Environ Biol Fish (2021) 104:253–264
https://doi.org/10.1007/s10641-021-01070-2

Non-native freshwater fish species in the Yellow River Basin: origin, distribution and potential risk

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Received: 26 January 2020 / Accepted: 14 February 2021 / Published online: 25 February 2021

Abstract Invasions of non-native fishes are recognized as a serious threat to freshwater biodiversity across the globe. Being the China's second-largest river, the Yellow River has experienced severe invasion pressure of non-native fishes during recent decades. However, much less is known about species composition and distribution of non-native fishes in this river basin. Here, we investigated and summarized the literatures about non-native freshwater fish in the Yellow River Basin (YRB), to examine their taxonomic diversity, geographical origin, longitudinal distribution and potential risk. We found that 40 non-native fish species, belonging to 9 orders, 18 families and 35 genera, have invaded the YRB. Of which 19 exotic species came from other regions, while 21 translocated species were introduced into the upstream from midstream and downstream of the YRB. The aquaculture was the main vectors responsible for non-native fish introductions. An average of 8.24 non-native fish species was introduced and established per sub-region, accounting for 25.5 % of total fish species. The percentage of non-native species showed a significant unimodal model against average elevation, with the highest values (ca. 70 %) in upstream mainstream reaches and tributaries. Non-native species from historically absent or species-poor orders (Salmoniformes, Osmeriformes and Perciformes) were the most successful invaders. Furthermore, the species composition of non-native fishes changed markedly along the longitudinal gradient (i.e., from source region to downstream). The negative impacts of non-native fish introductions to native fish species, e.g., competition for resource, predation and hybridization were emerged in many introduce regions and could get worse in the future due to global warming and human activities. This study can help improve the management of non-native fish introductions and biodiversity conservation of native and endemic fish species in the YRB.

Keywords Invasive fish · Aquaculture · Exotic species · Translocated species · The Yellow River · Threat · Elevational gradient

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Introduction

Biological invasions of non-native species are an increasingly serious threat to global biodiversity, resulting in dramatic biodiversity decline as well as social and economic damages (Pimentel et al. 2005; Sala et al. 2000; Simberloff et al. 2013). Freshwater ecosystems are among the most susceptible ecosystems to invasive alien species (Strayer 2010), where non-native fishes are the most frequently-introduced and major threat to aquatic biodiversity worldwide (Ding et al. 2017; Rahel 2002; Xiong et al. 2015). Therefore, during the recent decades, the impacts of non-native fish invasions

have drawn exponentially increasing attention by scientists, government managers and the public (Cucherousset and Olden 2011; Li et al. 2016; Vitule et al. 2009).

China is the country with the highest amount of introduced non-native fish species in the world, due to the high demand for fishery products and increasing yield of the aquarium (Li et al. 2016; Liu and Li 2010; Xiong et al. 2015). In a recent study, Xiong et al. (2015) complied a comprehensive list of non-native fish species in China, including a total of 439 species belonging to 22 orders, 67 families, and 256 genera. Many alien freshwater fish species escaped from aquaculture ponds or were directly introduced into lakes and reservoirs for the enrichment of wild fisheries and have established feral populations (Xiong et al. 2015). These invasions inevitably caused dramatic loss of native aquatic biodiversity throughout China, such as river and lakes in the Yun-Gui Plateau (Jiang et al. 2019; Zhang et al. 2018, 2019), the Qinghai-Tibet Plateau (Tang and He 2015) and Xinjiang Uygur Autonomous Region (Li and Xie 2002).

The Yellow River is the second-longest mega river ecosystem in China, covering a wide range of geological terrain, e.g., latitude, longitude, altitude, and climate types. The complex and diverse environmental conditions in this large river support high levels of both species number and endemism of fish fauna (Li 2017; Wu and Tan 1991). However, the river has been severely impacted by intensifying human-mediated disturbances during the past 50 years, including intensive constructions of cascade dams, water pollution, invasions of alien fish species and overfishing, which seriously threaten fish resources and biodiversity (CTFRYR 1986; Xie et al. 2018). Since the 1980s, with the extensive exploitation of hydropower plants in the mainstream and tributaries in the YRB, several commercial fishes, such as rainbow trout (*Oncorhynchus mykiss*), pond smelt (*Hypomesus olidus*), icefish (*Neosalanx taihuensis*, *Protosalanx hyalocranius*) were widely introduced into reservoirs for fisheries purpose, accompanied by unintentionally introduced small fishes (e.g., *Rhinogobius cliffordpopei*, *Abbottina rivularis*, *Paramisgurnus dabryanus*, *Pseudorasbora parva*) (Tang and He 2015). CTFRYR (1986) first reported three non-native freshwater fish species in the YRB according to their large-scale survey in 1981–1982. Several subsequent studies examined non-native fish's situation in some mainstream segments and tributaries of the Yellow River (Hou et al. 2016; Shen et al. 2007; Tang and He 2015; Wu and Wu 1992). These studies emphasized negative impacts on native fish assemblage due to rapid increase in abundance and distribution of invasive fish species. However, a comprehensive understanding of non-native freshwater fish species list and their distribution patterns within this river basin is still lacking. Therefore, there is an urgent need to examine the species, number, distribution, trait and possible risk of non-native freshwater fishes in the whole YRB, towards decision-making concerning control, mitigation, and eradication of impacts of freshwater fish invasions (Li et al. 2016).

In the present study, based on field investigation and literatures collections about non-native fishes in the YRB, we aim to (1) compile a list of field observed non-native fish species in the Yellow River Basin and summarize their taxonomic status and origins, (2) examine the spatial distribution of non-native fish species in this basin, (3) annotate the impacts of freshwater invasions.

Materials and methods

Study area

The Yellow River is the fifth-longest river in the world and the second-largest river in China, with a mainstream length of 5,464 km and a basin area of 752,443 km^2. This large rivers flows from west to east through nine provinces, spanning about 10° of latitude (N 32° − 42°) and 23° of longitude (E 96° − 119°) (CTFRYR 1986). The Yellow River originates from the northeastern margin of the Tibetan Plateau at maximum elevation up to 4800 m, and then flows eastward through the Loess Plateau and the North China Plain into the Bohai Sea. Most of the drainage basin is semi-desert or steppe grasslands with an average annual rainfall to only 300 mm (Xu and Zhang 2006).

Here, following the previous region demarcation of the YRB based on landscape terrian, fish fanua, dams distribution and data availability of fish species (Li 2017; Xie et al. 2018), we divided the YRB into 15 mainstream reaches and 6 primary tributaries (hereafter we called them 21 sub-regions) (Fig. 1). The 15 mianstream reaches are as follows: Eling lake-Maduo (Above MD), Maduo-Maqu (MD-MQ), Maqu-Yangqu (MQ-YQ), Yangqu-Longyangxia

(YQ-LYX), Longyangxia-Liujiaxia (LYX-LJX), Liujiaxia-Heishanxia (LJX-HSX), Heishanxia-Qingtongxia (HSX-QTX), Qingtongxia-Dengkou (QTX-DK), Dengkou-Hequ (DK-HQ), Hequ-Hukou (HQ-HK), Hukou-Sanmenxia (HK-SMX), Sanmenxia-Xiaolangdi (SMX-XLD), Xiaolangdi-Jianhetan (XLD-JHT), Jianhetan-Sunkou (JHT-SK), Sunkou-Mouth (SK-MOU). The 6 tributaries are the Huang River, Tao River, Fen River, Qin River, Wei River and Yiluo River (Fig. 1). The 21 sub-regions represent different kinds of fish habitats, covering a great variation of different landscape terrain and altitudes. According to the previous geographic division of the YRB, the 21 sub-regions were classified into 4 groups: source region (Above MD, MD-MQ and MQ-YQ), upstream (YQ-LYX, LYX-LJX, LJX-HSX, HSX-QTX, QTX-DK, Huang River and Tao River), midstream (DK-HQ, HQ-HK, HK-SMX, SMX-XLD, Fen River and Wei River) and downstream (XLD-JHT, JHT-SK, SK-MOU, Qin River and Yiluo River).

Data collection

In the present study, fish occurrence data for the 15 mainstream reaches and 6 tributaries were constructed from published literatures, dissertations, online databases (see details in Appendix I, II), and data from our sampling surveys from 2018 to 2019. All scientific names were revised according to ''Fishes of the World'' (Nelson et al. 2016). For each mainstream reach and tributary, at least four-season investigations were carried out using multiple types of fishing gears, including cast nets (mesh size 1 cm), drift gillnets (stretched mesh size 2.5 cm) and ground cages.

In the present work, non-native freshwater fish species only refers to established species, and two different kinds of non-native fishes have been considered: (1) translocated fish species that are native to the Yellow River Basin (YRB) but have been translocated outside of their natural range within YRB and (2) exotic species introduced into YRB from other regions or countries.

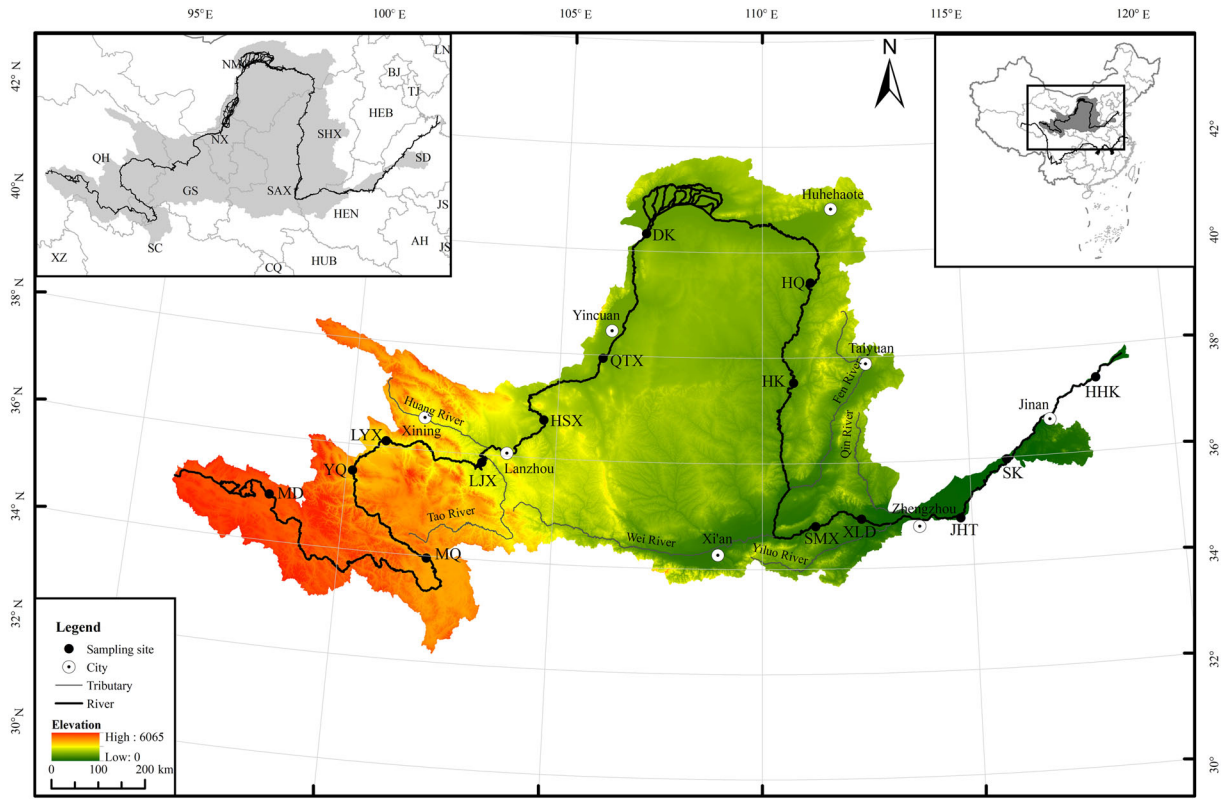

Fig. 1 Topographic map of Yellow River Basin and 21 sub-regions (15 mainstreams and 6 tributaries)

Data analysis

The species richness of non-native fish species within each sub-region was first counted. As the varied species richness of fish assemblages between different sub-regions (total species richness range from 8 to 52), the same number of non-native species would denote quite different introduction pressure, hence we calculated total percentage of non-native species (i.e., ratio of introduced non-native/total species) in each sub-region, following many recent studies concerning invasions of non-native freshwater fishes (e.g., Ding et al. 2017; Jiang et al. 2019; Zhang et al. 2018). We also calculated the percentage of non-native species in different orders. Then the Pearson Chi-squared test was explored to compare the differences between the proportion of non-native species within each order in the YRB and that in China reported by Xiong et al. (2015). We also compared the rate of invasion (overall species and five orders) among four sub-region groups, using non-parametric analysis of variance analysis (Kruskal–Wallis ANOVA and Mann-Whitney post hoc test). Least-squares regression analysis was utilized to examine the relationships between the rate of invasion and the average altitudes among the 21 regions. Both the linear or quadratic models predicted by the elevations were explored. Finally, non-metric multidimensional scaling (MDS) was performed based on Sørensen similarity index to visualize the spatial patterns of non-native fish assemblages in the YRB. The Pearson Chi-squared test, ANOVA and regression analyses were conducted in the SPSS version 19.0 programs, while MDS was computed in the PRIMER version 6 package (Clarke and Gorley 2006).

Results

A total of 40 non-native freshwater fish species belonging to 9 orders, 18 families and 35 genera were recorded. Among the 40 non-native species, there were 19 exotic and 21 translocated species (Table 1). Cypriniformes is the most dominant order, including 16 non-native species (2 exotic and 14 translocated), followed by Perciformes (4 exotic and 3 translocated), Salmoniformes (6 exotic), Siluriformes (3 exotic and 1 translocated) and Osmeriformes (4 exotic and 3 translocated). The other four orders, Acipenseriformes, Beloniformes, Cyprinodontiformes and Synbranchiformes, all include only one species (Table 2). For the proportion of non-native species (invasion%) within the 9 orders, the Chi-squared test showed that invasion% of Cypriniformes and Osmeriformes in the YRB were significantly higher than that in the rest of China (Table 2), whereas the invasion% of the other 7 orders did not differ between the YRB and the rest of China. The most common invasive species were *Rhinogobius cliffordpopei* (established at 15 subregions), *Hypomesus olidus* (13), *Protosalanx hyalocranius* (8), *Oncorhynchus mykiss* (7), *Paramisgurnus dabryanus* (7) and *Abbottina rivularis* (7).

For the geographic origin of the 40 non-native species, there are 8 exotic species originated from other regions in China, followed by Europe (5 species), North America (4 species) and Africa (2 species). The 21 translocated species were all originated from downstream or midstream of the YRB and currently successfully invaded in the upstream regions (Table 1).

For the vector of introduction, aquaculture was the most popular source of non-native fish introduction, with 30 non-native species (15 exotic and 15 translocated, accounting for 75.0 % of all non-native species). Aquarium was the second most frequent reason for introductions (2 exotic and 4 translocated, 15.0 %), followed by religious release (1 exotic and 2 translocated, 7.5 %) and biocontrol (1 exotic).

An average of 8.24 non-native (range from 0 to 30) fish species were introduced and established per sub-region. Among which, 3.48 species were from the order Cypriniformes (accounting for 42.2 %), 1.67 species from Perciformes (20.3 %), 1.29 species from Osmeriformes (15.7 %), 0.86 species from Salmoniformes (10.4 %) and 0.62 species from Siluriformes (7.5 %) (Table 3). On average, the percentage of non-native species accounted for 25.5 % of total fish species per sub-region. ANOVA showed that invasion rate of all non-native species and three dominant orders (Cypriniformes, Perciformes and Osmeriformes) differed significantly ($P < 0.05$) among four sub-region groups, while invasion rate of Salmoniformes and Siluriformes were not significantly different (Fig. 2). In general, the proportion of non-native fish species was highest in upstream sub-regions, followed by midstream sub-regions, and lowest in source region and downstream sub-regions. Based on the regression analysis, the invasion rate of all non-native species and most dominant orders (except Siluriformes) showed a

Table 1 List of non-native freshwater fishes in the Yellow River Basin (YRB)

Order	Species	Origin	Vector of introduction
Exotic			
Acipenseriformes	*Acipenser gueldenstaedti*	Europe	Aquaculture
Cypriniformes	*Leptobotia elongata*	China	Aquaculture
	Megalobrama amblycephala	China	Aquaculture
Cyprinodontiformes	*Gambusia affinis*	North America	Biocontrol
Osmeriformes	*Hypomesus olidus*	China	Aquaculture
	Neosalanx taihuensis	China	Aquaculture
Perciformes	*Oreochromis niloticus*	African	Aquaculture
	Rhinogobius cliffordpopei	China	Aquarium
	Rhinogobius lindbergi	China	Aquarium
	Sander lucioperca	Europe	Aquaculture
Salmoniformes	*Coregonus peled*	Europe	Aquaculture
	Coregonus muksum	Europe	Aquaculture
	Coregonus autumnalis	Europe	Aquaculture
	Oncorhynchus mykiss	North America	Aquaculture
	Salvelinus fontinalis	North America	Aquaculture
	Hucho taimen	China	Aquaculture
Siluriformes	*Pelteobargus nitidus*	China	Religious release
	Clarias gariepinus	African	Aquaculture
	Ictalurus punctatus	North America	Aquaculture
Translocated			
Beloniformes	*Oryzias sinensis*	YRB	Aquarium
Cypriniformes	*Misgurnus anguillicaudatus*	YRB	Religious release
	Paramisgurnus dabryanus	YRB	Religious release
	Cyprinus carpio	YRB	Aquaculture, religious release
	Carassius auratus	YRB	Aquaculture, religious release
	Pseudorasbora parva	YRB	Aquaculture, religious release
	Abbottina rivularis	YRB	Aquaculture, religious release
	Ctenopharyngodon idella	YRB	Aquaculture, religious release
	Acanthorhodeus chankaensis	YRB	Aquaculture, religious release
	Rhodeus sinensis	YRB	Aquaculture, religious release
	Rhodeus ocellatus	YRB	Aquaculture, religious release
	Hemiculter leucisculus	YRB	Aquaculture
	Parabramis pekinensis	YRB	Aquaculture
	Hypophthalmichthys molitrix	YRB	Aquaculture
	Aristichthys nobilis	YRB	Aquaculture
Osmeriformes	*Protosalanx hyalocranius*	YRB	Aquaculture
Perciformes	*Micropercops swinhonis*	YRB	Aquarium
	Rhinogobius giurinus	YRB	Aquarium
	Macropodus opercularis	YRB	Aquarium
Siluriformes	*Silurus meridionalis*	YRB	Aquaculture, religious release
Synbranchiformes	*Monopterus albus*	YRB	Aquaculture, religious release

Exotic means species introduced into the YRB from other regions or countries, and translocated represents fish species that are native to the Yellow River Basin (YRB) but have been translocated outside of their natural range within the YRB

Table 2 Taxonomic diversity in the orders of non-native fish species in Yellow River Basin (YRB)

Orders	No. Non-native	No. Exotic	No. Translocated	YRB (%)	China (%)	χ^2	P-value
Cypriniformes	16	2	14	13.11	3.15	30.14	**<0.001**
Perciformes	7	4	3	35.0	51.21	1.983	0.159
Salmoniformes	6	6	0	75.0	38.89	3.443	0.064
Siluriformes	4	3	1	26.67	27.60	0.001	0.978
Osmeriformes	3	2	1	37.5	4.55	5.514	**0.019**
Acipenseriformes	1	1	0	20.0	43.75	0.911	0.340
Beloniformes	1	0	1	33.33	25.0	0.076	0.782
Cyprinodontiformes	1	1	0	100	80.0	0.247	0.619
Synbranchiformes	1	0	1	50.0	14.29	1.148	0.284

Yellow River Basin (%) represents the number of non-native fish species in each order in Yellow River Basin: the total number of species in each order in Yellow River Basin. China (%) represents the number of non-native freshwater fish species in each order in China: the total number of species in each order in China. The China (%)came from Xiong et al. (2015)

P-values < 0.05 are bolded

significant unimodal model against average elevation. The proportion of non-native species was lowest (close to zero) in the source reaches with the highest elevation, whereas it approached the peak in the upstream-midstream reaches (e.g., LYX-LJX, YQ-LYX) and tributaries (e.g., Huang River) with elevation ca. 2200 to 2600 m, and decreased downstream with decreasing elevation (Fig. 3).

MDS ordination plot showed a clear separation of four sub-region groups (source region, upstream, midstream and downstream), indicating remarked changes in species composition of non-native fishes along the longitudinal gradient of Yellow River (Fig. 4).

Discussion

The present study revealed that 40 non-native (19 exotic and 21 translocated) freshwater fish species have been introduced into the YRB. This number is 13.3 times of the first report about non-native freshwater fishes in the YRB in the early 1980s (3 non-native species; CTFRYR 1986) and also higher than the 26 non-native species reported by a recent whole-basin study (Xie et al. 2018). Compared to other Chinese large rivers, e.g., 22 exotic fish species in the Lancang River (Zhang et al. 2018) and 24 exotic species in the Yangtze River (Liu 2014), the YRB has received similar pressure of fish invasions (the two study did not report the number of translocated species). Like other freshwater ecosystems, the risk of invasions of non-native fish in the YRB should be highly altered due to the sharp increase in species number and distribution ranges of non-native fishes (Liu et al. 2019).

For the taxonomic composition of freshwater non-native fish species (the percentage of non-native species belonging to different orders), the YRB shows a somewhat different representation of species-rich and species-poor orders from that of China. Although the top two most prevalent (Cypriniformes and Perciformes) orders in the YRB are also major components of non-native fishes in China and other regions of the world (De Silva

Table 3 Mean value, SD, and range (Min and Max) of number and percentage of non-native species for all species and dominant orders among the 15 mainstream reaches and 6 tributaries in the Yellow River Basin

	Mean	SD	Min	Max
No. non-native species				
All species	8.24	7.45	0	30
Cypriniformes	3.48	4.01	0	13
Perciformes	1.67	1.53	0	5
Salmoniformes	0.86	1.68	0	6
Siluriformes	0.62	0.97	0	3
Osmeriformes	1.29	0.85	0	2
Percentage of non-native species				
All species	25.5%	23.3%	0	71.4%
Cypriniformes	16.3%	19.7%	0	56.3%
Perciformes	45.3%	39.1%	0	100%
Salmoniformes	33.3%	48.3%	0	100%
Siluriformes	14.9%	26.0%	0	100%
Osmeriformes	72.2%	43.2%	0	100%

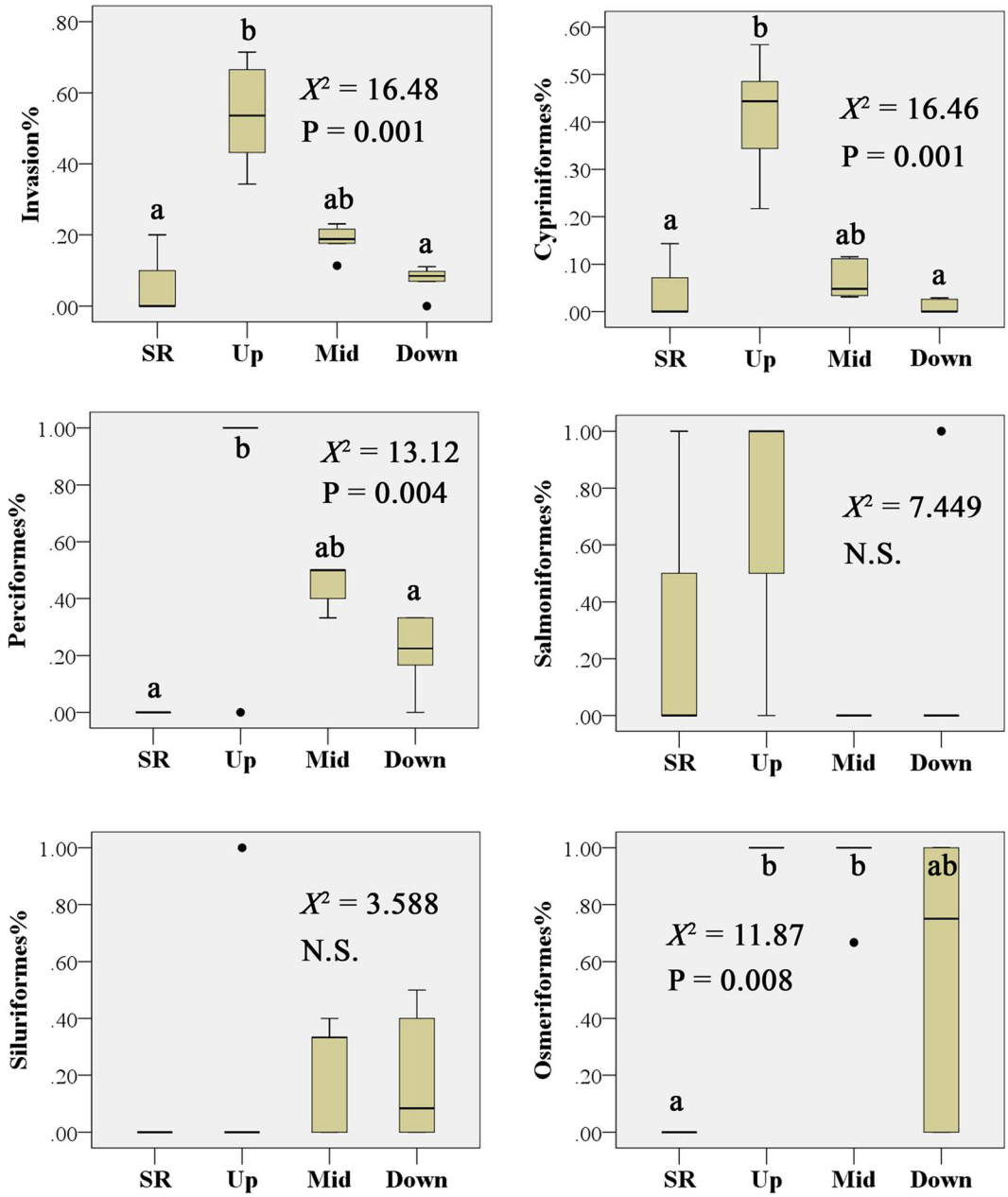

Fig. 2 Box plots of percentage of non-native freshwater species and the five dominant orders (Cypriniformes, Perciformes, Salmoniformes, Siluriformes and Osmeriformes) among four sub-region groups in the Yellow River Basin. The middle solid lines in boxes are medians, box ends are first and third quartiles, whiskers represent maximum and minimum values and black circles are the outliers. The results of Kruskal–Wallis ANOVA and Mann-Whitney pairwise tests are also shown. The boxes with different letters are significantly different. SR: source region; Up: upstream; Mid: midstream; Down: downstream

1989; Nelson et al. 2016; Xiong et al. 2015), the percentage of non-native species from the orders Cypriniformes, Salmoniformes and Osmeriformes in the YRB were higher than that in rest of China. Furthermore, the dominant non-native orders Characiformes and Cyprinodontiformes in China were absent or species-poor in the YRB. Cypriniformes, as the species-richest order in the YRB, is mainly composed of translocated species from middle and lower reaches. Because Xiong et al. (2015) did not count translocated species in their

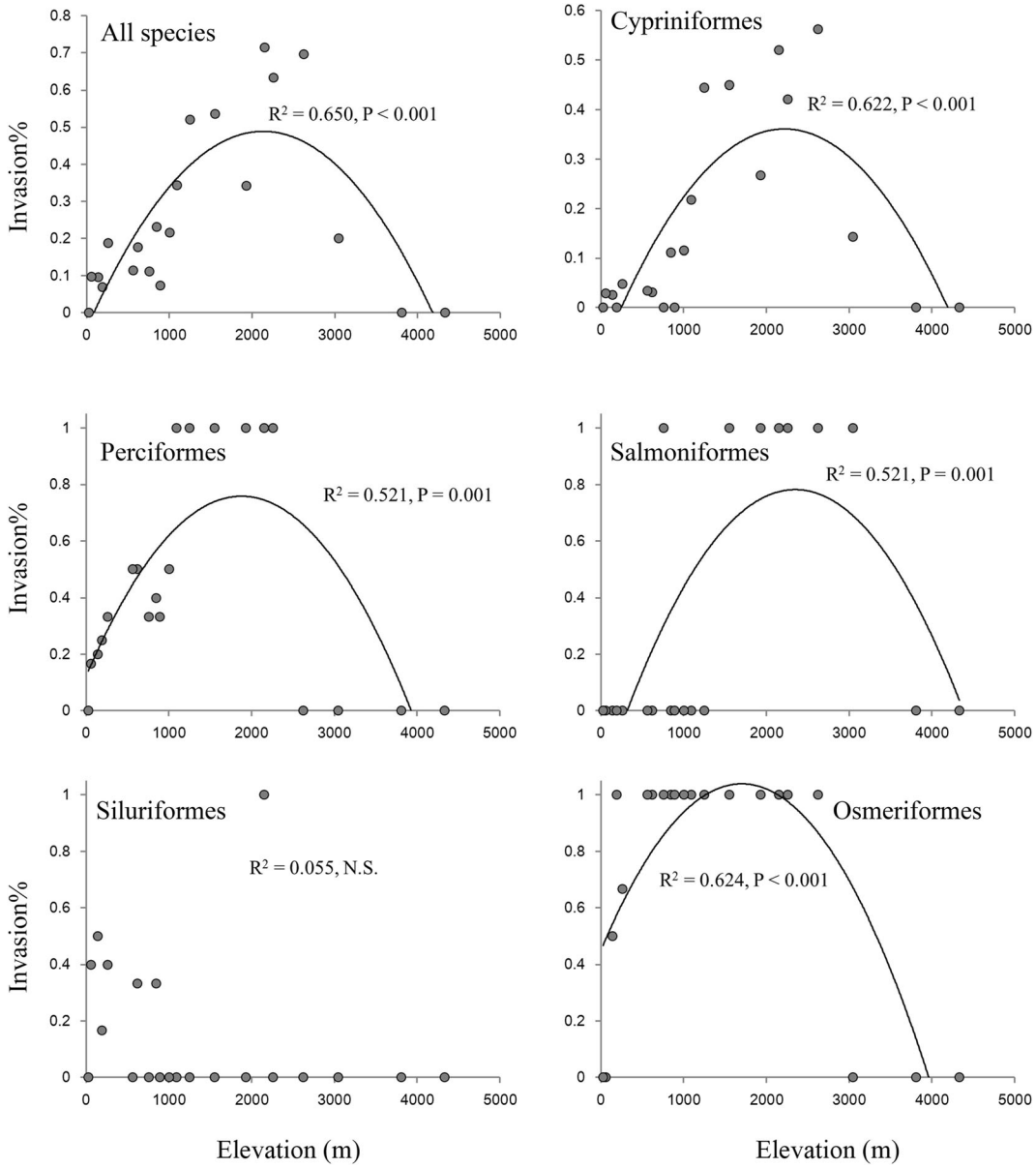

Fig. 3 Relationships between percentage of non-native freshwater species and average elevation for all species, and the five dominant orders (Cypriniformes, Perciformes, Salmoniformes, Siluriformes and Osmeriformes). The regression lines are shown when the relationships are significant ($P < 0.05$)

non-native species list, this should be the reason why we found a much higher proportion of non-native species within Cypriniformes. Due to the demand for fisheries product, non-native cold-water species from Salmoniformes (e.g., *Oncorhynchus mykiss*, *Coregonus peled*) and Osmeriformes (*Hypomesus olidus*, *Protosalanx hyalocranius* and *Neosalanx taihuensis*) were introduced into upstream reservoirs and ponds (Li et al. 2008; Tang and He 2015), resulting in the high degree of invasion of the two orders. Therefore, compare to non-native freshwater fishes in China, the fauna composition in the YRB is of certain particularity.

Inter-region translocations within the YRB or China contributed major component of non-native freshwater fish species in the YRB, with over half of non-native species originated from the downstream of the YRB and ca. 3/4 of them from China. The inter-regional biological invasion, i.e., the invasion of alien species from one

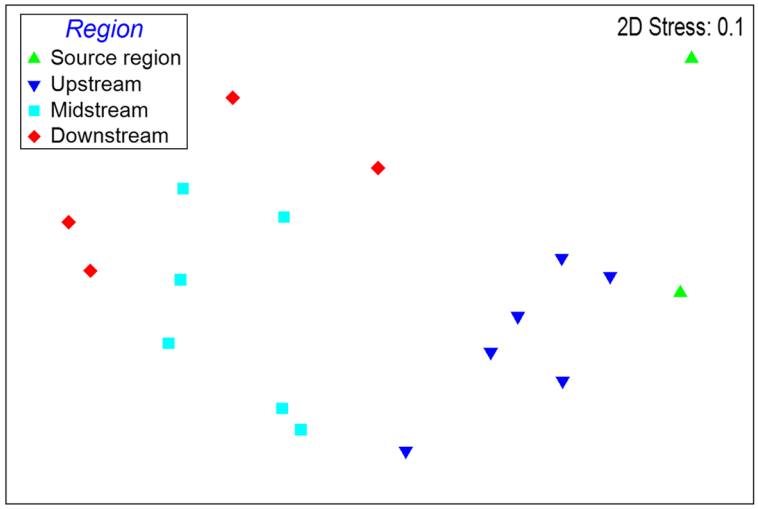

Fig. 4 Non-metric multidimensional scaling (MDS) plots of non-native fish assemblages from the 18 sub-regions. 3 sub-regions, including 2 in source region (above MD and MD-MQ) and 1 in downstream (SK-MOU), were excluded in the MDS plot due to the absence of non-native species

locality to another locality within a country or river basin, is a relatively new concept and receives less attention than the invasion of exotic species from other countries or continents (Jiang et al. 2010). However, the inter-regional invasion is increasingly serious in the world, especially in large countries (e.g., the Russia, Canada, China and USA) (Jiang et al. 2010; Musselman 1994). Compared to abroad exotic invasion, an inter-region invasion is more difficult to manage and control due to the intensive domestic personnel- and goods flow. Since the 1950s, more than 100 species of native freshwater fishes were translocated outside of native regions for aquaculture within China (Ma et al. 2003). The translocations of non-native freshwater fishes extensively occurred in the lakes and rivers of the Yun-Gui Plateau (Ding et al. 2017; Zhang et al. 2018) and Xinjiang (Li and Xie 2002), resulting in a serious decline of native and endemic fish species. Therefore, we appeal to the government to strengthen the management and legislative supervision of the domestic invasions of non-native freshwater fishes.

Aquaculture is the most frequent reason for the current fish introductions in the YRB, followed by aquarium. Because we only considered non-native freshwater fish species occurred in field environment, the number of non-native species for the aquarium was possibly underestimated. Most introduced non-native fishes in the YRB were indeed brought intentionally or unintentionally for aquaculture. However, the introduction of non-native fish species into the YRB for aquarium industry also significantly increased during recent decade (Hou et al. 2016), as the case in China (Xiong et al. 2015). The invasion risk of aquarium trade should be intensively studied in future studies.

Introduction pressure of non-native fishes are quite strong in the YRB, with a percentage of non-native species reaches ca. 1/4 (highest value > 70 %) of the fauna. Such invasion level is much higher than that found at most of the world's river basins (< 5 %, Leprieur et al. 2008) and Oriental (ca. 5 %) and Palaearctic (ca. 16 %) river systems (Brosse et al. 2013). Moreover, we found the percentage of non-native species varied considerably along the longitudinal gradient of Yellow River, with the highest level of invasion in the Yangqu to Liujiaxia (YQ-LYX and LYX-LJX) segment and tributary Huang River with an average elevation of ca. 2200–2600 m, but relatively low level of invasion both in headwater and downstream sub-regions. The establishment of many non-native fish populations requires certain conditions, such as suitable water temperature, depth, current velocity and food resource. In the Yangqu to Liujiaxia segment, a number of large reservoirs (e.g., Longyangxia and Liujiaxia reservoirs) were constructed due to the cascade hydropower development. The environmental condition of reservoirs above the dam was more suitable for the growth and reproduction of several non-native fish species, such as *Neosalanx taihuensis* and *Hypomesus olidus* (Havel et al. 2005; Zhang et al. 2018). Furthermore, the native fish assemblage in this region is still characterized by the ichthyological fauna of Qinghai-Tibet Plateau, mainly composed of cold-water taxa (e.g., Schizothoracinae, genus *Triplophysa*) belonged to the order Cypriniformes. The simple fish fauna would be less resistant to non-native freshwater

fish species from historically absent orders and families (e.g., the orders Salmoniformes, Osmeriformes and Perciformes), as invaders distantly related to native species are more likely to seriously impacted the native assemblages (Daehler 2001; Jiang et al. 2019; Ricciardi and Mottiar 2006). Such were the reasons why we observed the highest levels of invasions of non-native fishes in these reaches and tributary.

The number of non-native fish species in headwater reaches was very low (zero in the two headwater region). The high altitude (> 3500 m) and harsh environment (low water temperature and unstable channel condition) in headwater reaches would prevent the human-mediated introductions and establishment of non-native species (Zhang et al. 2018), and then resulted in a low level of non-native fish invasions. In the downstream reaches and tributaries, the invasion level was also quite low. This is because fish assemblage in downstream of the Yellow River is quite complex, belonging to river-floodplain fish fauna (Li 2017), make them more resistant to the introduction of non-native fishes.

The introductions of non-native fish significantly improve the production and value of fisheries and aquaculture, and some non-native fish played an important role in aquaculture production and economic development in many regions and countries. For example, the introduced non-native fishes contributed to 25 % of the total yield in China (Lin et al. 2015) and 17 % of overall global production (Shelton and Rothbard 2006). However, non-native fish have also caused enormously negative impacts on native species and ecosystems. Firstly, the non-native fish species usually have the advantages of fast growth rate, strong adaptability, and high disease resistance, making them invasive (i.e., competition for food and habitat, predation) in most introduced regions (Webber and Riordan 1976). Secondly, non-native fish can carry parasites or viruses that are diseased or potentially fatal to native fish populations (Ye et al. 2009). Thirdly, hybridization would be occurred between native species with non-native species and caused the genetic erosion of native endemic fish species (Tang and Chen 2012). Fourthly, some invasive fishes can cause habitat and ecosystem alterations by diminishing the abundance of macrophytes, planktons and invertebrates (McDowall 2006). Such cases also occurred in the YRB. For example, *Hypomesus olidus* and *Oncorhynchus mykiss* have become the dominant species in several upstream reservoirs (e.g., Longyangxia and Liujiaxia reservoirs) and severely threaten native fish populations (Tang and He 2013). Hybridization between native common carp (*Cyprinus carpio*) and German mirror carp (*Cyprinus carpio* var.) was frequently found in field investigations (Li et al. 2008), significantly diminishing the native fish populations.

Invasiveness of non-native freshwater fish species has become a major environmental problem in the world, seriously impacting ecosystem structure and functions worldwide. China is experienced the strongest invasions of introduced non-native freshwater fish compared to other countries (Xiong et al. 2015). In the present study, we found the YRB has experienced a remarkably high introduction level of non-native freshwater fish species, with translocated species (within YRB) and domestic non-native species as the major component of introduced species. These most successful invaders were mainly from historically absent or species-poor orders (Salmoniformes, Osmeriformes and Perciformes), these non-native species distantly related to native species are more likely to impact native species and modify taxonomic and phylogenetic structure of fish assemblages (Jiang et al. 2019, 2020; Zhang et al. 2019). Some upstream mainstream reaches and tributaries experienced considerably high level of non-native fish invasion (accounting for 70 % of local fish assemblages). The negative impacts of non-native fish introductions to native fish species, e.g., competition for resource, predation and hybridization were emerged in many introduce regions. The two headwater reaches are still unaffected by non-native fishes due to the high elevation and harsh environment, however, with the climate warming and increasing human disturbances in the Tibetan Plateau, the non-native fish species are very likely to expand to high elevation areas. Therefore, we appeal to the environmental researchers and local governments pay more attention to non-native freshwater fish species in the YRB.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10641-021-01070-2.

Acknowledgements This work was financially supported by the National Natural Science Foundation of China (51709225 & 51939009), Natural Science Foundation of Shaanxi Province (2018JQ5121) and Innovation Team of Young Science and Technology in Xi'an University of Technology (104-451217015). Many thanks are given to Three-River-Source National Park Administration, Department of Agriculture and Rural Affairs in Qinghai Province, and local fisheries authorities in fish investigation and data collection.

References

Brosse S et al (2013) Fish-SPRICH: a database of freshwater fish species richness throughout the World. Hydrobiologia 700(1):343–349

Clarke KR, Gorley RN (2006) PRIMER v6: User Manual/Tutorial (Plymouth Routines in Multivariate Ecological Research). PRIMER-E, Plymouth

CTFRYR (The cooperative team of fishery resource research on the Yellow River system) (1986) Fishery resource in the Yellow River system. Liaoning Science and Technology Publishing House., Liaoning

Cucherousset J, Olden JD (2011) Ecological Impacts of Nonnative Freshwater Fishes. Fisheries 36(5):215–230. https://doi.org/10.1080/03632415.2011.574578

Daehler CC (2001) Darwin's naturalization hypothesis revisited. Am Nat 158(3):324–330. https://doi.org/10.1086/321316

De Silva SS (1989) Exotic aquatic organisms in Asia. Asian Fisheries Society, Manila

Ding C, Jiang X, Xie Z, Brosse S (2017) Seventy-five years of biodiversity decline of fish assemblages in Chinese isolated plateau lakes: widespread introductions and extirpations of narrow endemics lead to regional loss of dissimilarity. Divers Distrib 23:171–184. https://doi.org/10.1111/ddi.12507

Havel JE, Lee C, Zanden J (2005) Do reservoirs facilitate invasions into landscapes? Bioscience 55(6):518–525

Hou S, Li W, Wang Y, Wen S, Li H, Gao Z (2016) The current situation of aquatic animals invasion of Shaanxi stretch of the Yellow River. J Northwest Univ Nat Sci Ed 46(1):82–86

Jiang W, Cao W, Feng Y, Jing F, Li Y (2010) Inter-regional biological invasion in China: Present status and countermeasures. Chin J Ecol 29:1451–1457

Jiang X, Ding C, Brosse S, Pan B, Lu Y, Xie Z (2019) Local rise of phylogenetic diversity due to invasions and extirpations leads to a regional phylogenetic homogenization of fish fauna from Chinese isolated plateau lakes. Ecol Ind 101:388–398. https://doi.org/10.1016/j.ecolind.2019.01.041

Jiang X, Pan B, Sun Z, Cao L, Lu Y (2020) Application of taxonomic distinctness indices of fish assemblages for assessing effects of river-lake disconnection and eutrophication in floodplain lakes. Ecol Ind 110:105955. https://doi.org/10.1016/j.ecolind.2019.105955

Leprieur F, Beauchard O, Blanchet S, Oberdorff T, Brosse S (2008) Fish invasions in the world's river systems: when natural processes are blurred by human activities. Plos Biol 6(2):404–410

Li F, Zhang J, Yuan Y, Feng H, Zhang J, Yang X (2008) Present situation and problems on fish introduction in Yellow River system. J Anhui Agric Sci 36(34):15024–15026

Li S (2017) Fishes of the Yellow River. China Ocean University Press, Qingdao

Li S, Chen J, Wang X (2016) Global distribution, entry routes, mechanisms and consequences of invasive freshwater fish. Biodivers Sci 24(6):672–685

Li Z, Xie Y (2002) Invasive alien species in China. China Forestry Publishing House, Beijing

Lin Y, Gao Z, Zhan A (2015) Introduction and use of non-native species for aquaculture in China: status, risks and management solutions. Rev Aquac 7(1):28–58

Liu C, Comte L, Xian W, Chen Y, Olden J (2019) Current and projected future risks of freshwater fish invasions in China. Ecography (42):2074–2083. https://doi.org/10.1111/ecog.04665

Liu F (2014) List and negative effects of exotic fish species in the Yangtze River. China Nat 2:38–40

Liu J, Li Z (2010) The role of exotics in Chinese inland aquaculture. In: DS SS (ed) Success Stories in Asian Aquaculture. Springer, Dordrecht, pp 173–185

Ma X, Xiong B, Wang Y, Wang M (2003) Intentionally introduced and transferred fishes in China's inland waters. Asian Fish Sci 16:279–290

McDowall RM (2006) Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxioid fishes? Rev Fish Biol Fish 16(3–4):233–422

Musselman LJ (1994) Harmful non-indigenous species in the United States. Econ Bot 48(2):138–138. https://doi.org/10.1007/BF02908200

Nelson JS, Grande TC, Wilson MV (2016) Fishes of the world. Wiley, Hoboken

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52(3):273–288. https://doi.org/10.1016/j.ecolecon.2004.10.002

Rahel FJ (2002) Homogenization of freshwater faunas. Annu Rev Ecol Syst :291–315. https://doi.org/10.1146/annurev.ecolsys.33.010802.150429

Ricciardi A, Mottiar M (2006) Does Darwin's naturalization hypothesis explain fish invasions? Biol Invasions 8(6):1403–1407. https://doi.org/10.1007/s10530-006-0005-6

Sala OE et al (2000) Global biodiversity scenarios for the year 2100. Science 287(5459):1770–1774

Shelton WL, Rothbard S (2006) Exotic species in global aquaculture - a review. Isr J Aquacult Bamidgeh 58(1):3–28

Shen H, Li K, Zhang M (2007) Investigation and analysis of fish resources in the upstream Yellow River. Hebei Fish 162(06):37–41. https://hbyu.chinajournal.net.cn/WKB2/WebPublication/paperDigest.aspx?paperID=e2bbf271-0776-4f66-8c41-2115cec92629

Simberloff D et al (2013) Impacts of biological invasions: what's what and the way forward. Trends Ecol Evol 28(1):58–66. https://doi.org/10.1016/j.tree.2012.07.013

Strayer DL (2010) Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshw Biol 55(s1):152–174. https://doi.org/10.1111/j.1365-2427.2009.02380.x

Tang W, Chen Y (2012) Hybridization between native barbless carp (Cyprinus pellegrini) and introduced common carp (C. carpio) in Xingyun Lake, China. Zoologicalence 29(5):311–318

Tang W, He D (2013) Fish resource survey on Cihaxia to Jishixia stretches in the upper reaches of Yellow River (2005–2010). J Lake Sci 25(4):600–608

Tang W, He D (2015) Investigation on alien fishes in Qinghai Province, China(2001–2014). J Lake Sci 27(3):502–510

Vitule JRS, Freire CA, Simberloff D (2009) Introduction of non-native freshwater fish can certainly be bad. Fish Fish 10(1):98–108

Webber HH, Riordan PF (1976) Criteria for candidate species for aquaculture. Aquaculture 7(2):107–123

Wu Y, Tan Q (1991) Characteristics of the fish fauna of the characteristics of Qinghai-Xizang plateau and its geological distribution and formation. Acta Zool Sin 37:135–152

Wu Y, Wu C (1992) The fishes of the Qinghai-Xizang Plateau. Sichuan Science and Technology Press, Chengdu

Xie JY, Tang WJ, Yang YH (2018) Fish assemblage changes over half a century in the Yellow River, China. Ecol Evol 8(8): 4173–4182

Xiong W, Sui X, Liang S-H, Chen Y (2015) Non-native freshwater fish species in China. Rev Fish Biol Fish 25(4):651–687. https://doi.org/10.1007/s11160-015-9396-8

Xu Z, Zhang N (2006) Long-term trend of precipitation in the Yellow River basin during the past 50 years. Geogr Res 25:27–34

Ye S, Li H, Qiao G, Li Z (2009) First case of Edwardsiella ictaluri infection in China farmed yellow catfish Pelteobagrus fulvidraco. Aquaculture 292(1–2):6–10

Zhang C et al (2019) Large-scale cascaded dam constructions drive taxonomic and phylogenetic differentiation of fish fauna in the Lancang River, China. Rev Fish Biol Fish 29(4):895–916. https://doi.org/10.1007/s11160-019-09580-0

Zhang C, Ding L, Ding C, Chen L, Sun J, Jiang X (2018) Responses of species and phylogenetic diversity of fish communities in the Lancang River to hydropower development and exotic invasions. Ecol Ind 90:261–279