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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 human-influenced drainage basins worldwide. Since the founding of P. R. China in 1949, this 30 large river system has suffered increasing human perturbation and its sustainable development 31 is now severely challenged. Meta-analysis showed that Yangtze River fisheries have 32 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 fisheries appear to have collapsed over the past four decades, with yield decreasing to only 25% 35 of an historic peak of 400,000 metric tonnes in the late 1950s. Endemic, migratory and rare 36 37 fishes have been highly threatened with obvious changes in fish community structure and aquatic biodiversity. Anthropogenic activities, including impoundment of water in dams, 38 discharge of pollutants, and riverine modification for vessel navigation, have caused large 39 decreases in fisheries yields. Projections from surplus production modelling showed potential 40 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 changes evident in the Yangtze River fish populations can serve as an informative global 46

- 47 reference.
- Key words: biodiversity conservation, China, fishing ban, food security, human impact,
  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 **3 RESULTS** 60 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 3.4 Biomass projection in the future 64 3.5 Fishing and biodiversity threats in global large rivers 65 **4 DISCUSSION** 66 67 4.1 Limitations of methods 68 4.2 Fisheries utilization and protection in the Yangtze 4.3 Challenges for Yangtze aquatic biodiversity 69 70 4.4 Fishing pressure and biodiversity threat of global rivers
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#### 4.5 Future management implications

#### 72 ACKNOWLEDGEMENTS

#### 73 DATA AVAILABILITY STATEMENT

- 74 REFERENCES 75 76
- 77 **1 INTRODUCTION**

Freshwater capture fisheries are essential for food security and biodiversity conservation 78 worldwide (Food and Agriculture Organization of the United Nations [FAO], 2016; Funge-79 Smith & Bennett, 2019; Lynch et al., 2017; McIntyre, Reidy Liermann, & Revenga, 2016; 80 Welcomme, Valbo-Jorgensen, & Halls, 2014; Youn et al., 2014). Global production from 81 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 fisheries provide a source of animal protein which is equivalent to the total requirements of 84 85 approximately 119.1 million people, based on 36 countries where protein consumption data were available (Fluet-Chouinard, Funge-Smith, & McIntyre, 2018); moreover, these fisheries 86 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 production for human needs, conserving freshwater fish diversity is critically important for 89 maintaining ecosystem function and provision of ecosystem services (Harrison et al., 2014). 90 Freshwater areas represent less than 1% of the entire surface area of the Earth, yet contain 40% 91 (i.e. 13,000 strictly freshwater species) of all fish species, whereas saline waters covering 70% 92 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 evolved and specialized with some only able to live in specific local habitats (Tedesco et al., 95 2012). In Western Europe and the USA, riverine fish extinction rates are ~112 times higher 96 97 than background extinction rates (Dias et al., 2017). Human influences such as fishing This article is protected by copyright. All rights reserved

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

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

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Fishes in the Yangtze River are very important for both fisheries development and aquatic biodiversity conservation (Yang et al., 2007, 2009, 2011; Zeng, 1990). Like the Amazon, Mekong and Niger rivers, the wild capture fishery in the Yangtze River supplies a vital food source for local residents in a myriad of communities in its catchment (FAO, 2016; 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 al., 2007, 2009, 2011). Currently, among the 35 major freshwater aquaculture species in 127 128 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 considered to be the best among all aquatic systems in China. Prior to success in artificial 132 propagation techniques for the four major Chinese carp species, more than 10 billion fish 133 134 larvae and juveniles were caught each year from the middle reaches of the Yangtze River for aquaculture during the period of 1958–1962, with the highest number of 20 billion reported in 135 1960 (Hubei Provincial Water Resources and Electric Power Bureau, 1975). Thus the 136 Yangtze River has been greatly supporting development of China's freshwater culture as well 137 138 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 et al., 2007, 2009, 2011). There are approximately 416 fish species and subspecies in the 140 Basin, of which 362 are strictly freshwater species and 178 are endemic (Ye, Li, Liu, Zhang, 141 142 & Xie, 2011). In addition, there are some unique aquatic mammals, amphibians and reptiles, such as Baiji (Lipotes vexillifer, Lipotidae), Yangtze finless porpoises (Neophocaena 143 asiaeorientalis, Phocoenidae), Chinese giant salamander 144 (Andrias davidianus, Cryptobranchidae), and Chinese alligator (Alligator sinensis, Alligatoridae) (Yang et al., 2007, 145 146 2009, 2011).

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Fisheries sustainability and biodiversity conservation in the Yangtze River have both faced
great challenges, in common with most large-river systems throughout the world (Dudgeon,
2010, 2011; Jackson, Loewen, Vinebrooke, & Chimimba, 2016; Vörösmarty et al., 2010;
Youn et al., 2014). With continual socio-economic development associated with the Yangtze
River Basin, various human activities have adversely affected the Yangtze River's aquatic
organisms and their habitats (Chen, Duan, Liu, & Shi, 2003; Chen, Xiong, Wang, & Chang,
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, Xu, Ouyang, & Wu, 2019; Wang, Li, Duan, Chen, et al., 2014; Wang, Li, Duan, Luo, et al., 156 157 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 navigation (Huang & Li, 2016; Xie, 2017a, 2017b). To date, wild capture fisheries production 160 has already decreased to less than 100 thousand tonnes, falling well short of the maximum 161 production of 427 thousand tonnes in 1954 (Zeng, 1990). The quantity of newly produced 162 eggs and larvae of the four major Chinese carp species (i.e. the dominant commercial species 163 in the Yangtze River) was approximately 1.11 billion in 2015, accounting for only 1% of 164 historic production (118.4 billion) estimated for 1964–1965 (Yi, Yu, & Liang, 1988; Zhang et 165 al., 2017). Sixty-five Yangtze River fish species (15.6% of total) were registered in various 166 167 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 Reeves shad (Tenualosa reevesii, Clupeidae) are thought to be functionally extinct because no 169 living specimens of these species have been found for over 15 years (Yang et al., 2007, 2009, 170 171 2011). The Yangtze finless porpoise and Chinese sturgeon (Acipenser sinensis, Acipenseridae) are highly endangered (Mei et al., 2014; Wu et al., 2015). In particular, the natural spawning 172 activity of Chinese sturgeon has been interrupted several times in the year of 2017–2019 (Wei 173 et al., unpublished data), which may be due to the decline of its breeding population and the 174 175 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).

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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 This article is protected by copyright. All rights reserved 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; Yang et al., 2007, 2009, 2011). This new policy is critical for recovering depleted fisheries 189 resources and halting declines in aquatic biodiversity as further delay will limit the extent to 190 191 which the Yangtze River ecosystem and the services it provides can be restored.

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193 The Yangtze River has experienced extraordinary of an process 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 (population, diet habits, etc.), economic (GDP, agriculture, industry, etc.), and natural 197 (climate, hydrology, topography, biology, etc.) dimensions, most will nevertheless experience 198 199 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 fisheries resources between 1997 and 2016 were investigated, and their impacts on fisheries 206 207 yields were examined. Third, fish biomass under three different fishing regulation scenarios up to 2030 was predicted. Finally, fishing pressure and biodiversity threats faced by the 30 208 largest river systems in the world were reviewed. The objective of this study was to explore 209 changes in Yangtze River fisheries including their interactions with human activities in such a 210 highly human-dominated ecosystem over the past 80 years, and ultimately to provide 211 212 meaningful management guidance for large river systems worldwide.

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#### 214 2 MATERIALS AND METHODS

#### 215 **2.1 Study area**

The Yangtze River stretches from Tibet to Shanghai (24°30′-35°45′ N, 90°33′-122°25′ E) 216 where it finally flows into the East China Sea (Figure 2) (Yang et al., 2007, 2009, 2011). The 217 mainstream is more than 6,300 km long within a catchment area of  $1.8 \times 10^6$  km<sup>2</sup>. Most areas 218 of the basin have a subtropical monsoon climate. The total annual flow and sediment 219 220 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, P. R. China, 2017). The elevation difference from the headwater to the estuary is 222 approximately 5,400 m, with riverbed gradients ranging from 54×10<sup>-4</sup> to 0.097×10<sup>-4</sup> (Yu & 223 Lu, 2005). The basin has more than 10,000 tributaries; among them 437 have catchment areas 224 larger than 1,000 km<sup>2</sup>, and 22 have catchment areas larger than 10,000 km<sup>2</sup> (Yu & Lu, 2005). 225 226 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).

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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 latest research identified approximately 416 fish species and subspecies, 362 of which are 233 strictly freshwater species (Ye et al., 2011). The number of endemic fish species is 178 234 (42.8%), out of which 65 are on the China Species Red List (Ye et al., 2011). The most 235 species-rich phylogenetic orders in the river are Cypriniformes (280 species), Perciformes (50 236 species), and Siluriformes (40 species). The Yangtze River mainstream can be divided into 237 five sections (Figure 2): riverhead (above Batang), upper reach (Batang-Yichang), middle 238 239 reach (Yichang-Hukou), lower reach (below Hukou), and estuary. The number of fish species (endemic species) in each section is 14 (8), 279 (147), 227 (70), 158 (23), and 142 (10), 240 This article is protected by copyright. All rights reserved

respectively (Ye et al., 2011). The number of species registered in various threatened categories of the China Species Red List is 4, 48, 20, 9 and 12, for the five sections respectively (Ye et al., 2011).

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The Yangtze River Basin is one of the most exploited regions in China (Liu & Diamond, 245 2005; Yang et al., 2007, 2009, 2011). For example, the river has tens of thousands of dams on 246 247 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 changed the fluvial environment and aquatic ecosystem (Liu, Wang, & Cao, 2012; Wu et al., 254 2004; Wu, Huang, Han, Xie, & Gao, 2003; Yang, Gao, Li, Ma, & Liu, 2012). A number of 255 256 issues, such as isolation of lakes from the river and reclamation of some of them for farmland, have been controversial. To date, only two large lakes remain connected to the Yangtze 257 258 mainstream (Huang, Wu, & Li, 2013; Xie, 2017a, 2017b). Furthermore, other human activities, including overfishing, water pollution, waterway construction and vessel navigation, 259 260 river channelization, port construction, and sand and gravel extraction, have seriously affected the aquatic ecosystem of the Yangtze River (Yang et al., 2007, 2009, 2011). 261

262

## 263 2.2 Data on fisheries yields and fish communities

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

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 al., 2003; Zeng, 1990), and since 1996, they have been based on four major yield producing 274 areas (Liu & Gao, 2012; Lu et al., 2016; Table S1): Three Gorges Reservoir, middle reach of 275 Yangtze, Dongting Lake and Poyang Lake. The data on fisheries production (wild capture and 276 277 aquaculture) were obtained from a series of the China Fisheries Statistical Yearbook from 1979 to 2017. Data on fish community structure were compiled chiefly from Zeng (1990), 278 Yang et al. (2007, 2009, 2011), Ye et al. (2011), Liu and Gao (2012), and a series of the 279 Bulletin of the Three Gorges Project from 1997 to 2017, which included special reports. The 280 281 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 (12 factors) of environmental variables were selected based on present knowledge (Yang et al., 285 2007, 2009, 2011; Zeng, 1990). These categories included i) river runoff (i.e. total discharge 286 287 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 capacity); iii) water pollution (i.e. the total volume of waste water emissions and ratio of low 289 290 water quality reach, that is, the ratio of river reach with water quality belonging to Categories IV, V, and above, according to Environmental Quality Standards for Surface Water (GB 291 292 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 estimate, we used wild capture fisheries yields, which are highly correlated with biomass. 294 295 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, This article is protected by copyright. All rights reserved

as well as the interconnections among the environmental factors themselves, the Spearman
correlation analysis was used. To exclude co-correlations of factors and identify key
environmental factors, a stepwise regression analysis in the PASW Statistics 18 (IBM, USA)
was performed.

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## **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 been the major fishing areas since 1990s (Figure 2). Since a number of large lakes in the 306 307 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 resources. Despite rich biodiversity in its headwaters, commercial fisheries production in the 309 Yangtze's upper reaches is relatively low and so is not an important fishing area. A surplus 310 production model was selected to estimate fish biomass in the three major fishing areas. This 311 312 model was selected because it only requires catch and effort data (Hoggarth et al., 2006). It was considered to be the most suitable model for the Yangtze River due to a general lack of 313 314 biological information which would be needed as inputs and parameters for more complex models. The fundamental concept of this model is that fish populations follow a depletion 315 316 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 in fish populations can be reflected in trends in catch per unit effort (CPUE), which will 318 319 decrease in proportion to decreasing exploitable biomass (Hilborn & Walters, 1992). The biomass estimation was conducted using the CEDA 3.0.1 package (MRAG Ltd, UK), which 320 321 is based on the standard dynamics of surplus production models but uses non-equilibrium fitting methods and three different error models (Hoggarth et al., 2006). After test running, the 322 Schaefer and Fox production models were used to conduct the estimation (Equations 1–3): 323

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

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

325

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

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

330

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

338

### 339 2.4.2 Scenario settings

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

It was assumed that there was no fishing in all aquatic protected areas since the Chinese 352 government announced a ban on any kind of fishing in the 332 aquatic protected areas in the 353 Yangtze River as of 2018 (Yi & Yu, 2018). The protected areas include 53 natural protected 354 areas and 279 aquatic germplasm protected areas (for protecting species with potential 355 commercial benefit) at national, provincial and municipal levels. The proportion of the 356 combined total of these two kinds of protected areas to the entire water area was estimated. 357 358 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 the362 entire Yangtze River during the period 2017–2030.

363

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

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

374

#### 375 **3 RESULTS**

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

Fisheries yields in the Yangtze River showed declining trends during 1949–2016 (Figure 3). 377 The average decadal yields from 1950s to 2010s were 324.65, 252.77, 166.96, 242.33, 149.85, 378 379 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 =393.08e<sup>-0.027x</sup>,  $R^2 = 0.71$ . The ratios of the yields from fisheries in the Yangtze River to the 382 total fisheries production in China presented an obvious declining trend. The maximum ratio 383 384 of the yield from the Yangtze River to the freshwater capture yield in China was 67.40%; that to the freshwater capture and aquaculture in China was 44.39%; and that to the total fishery 385 production in China was 31.63%. However, in 2016, the above three ratios were 2.86%, 386 0.19%, and 0.10%, respectively, indicating that the contribution of the capture fishery in the 387 Yangtze River to food security in China was extremely low at that point in time. 388

389

In Dongting Lake, wild capture production was 24.22±8.96 (10.37–55.00) thousand tonnes 390 during 1950–2016, with a coefficient of variation (CV) of 37.0% (Figure 3). In Poyang Lake, 391 392 the production was  $25.55\pm10.83$  (10.02–71.90) thousand tonnes during 1949–2016, with a CV of 42.4%. It is noteworthy that yield from the Three Gorges Reservoir increased, whereas in 393 394 the middle Yangtze it clearly decreased. The spatio-temporal pattern of yields associated with the provincial area had no obvious change; however, there was clearly observable annual 395 variation in each area (Figures 3 and 4). The spatial distribution of average yield density 396 (1949–1985) among seven provinces declined from the estuary to the upstream region (Figure 397 4). Until 1985, the latest available data, the areas near the estuary, such as Shanghai and 398 Jiangsu, had the highest yield densities (1,125.21 and 949.30 kg/km<sup>2</sup>, respectively). The areas 399 400 in the middle and lower reaches, such as Hubei and Anhui, had the second highest yield densities, and those in the two large-lake provinces (i.e. Dongting Lake in Hunan and Poyang 401 Lake in Jiangxi) had the third highest yield densities. Finally, the upper reach (Sichuan) had 402 the lowest yield density (only 15.14 kg/km<sup>2</sup>). 403

404

#### 405 **3.2 Structural changes in fish community**

The community structure of fishes, such as the proportions of endemic and migratory species, 406 and the number of rare and endangered species have been considerably altered during the 407 fisheries development process (Figure 5). During 1997–2016, the percentage of endemic fish 408 409 species among all fishes in the upper Yangtze reach was  $22.8\pm2.9\%$  (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 Gorges Reservoir) (Figure 2), a decreasing trend with a slope of -0.60 was clearly observed. 411 412 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 required flowing water. From the 1950s to the 2010s, the biomass percentages of the four 414 415 major Chinese carp species (i.e. the most commercially important migratory fishes in the Yangtze River; the biomass percentage is based on their proportion of total catch weight) in 416 417 Dongting and Poyang lakes were  $12.8\pm5.0\%$  (6.7–21.0%) and  $8.4\pm2.8\%$  (5.9–12.5%), respectively (Figure 5b). Both showed decreasing trends, with the trend in Dongting Lake was 418 more obvious than that in Poyang Lake. It was concluded that either physically disconnected 419 420 (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 nevertheless showed changes in species composition. In addition, fishing activities also 423 424 altered fish composition due to their selectivity of specific fish species.

425

Owing to the Gezhouba Dam impeding the river since 1981, the number of rare and 426 endangered fishes diminished rapidly (Figure 5c and 5d). The number of mature Chinese 427 428 sturgeons below the Gezhouba Dam was estimated to be approximately 2,500 individuals in the early 1980s but declined to approximately 50 by 2014–2016 (Figure 5c). Bycatch numbers 429 of Chinese paddlefish and Yangtze sturgeon (Acipenser dabryanus, Acipenseridae) peaked in 430 431 1985 and then dropped dramatically (Figure 5d). These two fishes are migratory species that were widely distributed in the upper, middle and lower reaches of the Yangtze River, 432 433 although their spawning areas were located in the upper reach. As the Gezhouba Dam in the This article is protected by copyright. All rights reserved

middle reach blocked the migration route of these two fishes in 1981, their juveniles of 434 435 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 gradually increased to its peak then started to decrease. The decrease implies that their 439 populations were declining, and the last living specimen of the Chinese paddlefish was found 440 in 2003 in the upper Yangtze. No Yangtze sturgeon was found below the Gezhouba Dam 441 during 1995–2000, indicating the rapid decline of its favored habitat. Currently, 70 aquatic 442 animals in the Yangtze River Basin have been listed as nationally and/or internationally 443 protected species (Table 1, Table S2), which implies a serious loss in aquatic biodiversity. 444

445

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

The environmental factors in each of the four categories varied greatly during 1997–2016 447 (Figure 6, Table 2). The total flow discharged at the three stations varied among years, yet 448 449 there was no clear trend, while the mean sediment concentration at the stations has obviously decreased since 2003 (i.e. the trial operation of the Three Gorges Project). In particular, the 450 mean sediment concentration at Yichang, which is located just below the Three Gorges Dam, 451 452 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, while the ratio of low water quality has decreased since 2010 (Figure 6c). This result implied 454 455 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
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correlations were found between production and runoff characteristics, e.g. the total discharge 462 (r=0.50-0.62, P<0.05) and the average sediment concentration (r=0.57-0.75, P<0.05), at the 463 three stations. Correlations between capture production and water impoundment (r=-0.63, 464 -0.68, P<0.01) as well as between capture production and water pollution (r=-0.72, -0.72, 465 P<0.01) were significantly negative. Ship cargo volume was negatively correlated with 466 capture production (r=-0.69, P<0.01), whereas total passenger traffic had a positive 467 correlation with capture production (r=0.80, P<0.01). In addition, weak positive correlations 468 were found between the two runoff variables because they were inherently related. Water 469 retention in dams showed significant negative correlation with sediment concentration 470 because of its effects on the runoff process. Note that although some environmental variables 471 were significantly correlated, they did not have inherent cause and effect relationships with 472 each other and were more likely to have similarly developing trends with time. 473

474

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

480

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

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

488

The spatial analysis showed that the 332 aquatic protected areas were distributed in 13 provincial areas of the Yangtze River (Figure 8). The number of protected areas in each province was highly dependent on the proportion of the area included in the Yangtze River. For instance, Hubei had the largest number of 83, while Shanghai had the smallest number of only two. It revealed that these 332 protected areas occupied approximately 1/3 of the entire water area in the basin. Accordingly, the scenario settings for future biomass estimation are 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) and the final biomass in the two lakes were higher than those in the middle reach of the 502 Yangtze. Under the three management scenarios, the three areas showed very similar 503 504 variation in biomass (Figure 9). If fishing activity were to continue under the present situation, then the biomass would not change, remaining at its relatively low current level. If fishing 505 506 was banned in the protected areas, then the biomass would slightly increase. If fishing was completely banned from all areas of the river, then the biomass would rapidly increase and 507 remain at a relatively high level. However, as indicated by difference in the estimates of the 508 population growth rate parameter r (Table 5), the recovery period for fisheries resources in the 509 two lakes would be much faster (3-5 years) than that for the middle reach (8 years). In 510 comparison, the sum of the MSY in the three areas was ~76.17 thousand tonnes, which was 511 512 still far less (26.1%) than the average yield of 103.06 thousand tonnes reported during 1949–1985 in the corresponding provinces (i.e. Hubei, Jiangxi, and Hunan) (Figure 4). 513

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 This article is protected by copyright. All rights reserved threats on thirty large rivers globally were analyzed (Figure 10, Table S3). The analysis showed that the Mekong, Ganges, and Yangtze rivers had the first, second, and third highest fishing pressures, respectively. The Danube, Mississippi, and Shatt al-Arab rivers had the first, second, and third highest biodiversity threats, respectively, and the Yangtze River ranked in 6th place. By simply summing the two indices of fishing pressure and biodiversity threat, the Shatt al-Arab, Yangtze, Ganges, Mekong, and Niger rivers occupied the top five positions, 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 due to the huge spatio-temporal scale and lack of research effort (Chen et al., 2009; Liu & 528 Gao, 2012). Hydrological monitoring of the Yangtze River, which started in the late 19th 529 century, is more comprehensive than biological monitoring of its aquatic ecosystem (Yang, 530 531 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 that the correlation and projection analyses in this study were performed only from the late 534 1990s was because of limited data availability prior to then. However, to target the entire 535 Yangtze River, comprehensive fisheries surveys could not be undertaken due to deficiencies 536 in past investments in data collection, and a lack of systematic organization including data 537 538 sharing mechanisms. In this study, the surplus production model seemed to be the only feasible method which allowed the exploitable biomass to be estimated for such an enormous 539 study area (Hoggarth et al., 2006). The model assumed that fish migration in the evaluated 540 area was negligible. In fact, some fishes migrated to the middle reach and the two lakes, yet 541 their number and biomass were very low (Xie, 2007a, 2007b). Hence, it was reasonable to use 542 543 this model in the present study. Further monitoring using direct measurements like acoustic detection of fishes, could possibly improve the biomass estimation results in this study. Other 544

545 anthropogenic activities directly related to the fishery, such as artificial fish propagation and release (i.e. stocking), recreational fishing, illegal fishing, and dam ecological operations, 546 547 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 scenarios, i) maintaining the current level of fishing pressure, ii) banning fishing in protected 551 552 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 studies will be able to include more variables (Yang et al., 2007, 2009, 2011). 554

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). From the 1950s to the 1970s, the main role of the Yangtze River was to provide protein-rich 559 560 food (Zeng, 1990). Since the 1970s, after the construction of the Gezhouba Dam, the protection of migratory fishes (such as the four major Chinese carp species, Chinese sturgeon, 561 and others) started to receive more attention (Yi et al., 1988; Zhang et al., 2017). However, 562 563 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 well as their habitats has gradually been recognized as an important issue. In 2002, a tentative 565 fishing ban policy was trialed in the middle and lower reaches of the Yangtze River (Yi & Yu, 566 2018). In 2003, the fishing ban policy was officially implemented and became an important 567 568 national-level policy for all inland waters of China following on from a marine fishing moratorium. Since 2006, artificial fish propagation and release (i.e. stocking) projects 569 involving many species have been conducted after implementing conservation programs on 570 living aquatic resources (Chen et al., 2009). In general, stocking is for commercial harvesting 571 572 or rehabilitation of endangered or endemic species. For instance, stocking of Chinese mitten crab (Eriocheir sinensis, Varunidae), and the four major Chinese domestic carps, within the 573 This article is protected by copyright. All rights reserved

574 lakes in the middle and lower Yangtze Basin is mainly for harvesting, whereas stocking of protected species, such as Chinese sturgeon, Yangtze sturgeon and Chinese sucker, etc., is 575 576 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 Yangtze sturgeon, have been successively implemented (Yi & Yu, 2018). Since 2017, a 578 579 long-term fishing ban policy was implemented, first in a tributary of the upper Yangtze and subsequently extended to 332 nature and germplasm protected areas throughout the entire 580 581 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, which began in 2002, ceased in late 2018. Currently, more integrated and comprehensive 583 584 protection plans (a 10-year fishing ban) for the entire Yangtze aquatic ecosystem are being designed (Ministry of Agriculture and Rural Affairs of China, 2019; Yi & Yu, 2018). 585

586

#### 587 4.3 Challenges for Yangtze aquatic biodiversity

Yangtze River aquatic biodiversity is still facing a number of challenges even though the 588 fishing ban policy has been implemented (Chen et al., 2003, 2009; Huang & Li, 2016; Liu et 589 590 al., 2019; Ye et al., 2011). First, habitat fragmentation and its loss due to damming and sluice construction are difficult to remediate, while some endemic fishes remain exposed to a high 591 592 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 migration of fishes and altered the fluvial river reach into artificial reservoirs (Wu et al., 2003, 594 595 2004). This greatly decreased the diversity of endemic fishes as most of them were rheophilic so required flowing water. Currently, there is a plan to build 27 dams along the 2,290 km of 596 597 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, 2009, 2011). Moreover, a plan to construct a sluice at the confluence of Dongting Lake and 599 600 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 et al., 2013; Xie, 2017a, 2017b). In addition, although reclaiming lakes for farmland is now 602 This article is protected by copyright. All rights reserved

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 capture fisheries. In addition, issues of water pollution, waterway construction and 610 611 channelization, sand and gravel extraction, port construction, and noise and vibration from vessel navigation are extremely difficult to completely resolve (Yang et al., 2007, 2009, 2011). 612 613 Third, the recreational fishery and exotic species should be given more attention. Based on our experience, the recreational fisheries catch could be very high; thus, effective regulatory 614 615 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 recorded, out of which 11 had never been previously observed in the basin, such as several 617 kinds of tilapia, largemouth bass (Micropterus salmoides, Centrarchidae), freshwater 618 619 pompano (Piaractus brachypomus, Serrasalmidae) (Zhang et al., 2020, unpublished data). 620 Moreover, the abundance of exotic species gradually increases from the Yangtze estuary to the headwater, implying that the upstream regions are of greater concern in this regard. In the 621 past, although exotic fish species were occasionally caught in the Yangtze River, due to 622 623 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 cravifsh in Donging Lake. In 2017, its catch reached 11,300 tonnes, accounting for nearly 30% of the total capture production (FB-MARA-PRC, NFTECC, & CFA, 2019). If 626 fishing activities in this lake ceased, then the ecological impacts would be incalculable. 627 Accordingly, measures for controlling their possible sources should be instigated (Liu, 628 McGarrity, Bai, Ke, & Li, 2013). Lastly, an integrated and scientifically based strategic 629 management system for the entire Yangtze River aquatic ecosystem is urgently required 630 (Chen et al., 2009; Liu and Gao, 2012). 631

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

638

# 639 4.4 Fishing pressure and biodiversity threat of global rivers

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

649

The rapid change in fisheries development and biodiversity conservation in the Yangtze River 650 has many management implications for other large-river systems in the world (Castello & 651 652 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 circumstances between these large rivers and the Yangtze River in terms of fishing pressure 655 and biodiversity threats (Figure 10, Table S3), ecosystem management initiatives in the 656 Yangtze River could be informative for other globally large rivers to improve the 657 658 management outcomes for their ecosystems.

659

660 4.5 Future management implications

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

688 closures where appropriate to protect endangered and threatened species, ecosystems at risk, and vulnerable habitats (Ma et al., 2018). In addition, aquaculture in the basin should have 689 690 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 (Chen et al., 2009; Heiner, Higgins, Li, & Baker, 2011; Wang, Gao, Jakovlić, & Liu, 2017). 694 Finally, public education imparting knowledge and promoting understanding about the critical 695 696 roles and importance of the ecosystem of the Yangtze River and ecosystem services it provides for human well-being is also necessary, including changing the way people interact 697 698 with the river system e.g. avoidance of risks from releasing exotic species by ceasing this practice as a religious activity or irresponsible release of unwanted ornamental fish or fish 699 700 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 sophisticated approach to deal with the complexities of ecological interactions. 702

703

This study demonstrated that overexploited fisheries resources could be recovered by 704 705 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 will be extremely difficult if not impossible for them to be fully restored. The structure of the 707 708 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 the rare and endangered, endemic and migratory aquatic species of the Yangtze River Basin 710 require urgent intervention to prevent their extinction. 711

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## 721 DATA AVAILABILITY STATEMENT

- The data that supports the findings of this study are available in this published article and itssupporting information.
- 724

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- 1085
- **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	Critically Endangered, 16;	29				
Species	Endangered, 3;					
	Vulnerable, 1;					
	Near Threatened, 4;					
	Least Concern, 5					

	Convention on International	Appendix I, 5;	8					
	Trade in Endangered Species of	Appendix II, 3						
	wild Fauna and Flora							
	National Protected Wildlife in	Top Level, 5;	14					
	China O	Second Level, 9						
	China Species Red List (Fishes)	Extinct, 2;	65					
	$\mathbf{O}$	Extinct in the Wild, 2;						
	S	Critically Endangered, 5;						
		Endangered, 36;						
		Vulnerable, 20						
1087								
	σ							
	0							
	č							

The The	eme	Mean	SD	Capture production	Runo	ff proce	55				Water impound	ment	Water pollutio	n	Naviga	tion
				(n=20)	(n=17) n=20)					projects	(n=20)	=20) (n=20)		(n=20)		
Production and factor	#			1	2	3	4	5	6	7	8	9	10	11	12	13
Capture production	1	7.16	2.64	Х	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 (Vichang) (×10 <sup>9</sup> m <sup>3</sup> )	) 2	406.62	46.77		Х	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) (×10 <sup>9</sup> m <sup>3</sup> )	3	684.67	70.98			Х	0.93**	0.32	0.33	0.53*	-0.03	-0.04	0.04	-0.56*	-0.10	0.11
Summed discharge (Datong) (×10 <sup>9</sup> m <sup>3</sup> )	4	868.18	113.06				Х	0.17	0.16	0.42	0.13	0.10	0.16	-0.62**	0.03	0.03
Sediment concentration (Yichang) (kg/r	m <sup>3</sup> ) 5	0.201	0.256					Х	0.96**	0.93**	-0.81**	-0.87**	-0.83**	0.10	-0.91**	0.78**
Sediment concentration (Hankou) (kg/m	n <sup>3</sup> ) 6	0.195	0.109						Х	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							Х	-0.71**	-0.77**	-0.73**	-0.10	-0.81**	0.73**
Reservoir number (×10 <sup>3</sup> ind.)	8	55.74	11.33								Х	0.95**	0.92**	0.11	0.92**	-0.89**
Total reservoir capacity (×10 <sup>9</sup> m <sup>3</sup> )	9	335.43	186.37									Х	0.97**	0.13	0.98**	-0.94**
Waste water emissions (×10 <sup>9</sup> t)	10	29.30	5.53										Х	0.20	0.96**	-0.97**
Low water quality reach (%)	11	26.01	5.38											Х	0.13	-0.26
Ship cargo volume (×10 <sup>6</sup> t)	12	54.34	37.97												Х	-0.94**
Total passenger traffic (×10 <sup>6</sup> )	13	1.59	1.25													Х

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

1089\* Correlation is significant at the 0.05 level (2-tailed)This article is protected by copyright. All rights reserved

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

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Author Manuscr

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

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

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

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

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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 This article is protected by copyright. All rights reserved assumptions (LSQ, least squares; and Log, log transform). IP, initial proportion; K, carrying
capacity of the population; q, catchability coefficient; r, intrinsic rate of growth; MSY,
maximum sustainable yield; R. Yield, replacement yield; R<sup>2</sup>, coefficient of determination.

Area	Model	Fit	IP	K (t)	q(×10 <sup>-4</sup> )	r	MSY (t)	R. yield (t)	Final biomass (t)	<b>R</b> <sup>2</sup>
Middle	Schaef	er LSQ	0.5	22377.51	5.71	0.395	2208.94	1947.48	15038.15	0.156
reach	Schaef	er Log	0.5	23943.21	5.39	0.367	2194.44	1967.41	15822.29	0.137
Dongting	Fox	LSQ	0.4	78054.91	2.15	1.297	37247.91	28985.09	49863.66	0.686
Lake	Fox	LSQ	0.5	96321.65	1.69	1.116	39530.38	28804.40	64577.12	0.681
Poyang	Fox	LSQ	0.2	92974.70	1.17	1.119	38279.83	27435.70	63008.21	0.907
Lake	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 the1105 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

and Endemic Fishes, which is the largest protected area  $(3.32 \times 10^4 \text{ ha})$  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

Jan 11, 2019 Issued the "Implementation plan for Fishing Ban in the Yangtze River"

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1107 **Figure legends**:

1108

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

1114

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

1122

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

1127

Figure 4 The spatial distribution of fisheries capture production in the Yangtze River during
the period of 1949–1985 (n = 27–37, Zeng, 1990). Map shows the mean yield density (kg/km<sup>2</sup>)
in 7 provinces (Chongqing municipality belonged to Sichuan Province at that time). The
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vertical bars in the 7 boxes indicate the capture yields (×10<sup>3</sup> t) by year (1949–1985). The
average yield is seen in the title of the box. TGR-Three Gorges Reservoir, MR-middle reach,
DTL-Dongting Lake, and PYL-Poyang Lake. Figure appears in colour in the online version
only.

1135

Figure 5 Variations in fish community and number in the Yangtze during capture fisheries 1136 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. Figure appears in colour in the online version only. 1143

1144

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

1149

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

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

1157

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

1161

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

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