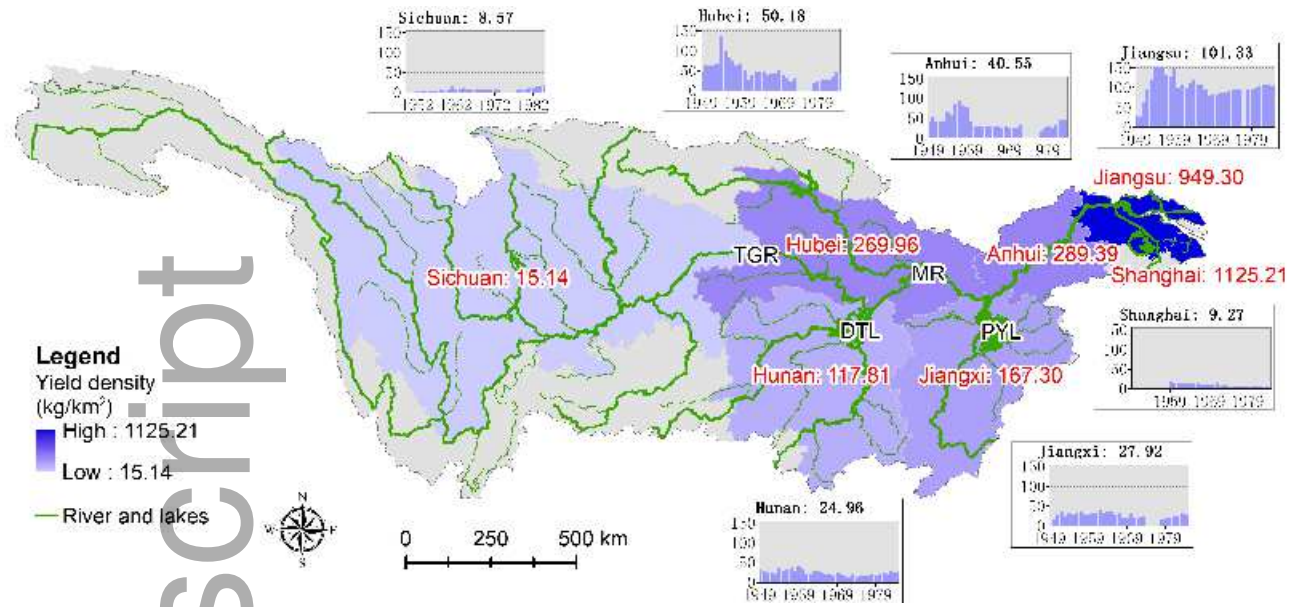


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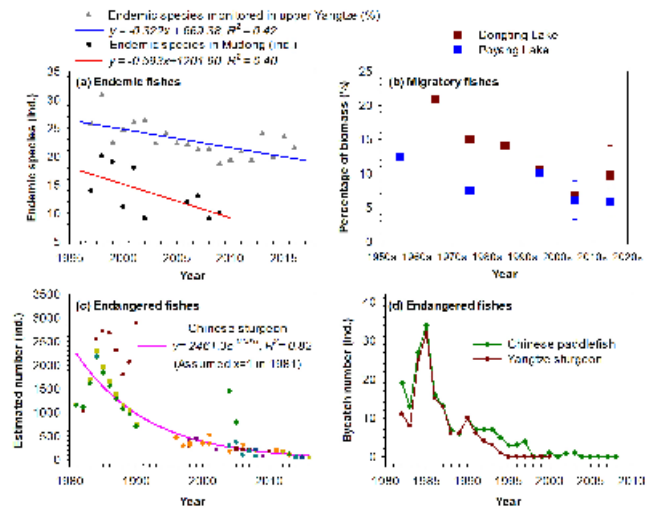
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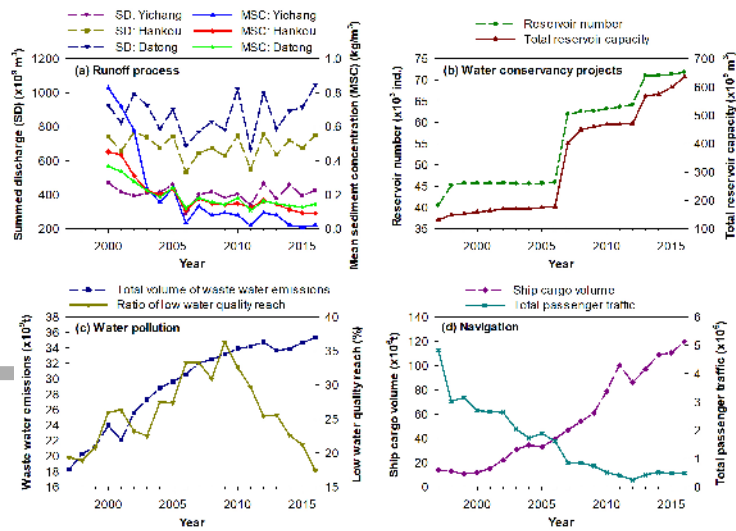
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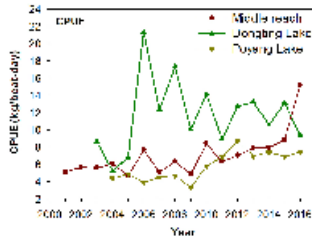
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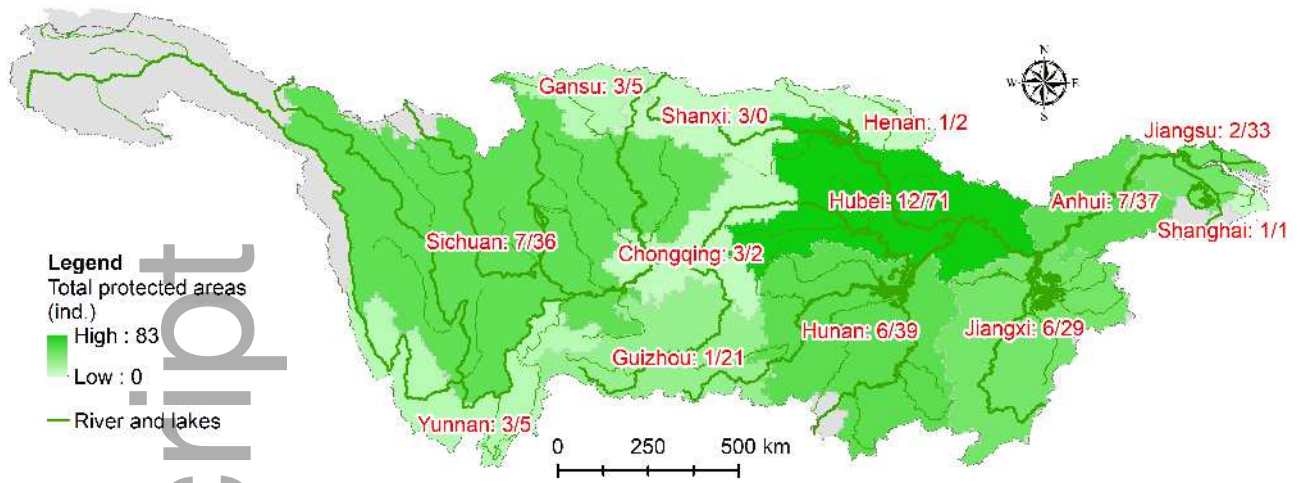
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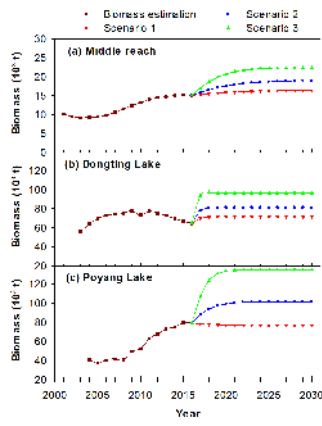


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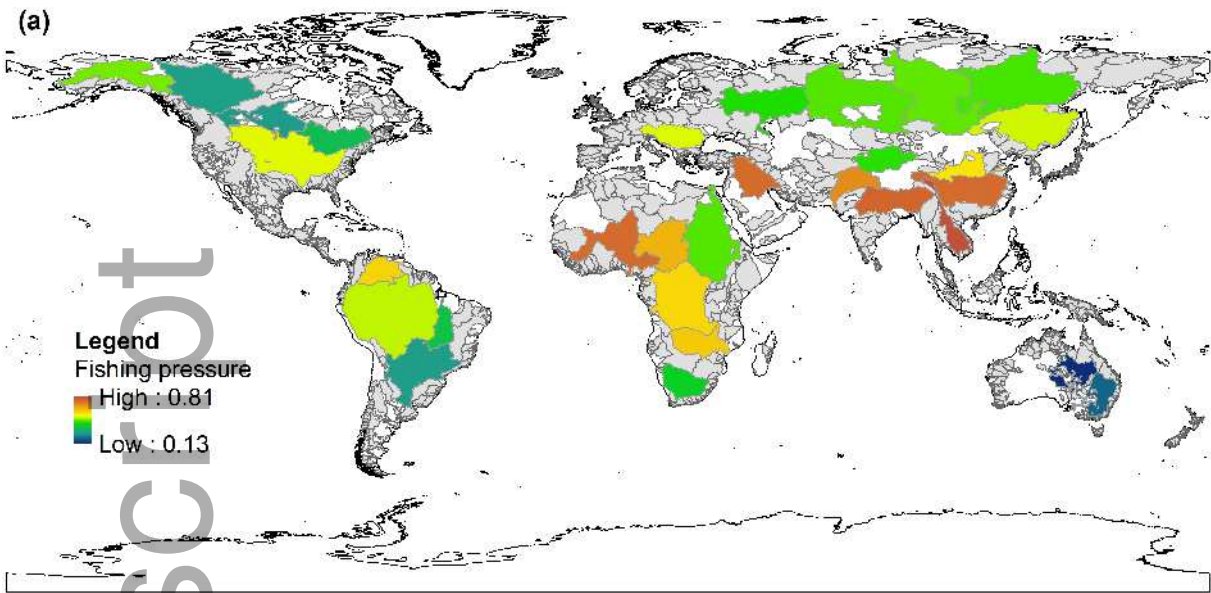


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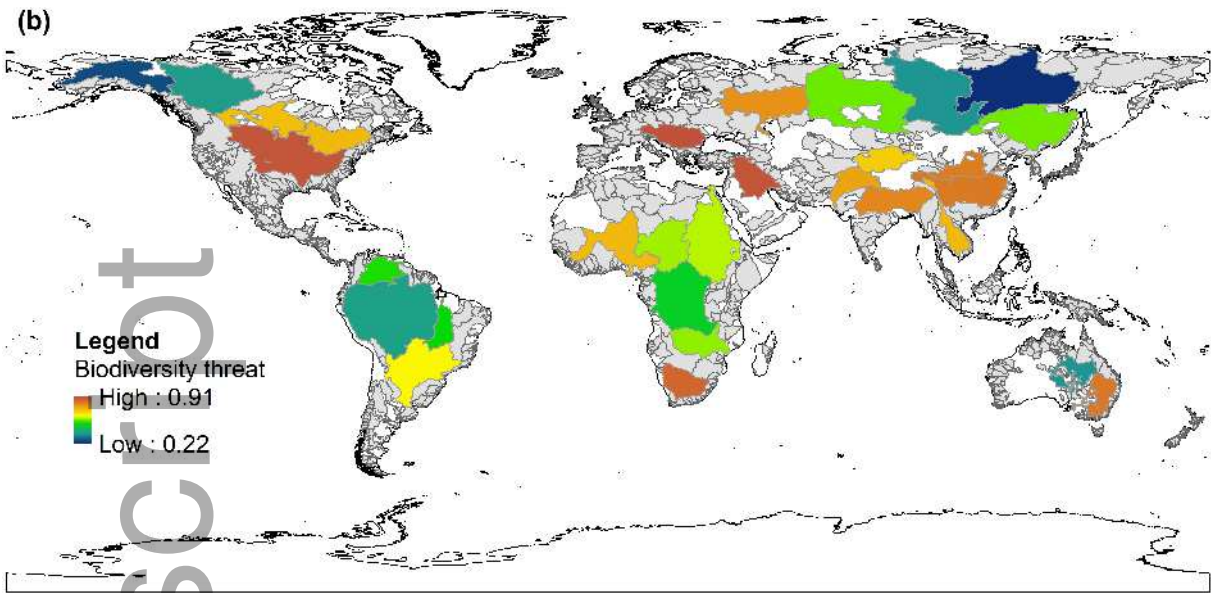


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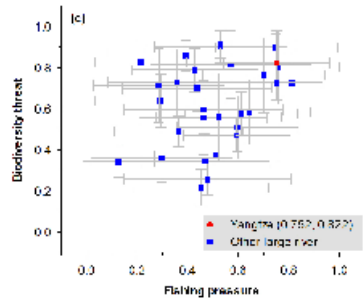
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