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Research Article

Non-native aquatic species in the Yellow River Basin, China

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Abstract

The Yellow River is the second largest river in China and it supports a rich biodiversity and numerous endemic fish species (*Atrilinea macrolepis*, *Brachymystax lenok tsinlingensis*, and *Hucho taimen*). It is one of China's most important freshwater aquaculture and mariculture regions, and many non-native species have been introduced into the region. This study provided the Yellow River Basin's first and current list of non-native aquatic species including a total of 112 species comprised of 59 fishes, 27 aquatic plants, 21 Mollusca, three reptiles, one crustacean and one amphibian. The primary introduction pathway is aquaculture (69 species), followed by the aquarium and ornamental trade (30 species), forage (four species), unintentional introductions (four species), ecological restoration (two species), religious releases (two species), and one species for biocontrol. Asia is the primary geographic origin of non-native species (39 species), followed by North America (33 species), South America (16 species), Europe (10 species), Africa (nine species) and Oceania (five species). Many non-native species have become important species in local aquaculture, the aquarium and ornamental trade or for other human uses. Many non-native species have caused significant negative economic, ecological and societal impacts. More research, field investigations and new guiding policies should be applied for the effective control and management of non-native species in the Yellow River Basin.

Key words: Biodiversity conservation, Biological invasions, Ecological and economic impacts, Sustainability

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Introduction

Non-native species have been identified as one of the drivers of the dramatic reduction in freshwater biodiversity that has occurred globally over the past century (Harrison et al. 2018; Dudgeon 2019; Tickner et al. 2020). The invasion of non-native species and its effects are acknowledged as a serious threat to the loss of biodiversity, particularly in freshwater habitats (Simberloff et al. 2013; Reid et al. 2019; Britton et al. 2023; Dudgeon and Strayer 2024). Numerous non-native aquatic species have been introduced for aquaculture, the ornamental and aquarium trade, and for other anthropocentric purposes (Xiong et al. 2015a, 2017a;

Wang et al. 2016, 2021). Some of the non-native species subsequently escaped and established wild populations, which has had a severe effect on the social, cultural, and biological elements of various freshwater ecosystems (Moyle and Light 1996). Therefore, one of the most crucial problems for the preservation and sustainable use of freshwater resources is the control and management of non-native aquatic species (Ricciardi and Rasmussen 1998; Britton et al. 2023).

Managing non-native species is essential for the conservation of biodiversity in freshwater ecosystems (Dudgeon et al. 2006; Strayer and Dudgeon 2010; Reid et al. 2019; Ahmed et al. 2022). Creating an inventory of non-native species in biodiversity hotspots is the first step in developing management and control methods (Xiong et al. 2018a, 2023b; Wang et al. 2021; Lieurance et al. 2023). For a considerable period of time, research on the management of non-native species has been a top priority in North America, Europe, Australia, and many other industrialized nations and areas (Pyšek et al. 2008; Qiu and Chen 2009). In recent years, numerous non-native species have been introduced due to economic incentives in some emerging nations, such as China, ASEAN (Association of Southeast Asian Nations) and Brazil (Xu et al. 2012; Freshse et al. 2016; Wang et al. 2021), which has led to a significant growth in their propagation and use (Naylor et al. 2001; Wang et al. 2016; Xiong et al. 2023a). In the last 20 years, there has been a sharp increase in the pace of the invasion of China's biodiversity hotspot wetland ecosystems, including the South China Sea and the Yangtze River (Xiong et al. 2015a, 2017a; Wang et al. 2016, 2021). There is little information regarding non-native species and their impacts in some biodiversity hotspots, such as the Yellow River, which sustains an extraordinarily rich biodiversity (He et al. 2020; Xiong et al. 2023b).

The Yellow River is the second longest river in China and the sixth longest river in the world. It passes through the Qinghai-Tibet Plateau, Loess Plateau and the north China plain. Some of these areas include National Parks and the National Key Ecological Functional Zone, such as the Sanjiangyuan, Qinlin Mountains located in the Yellow River Basin. These regions support the drinking water safety of 12% of Chinese population and 15% of the arable land with only 2% of Chinese water resources (Fan et al. 2020). This region has a rich aquatic biodiversity and high number of endemic and endangered species (Zhao et al. 2020; Sun et al. 2020). However, aquatic biodiversity has declined sharply in the Yellow River Basin due to the invasion of non-native species, human disturbance, and climate change (Li 2017; Jia et al. 2020). Prior to the present study, information about non-native species in the Yellow River Basin has been limited, which has restrained sustainable development in this region of China.

The purposes of this study are to develop and summarize an updated list of non-native aquatic species in the Yellow River Basin and to analyze the biological and ecological information about them (taxonomy, origin, introduction pathways, ecological and economic impacts). We provide recommendations for additional research on the management of non-native species in the Yellow River Basin.

Materials and methods

Study area

The Yellow River (39°28'N–41°05'N, 115°25'E–117°30'E) is the second longest river in China and the sixth longest river in the world with a total length of 5,464 km of mainstream and with a total drainage area of 752,773 km^2 (Jia et al. 2020). It originates on the east side of the Yaladazhe Mountain (Yahela Dahazhe Mountain) in Qinghai Province, and flows through a total of nine provinces (or Autonomous

Regions), including Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong (Fig. 1). It eventually turns eastward into the Bohai Sea.

The source of the Yellow River and its upper reaches are in Hekou Town, Toketo County, Inner Mongolia Autonomous Region. This upper area of the Yellow River Basin has a length of 3,471.6 km and a watershed area of 428,000 km^2, accounting for 53.8% of the Basin's total area. The middle reaches of the Yellow River extend from Hekou Town to Taohuayu in Zhengzhou City, Henan Province. The middle reaches of the river are 1206.4 km long, with a watershed area of 344,000 km^2, accounting for 43.3% of the total watershed area, with a drop of 890 meters and an average specific decline of 7.4‰. The downstream reach of Yellow River is from Taohuayu to the estuary of Bohai Sea. The lowermost zone of the Yellow River is 785.6 km. The watershed area of the lower most zone is 23,000 km^2, accounting for only 3% of the total watershed area. It has a drop of 94 m, and the specific decline in elevation is steeper at the reach's beginning and slower near the end of the zone, with an average drop of 1.11‰.

The climate of the Yellow River Basin is mainly controlled by the continental monsoon and transforms from semiarid and arid to subhumid to humid conditions. The average rainfall of the whole basin is 476 mm. However, precipitation is dispersed unevenly over temporal and spatial scales. There are a total of 3.9 million hectares of wetlands (including rivers, lakes, marshes, artificial wetlands, and offshore and coastal areas), which account for about 6% of the total area of Chinese wetland habitats (Sun et al. 2020; Zhao et al. 2020).

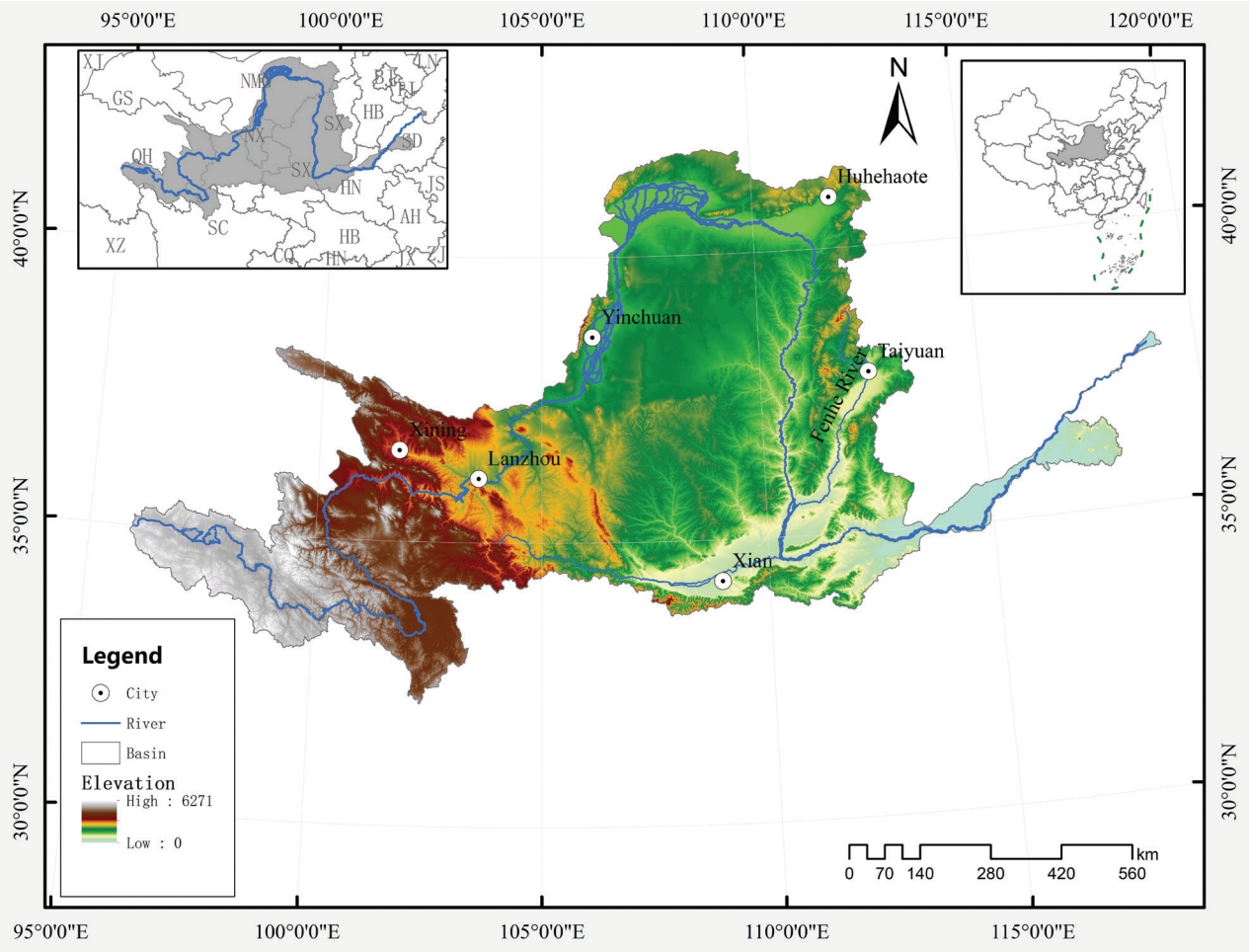

Figure 1. The location of the Yellow River Basin.

Data collection

Biological samples were collected between May and October between 2003 and 2024. Fish sampling was conducted in different waterbody types using several kinds of equipment including gillnets (20 × 10 m, mesh-size 5 mm), fish cages (0.5×0.5×10 m, mesh size 0.5 cm), dip nets (0.5 m in diameter with a stretched mesh size of 1 mm), and electrical fish sampling equipment (CWB-2000 P, 12V, 250 Hz). For descriptions of the sampling methodology see Xiong et al. (2015b, 2017b, 2019a). We also implemented botanical surveys beginning in 2003 and recorded non-native aquatic plant occurrences in rivers, lakes, ponds, reservoirs, and canals (for sampling methodology see Xiong et al. 2021, 2022, 2023c, 2023d, 2023e). We carried out non-native species investigations for other biological groups, including amphibians, Crustacea, Mollusca, and reptile species (Xiong et al. 2018a, 2023b, 2024a). A literature review was undertaken that contained the following combination of words: "alien OR exotic OR invas* OR non-native OR non-indigenous" and "the Yellow River" in the title, abstract, and keywords from the Web of Sciences database (WOS, https://www.webofscience.com/wos/alldb/basic-search) and Chinese National Knowledge Infrastructure database (CNKI, http://www.cnki.net). We also assembled relevant information from selected Chinese Books, such as "*Alien aquatic plants and animals in China*" (Li et al. 2007) and "*Illustrations of Alien Invasive plants in China*" (Yan et al. 2016). An updated inventory of non-native aquatic species in the Yellow River Basin based on our field surveys and literature review is provided in Suppl. material 1.

Results

Taxonomy

Based on our field surveys and literature review, a total of 112 non-native aquatic species belonging to 40 orders, 63 families and 88 genera occurred in the Yellow River Bain (Suppl. material 1). Fishes were the most species-rich taxonomic group (59 species), followed by plants (27 species), molluscs (21 species), reptiles (three species), and crustaceans and amphibians (one species each, respectively). The data for all taxonomic groups are presented in Fig. 2.

Introduction pathways

Sixty-nine non-native species (over 61.60% of the total number of non-indigenous species) were introduced for aquaculture and 30 species were imported for marketing through the aquarium and ornamental trade. Other pathways of entry include importation for use as forage (four species), unintentional introductions (four species), ecological restoration (two species), release for religious reasons (two species), and for biocontrol purposes (one species). All introduction pathways are presented in Fig. 3.

Geographic origins of the non-native species

The primary origins for these non-indigenous groups and taxa are Asia (39 species), followed by North America (33 species), South America (16 species), Europe (10 species), Africa (nine species), and Oceania (five species). The origins of non-native species are presented in Fig. 4.

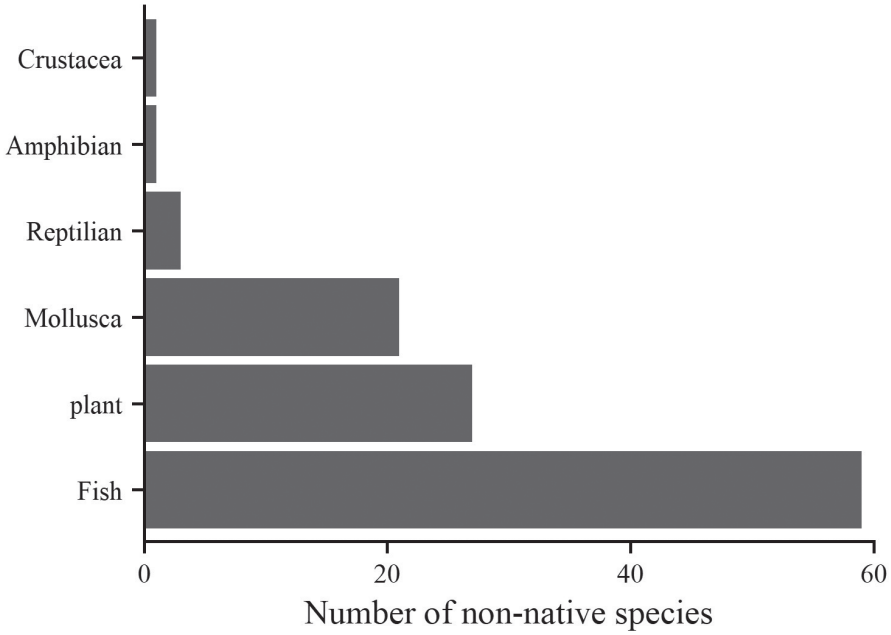

Figure 2. The number of non-native species in different biological taxonomic groups in the Yellow River Basin.

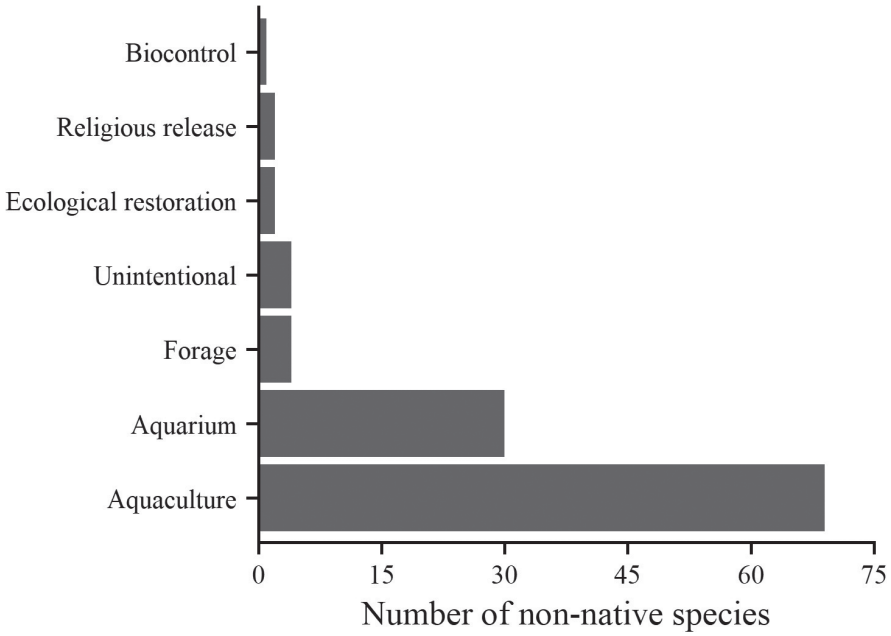

Figure 3. The number of non-native species introduced through different pathways of entry into the Yellow River Basin.

Distribution and suitable habitats

There are nine provincial districts (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong) of China that lie in the Yellow River Basin. Shandong Province has the greatest number of non-native species (70 species), followed by Gansu Province (40 species), Shanxi Province and Qinghai Province (38 species), Henan Province (30 species), Shaanxi Province (29 species), Ningxia Hui Autonomous Region (27 species), Sichuan Province (25 species), and Inner Mongolia Autonomous Region (23 species).

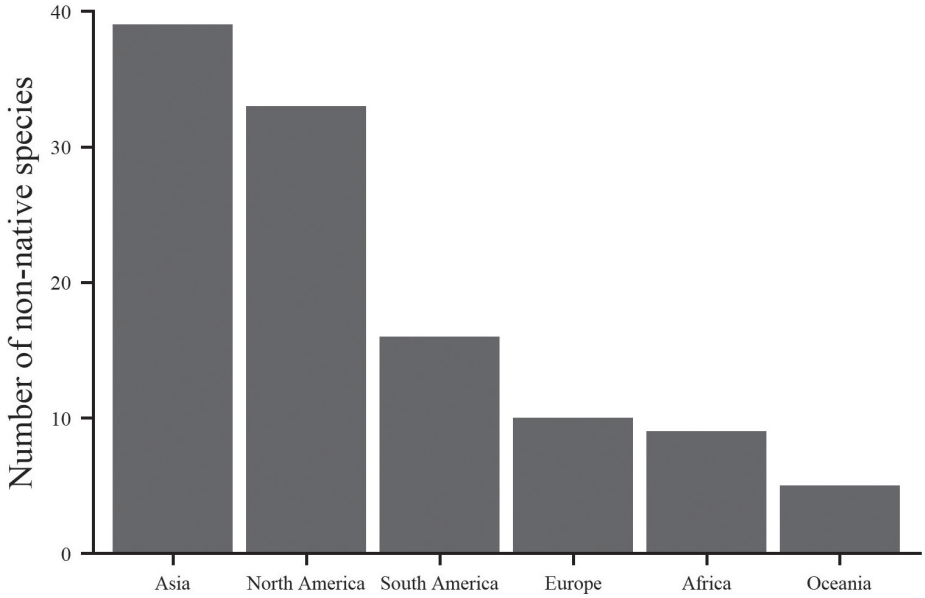

Figure 4. The number of non-native species by origin in the Yellow River Basin.

There are 77 non-native species that occur primarily in freshwater habitats, 26 species occupy marine habitats, and nine species occur in both freshwater and marine habitats.

Ecological and economic impacts

A great number of non-native species provide significantly positive impacts on local economic development, food safety and ecological function. It is difficult to estimate the exact economic value of these non-native species used in aquaculture, the aquarium and ornamental trade, and in other applications. Many species that are native to the Yangtze River drainage, such as black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*), clearhead icefish (*Protosalanx hyalocranius*) and Asian swamp eel (*Monopterus albus*) have been widely farmed or occur in almost all natural waterbodies in the Yellow River Basin. The per capita consumption of aquatic products increased from 7.26 kg in 1981 to 14.70 kg in 2015 in China (Yue et al. 2018).

Based on field investigations and our literature review, there are at least 78 non-native species that have caused negative impacts, including 61 non-native species have initiated two or more negative impacts (Suppl. material 1). The most frequent negative impact is competition with native species (76 species), followed by predation of native species (36 species), habitat and ecosystem alteration (23 species), herbivory on native aquatic plants and rice (four species), serving as intermediate hosts of parasites, hybridization and genetic introgression (one species each, respectively).

Discussion

Taxonomy

In this study, we report that 112 non-native species have been introduced and have successfully established feral populations in the Yellow River Basin (Suppl. material 1). This is substantive when compared with invasion data for other heavily colonized sites, such as 42 non-native species in the Three Gorges Reservoir of China (Xiong et al. 2018a) and 103 non-native species in Poyang Lake of China

(Xiong et al. 2023b). This may be because the area of the Yellow River Basin is 752,443 km^2, far greater than the areas of other invasion hotspots. A few species, such tilapia and the white freshwater prawn, were brought to China for aquaculture in the 1990s. Thus, it isn't certain that all 112 of these non-native species successfully colonized the Yellow River Basin after 2000 (Fig. 1). It is possible that reports of non-native species were made much later than when they were actually introduced. Nevertheless, there is a significant rate of non-native species invasion that is clearly evident in the Yellow River watershed during past twenty years.

In summary, a great number of non-native aquatic species have been imported to China and seriously threaten local biodiversity (Xiong et al. 2015a, 2017a; Wang et al. 2016, 2021). Many non-native aquatic species have been introduced in some biodiversity hotspots areas and have caused large ecological and economic impacts (Xiong et al. 2015a, 2018b, 2019b, 2023b). In some large waterbodies, rapid invasion of non-indigenous species created the highest invasion rates in the world (Xiong et al. 2018a, 2023b; Wang et al. 2021). Some studies have focused upon the Yangtze River, the largest river of China, which is one of the global invasion hotspots (Xiong et al. 2018a, 2023b). Other research has shown that invasion of non-native aquatic species has occurred widely throughout China (Xiong et al. 2018b, 2019b, 2021, 2022, 2023c, 2023d, 2023e, 2023f). The Yellow River, as the second longest river in China, supports a rich freshwater biodiversity (He et al. 2020; Zhao et al. 2020) and numerous endangered fish species, such as *Atrilinea macrolepis*, *Brachymystax lenok tsinlingensis*, and *Hucho taimen* (Cao et al. 2020). This study is the first comprehensive summary of basic information about non-native species in the Yellow River Basin.

Introduction pathways

The aquarium and ornamental trade was the primary introduction pathway for the global spread of non-native aquatic species (Gertzen et al. 2008; Chang et al. 2009; Strecker et al. 2011; Olden et al. 2021; Olden and Carvalho 2024). As one of the largest producers and consumers for the aquarium and ornamental trade, China has imported many aquatic plants, snails, crayfish, and amphibians (Lin et al. 2006; Xiong et al. 2015a; Wang et al. 2016). For example, there are nearly 500 non-native aquatic plant species that have been introduced to China (unpublished data). To meet high market demands, many non-native aquatic plants were brought into and have been widely planted in the Yellow River Basin. Inevitably, some of these aquatic plants, such as parrot's feather (*Myriophyllum aquaticum*), fanwort (*Cabomba caroliniana*), yellow bur-head (*Limnocharis flava*), yellow flag (*Iris pseudacorus*), and water lettuce (*Pistia stratiotes*), have established dense feral monospecific stands in natural waterbodies (Xiong et al. 2021, 2022, 2023c, 2023d, 2023e; Dong et al. 2023). The online trade has expanded greatly in Chinese markets during the past twenty years (Gao 2018), facilitating the spread of non-native aquatic species (Liu et al. 2021; Wang et al. 2023). For example, *Physella acuta* has been introduced into China as an aquarium snail. It has been discarded and unintentionally released by aquarium hobbyists, and thus, has become an invasive species in the northern regions of China (the lower reaches of the Yellow River) (Xiong et al. 2024b).

Aquaculture is one of the most important introduction gateways of non-native aquatic species (Naylor et al. 2001; Xiong et al. 2015a), and as the largest global producer of freshwater aquaculture organisms, China has introduced many non-native aquatic species to improve fishery quality and quantity (Lin et al. 2015; Wang et al. 2015). The Yellow River is one of the most important aquaculture and fishery regions in China, and it accounts for about 12.9% of the total fishery production of China in 2023 (MARA 1990–2024). Many non-native aquatic species, including fishes,

crayfish, frogs, snails, and turtles have been imported into the Yellow River Basin as important aquaculture species (Suppl. material 1). During the 1960–1970s, Chinese researchers had a breakthrough in artificial breeding techniques in the "Chinese four domestic fish", primarily distributed in the Yangtze River and Pearl River, including black carp, grass carp, silver carp, and bighead carp (Wu and Zhong 1964). Four carp species and some other Cyprinidae fish species such as common carp (*Cyprinus carpio*), goldfish (*Carassius auratus*), pond loach (*Misgurnus anguillicaudatus*), and large-scale loach (*Paramisgurnus dabryanus*), became established throughout almost all areas of the Yellow River Basin. Some fast-growing non-native species such as Nile tilapia (*Oreochromis niloticus*), red swamp crayfish (*Procambarus clarkii*), and largemouth black bass (*Micropterus salmoides*), were brought into the Yellow River Basin during the 1980s and 1990s. With reforms and the improvement of people's living standards, some highly valuable farmed species, such as peled or northern whitefish (*Coregonus peled*), muksun (*Coregonus muksun*), and rainbow trout (*Oncorhynchus mykiss*), have been imported and farmed in the upstream regions of the Yellow River Basin. These non-native species are important species for local aquaculture. More research, regulations and management measures are needed for these non-native farmed species.

Geographic origins of the non-native species

Asia was the origin of 34.82% of the non-native species introduced in the Yellow River Basin. This is because many fish species, such as grass carp, silver carp, common carp, and bighead carp, were brought from the Yangtze River to the Yellow River for aquaculture between 1960 and 1980. North America and South America were the second largest origin of non-indigenous species introduced to the Yellow River Basin (29.46%). Beginning in the 1970s, many fishes (such as channel catfish, brook trout, American eel, and largemouth black bass) and molluscs (mainly the Atlantic bay scallop and American cupped oyster) were introduced into China. South America is a large continent with a rich diversity of aquatic habitats supporting a great number of novel aquatic plants and fishes (Xiong et al. 2015a; Wang et al. 2016). Some aquatic plants and fishes were imported to the Yellow River Basin as part of the aquarium and ornamental trade and made South America (14.28%) the third greatest origin of non-native species in the Yellow River Basin.

Potential ecological and economic impacts

Many non-native species contribute significantly to economic, ecological and societal values (Schlaepfer et al. 2011; Sax et al. 2022), and some are important species in aquaculture, which is the largest and fast-growing agricultural sector in China (Wang et al. 2015; Xiong et al. 2015a; Kang et al. 2023). For example, tilapia species (mainly Nile tilapia, *Oreochromis niloticus*) have been widely introduced into many regions (Gansu, Sichuan, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong) of the Yellow River Basin for aquaculture (Xiong et al. 2023a). The total annual production of tilapia reaches 18,138 tons, which comprised about 9.98% of the production of China in 2023 (MARA 1990–2024). Shandong has become one of the most important mariculture regions of China, and its value increased sharply from 2.66 billion dollars in 2004 to 16.53 billion dollars in 2023 (MARA 1990–2024).

In the past thirty years, many non-native freshwater fish (nearly 400 species), aquatic plant species (nearly 500 species), and molluscs (over 30 species) have been introduced in China for the aquarium and ornamental trade (Xiong et al. 2015a, 2024b; Wang et al. 2016). Many of these non-native species were farmed in the Yellow River Basin. According to our research-based studies, some non-native aquatic

plants, such as yellow bur-head (*Limnocharis flava*), yellow flag (*Iris pseudacorus*), fanwort (*Cabomba caroliniana*) and parrots's feather (*Myriophyllum aquaticum*), have been widely planted in ponds and are sold as ornamental plants (Xiong et al. 2021, 2022, 2023c, 2023d). It is difficult to accurately value these non-native species within the aquarium and ornamental trade in the Yellow River Basin, but they comprise the greatest volume sold on the largest online trade platforms (Taobao website 2024).

On the other hand, many non-native species have caused significant negative impacts on local biodiversity, human health and in some cases economic sustainable development (Xiong et al. 2015a; Wang et al. 2016). Non-native fishes are the most common group of introduced species (Fig. 2), and some of these have become serious invasive species (Xiong et al. 2015a, 2017a; Wang et al. 2021). For example, tilapia are the sixth most important aquaculture freshwater fish in China (Xiong et al. 2023a) and have had ecological impacts through competition with native species for food and habitat, predation, hybridization, the introduction of new pathogens, and alteration ecosystem traits (Xiong et al. 2015a). The tilapia species (*Oreochromis mossambicus* and *Oreochromis niloticus*) have established widely distributed feral populations which have outcompeted native endangered native fishes, such as *Oryzias latipes* (Xiong et al. 2015b; Cheng et al. 2018). The Yellow River Basin provides suitable habitats for over 165 freshwater fish species (24 endemic fish species, He et al. 2020) and 135 waterbirds (19 endangered species in IUCN criteria and 34 National Protected Animals, China Green Times website 2024). The invasion of these non-native fish species has potentially influenced the survival of important elements of the native aquatic flora and fauna (Xiong et al. 2015a; Kang et al. 2023).

Non-native aquatic plant species are the second largest of the introduced non-native species groups and they have caused significantly negative economic and ecological impacts (Wang et al. 2016; Macêdo et al. 2024). As de facto ecological engineers, some non-native aquatic plants have escaped and established dense monospecific stands, displacing native aquatic plants and significantly decreasing native biodiversity (fishes, crayfish, snails, amphibians and insects) by changing ecosystem structure, physical and chemical characteristics, and the relationships between plants and animals (Schultz and Dibble 2012; Hussner et al. 2021). Some ornamental aquatic plants, such as parrot's feather, fanwort, yellow bur-head, yellow flag, and water lettuce established large feral populations and displaced some native aquatic plants (such as *Trapa bispinosa*, *Potamogeton crispus*, *Nymphoides peltate*, and *Eleocharis dulcis*) (Xiong et al. 2021, 2022, 2023c, 2023d). Another widely distributed species is smooth cordgrass (*Spartina alterniflora*), which forms dense monocultural stands that significantly decreased biodiversity in coastal mudflats of the Yellow River estuary (Ren et al. 2019; Jiang et al. 2022).

The estuaries of the Yellow River are important mariculture areas for shellfish farming (MARA 1990–2024). Many non-native molluscs have been introduced in the estuaries for mariculture (Xiong et al. 2024b) and have caused significant decreases and even the local extinction of certain native molluscs (Xiong et al. 2024b). For example, some native mollusc species, such as *Hyriopsis cumingii* have nearly disappeared because of hybridization with the non-native mollusc *Sinohyriopsis schlegelii* (Li et al. 2007).

Conclusions

As a first step for comprehensive utilization, control and management of non-native species, assembling a complete and current list and other basic information about them is fundamental (Pyšek et al. 2004; Xiong et al. 2023b). Our study provides the first inventory of non-native aquatic species in the Yellow River Basin, which fills the

gap of scant scientific information and helps effective management to protect native biodiversity, sustainable aquaculture and agriculture developments, and sustained and healthy social and economic development (Lodge et al. 2006; Hudgins et al. 2023). Many non-native species have become important species widely used in aquaculture (such as *Oreochromis niloticus* and *Procambarus clarkii*) and in the aquarium and ornamental trade (such as *Myriophyllum aquaticum* and *Cabomba caroliniana*) in the Yellow River Basin. Additional research is needed to assess risks associated with the introduction of new non-natives species and more individuals of already imported taxa (Xiong et al. 2015a, 2023a; Wang et al. 2016). Non-native species are already widely distributed throughout all regions of the Yellow River Basin, including 230 wetlands nature reserves, comprised of two National Parks, nine National Nature Reserves, 68 local Nature Reserves, 145 National Wetland Parks, and six Provincial Wetland Parks (Sun et al. 2020). Citizen education, field investigations, on-going monitoring, and eradication of non-native species are needed in the Yellow River Basin for more effective management and the control of invasion by non-native species.

Some regions of the Yellow River Basin are located within biodiversity hotspots (Olson and Dinerstein 1998; Myers et al. 2000). Most of the middle and lower reaches of the Yellow River Basin are densely populated areas and are important agriculture and aquaculture regions. We hope that this study will help managers better understand and more comprehensively control invasive non-native species, sustain the conservation of biodiversity, and guide agriculture and aquaculture sustainable development in large watersheds.

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Authors' contributions

WX, KC, and BW conceived the idea and designed the study. WX and WZ designed the methodology. WX, WZ, and ZD carried out the searches and organize the occurrence and environmental datasets, performed the analyses, and prepared the figures. WX, KC, and BW led the writing the manuscript. WX, KC, BW and PAB significantly contributed to the manuscript writing and critical review.

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Supplementary material 1

list of non-native aquaitc species in the Yellow River basin, China

Authors: Wen Xiong

Data type: xlsx

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