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Letter to the editor Open Access

Global freshwater assessment of establishment risk of invasive Alligator gar (*Atractosteus spatula*) and risks to freshwater ecosystems in China

DEAR EDITOR,

The introduction of freshwater fish into areas outside their native range has impacted freshwater ecosystems worldwide. In China, the non-native Alligator gar (*Atractosteus spatula*) fish has attracted attention due to its widespread occurrence and destructive effects on local fish populations, signaling a high potential of invasiveness. Here, we used Species Distribution Modeling (SDM) to assess the invasion risk of this aggressive freshwater predator species across global freshwater networks. Our MaxEnt model predicted the existence of four potential subequatorial invasion hotspots, involving more than 40 countries and regions, with the largest water system at risk of invasion found in China. Risk analysis of Chinese provinces and water basins revealed that high-risk areas were mainly concentrated in the Yangtze River Basin and Pearl River Basin. The global scale of species invasion in freshwater ecosystems suggests that invasion by the Alligator gar is still at an early stage; however, several reported invasion sites are in high-risk areas, indicating considerable danger of colonization and dispersal. We recommend immediate action to amend current Chinese national laws, combined with systematic research and increased public awareness, e.g., wildlife release, for further mitigation of this invasive species. This research should provide guidance for future study and management, not only for Alligator gars, but also other potentially harmful non-native freshwater species.

Global freshwater ecosystems are highly impacted by biological invasions (Bernery et al., 2022). Recently, more than a dozen “monster fish” sightings have been reported in different cities across China, attracting considerable public attention. In one instance, local firefighters spent two days capturing two Alligator gars in Ruzhou, Henan Province, which required draining lake water (Han, 2022). This game and commercial species is one of the largest native fish in North America and is widely distributed in the Mississippi River Basin. Sightings and collections in different countries have increased in recent years. Alligator gars were originally imported into China as pets and ornamental fish, but some were abandoned and released into the wild due to their large size and aggressive appearance. Currently, Alligator gars in China are thought to be primarily confined to parks or other artificial water landscapes (Han, 2022), with wild populations not yet established compared to other invasive aquatic species such as Sailfin catfish (*Pterygoplichthys* spp.) and Red-eared sliders (*Trachemys scripta elegans*) (Deng et al., 2021; Wei et al., 2017).

Alien species are those that have colonized non-native environments as a result of human activity, with some spreading rapidly and posing an invasive threat to local ecosystems (Pyšek et al., 2020). Alien species may have economic or positive ecosystem restoration functions, but invasive alien species (IAS) can cause severe ecological impacts. As an euryphagous fish and top predator, the Alligator gar feeds on native fish and possesses certain specialized traits (e.g., hardened scales and two rows of sharp teeth) that aid its survival in non-native habitats (Manna et al., 2021). Many reports on the invasion of this species have described dramatic declines in native local fish populations. Thus, scientific and systematic mitigation measures are urgently needed to prevent the spread and establishment of this species in non-native regions, including China. To date, however, little is known regarding the current range and risk of expansion of this IAS in the wild.

For aquatic species, accidental invasion typically occurs through unintended wildlife release or transport, resulting in long-range expansion, detrimental impacts on local fauna, and costly management. Thus, prevention is increasingly advocated to mitigate future IAS, rather than managing post-

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invasion impacts (Li et al., 2021). SDM is an efficient and cost-effective approach to help clarify the extent of alien species invasions and prevent further expansion (Huang et al., 2016).

In this study, we used a maximum entropy algorithm (MaxEnt; Phillips et al., 2006) to construct an SDM for the invasive Alligator gar to assess its global invasion risk and ecological requirements for establishment. We combined native distribution records of Alligator gars with geographic, climatic, and streamflow features to construct their ecological niche in North America and assess the risk of invasion in the global inland river networks. We then assessed the risk of invasion in China, providing insights for mitigating invasive freshwater species.

We collected 132 records of the Alligator gar within its native range and 50 records of sightings or captures in other countries based on an extensive review of literature and news reports (Supplementary Table S1). We constructed an SDM combining species occurrence in its native range and 12 environmental predictors, including climatic, topographic, and hydrological variables (Supplementary Table S2), with the modeling unit set to a grided water body network.

We selected the model with the lowest corrected Akaike's information criterion (AICc) by testing different regularization multipliers (RMs). Area under the receiver operating characteristic (AUC) curve and true statistical skill (TSS) were considered as criteria for model validation. Habitable sustainability ranges from the optimized model were interpreted to predict global invasion risk of the Alligator gar and classified using the 10th percentile training presence (10PTP) and maximum training sensitivity plus specificity (MTSS) logistic thresholds. Further details on methods and data sources are provided in the Supplementary Materials.

Overall, the model performed well, showing better discrimination of species geographic patterns than random prediction. The model was constructed with an optimized RM of 3.25, mean AUC of 0.98, and mean TSS of 0.80 (largest with MTSS threshold). Logistic model output was divided into no-risk, low-risk, medium-risk, and high-risk areas by 0.1294 (MTSS threshold), 0.2141 (10PTP threshold), and 0.8. The native model predicted that the geographic distribution of the Alligator gar was confined to the Mississippi River Basin, with a total length of potentially occupied river of 1.2×10^4 km and total area of potentially occupied lake of 1.4 km^2 (above MTSS threshold). Highly suitable native Alligator gar habitat was distributed along the north shore of the Gulf of Mexico and the Mississippi River (Figure 1A).

The response curves indicated that Alligator gars preferred regions with lower mean diurnal range (Bio2), gentler slopes, lower peak streamflow (Q1 and Q50), and higher precipitation of the driest quarter (Bio17). Alligator gars also showed the highest settling potential (invasion risk) where streamflow was less affected by rainfall (higher baseflow recession rate, k), with a mean annual temperature (Bio1) of 22 ℃, temperature seasonality (Bio4) of 600, mean temperature of wettest quarter (Bio8) of 27 ℃, and long-term base flow of 59% of total quantitative streamflow (baseflow index, BFI1). The species showed a significant preference for secondary rivers and lakes under 100 km^2 (Figure 1G). Bio4, Bio1, and elevation had the highest regularized training gains in the modeling process (Supplementary Figure S1A). Elevation had the greatest contribution among variables during modeling, with the Alligator gars showing strong preference for water bodies under 400 m (a.s.l.) (Supplementary Figure S1B).

After projecting the native model to a global scale, four Alligator gar invasion hotspots were identified along the Tropic of Cancer. Among the countries involved, China had the greatest river length and largest lake area at risk of invasion (Figure 1F). Saudi Arabia had the longest high-risk rivers (accounting for more than 8 000 km). The North African hotspot involved Algeria, Mali, Mauritania, and Niger (Figure 1B), with the high-risk area concentrated north of the Niger River. The West Asian and Arabian Peninsula hotspots involved Saudi Arabia, Iran, Iraq, and the United Arab Emirates (Figure 1C), with high-risk areas mainly located around the Persian Gulf. The South Asian hotspot included India, Pakistan, and Nepal (Figure 1D), centered largely on the Indus and Ganges rivers.

The East Asian hotspot mainly encompassed regions in southern China (Figure 1E), where the climate is warm and humid. The Yangtze River, Pearl River, Southeast coast, and Huaihe River were identified as at risk of invasion, with minor areas predicted in the Continental and South basins (Figure 1H). High-risk areas were identified in the Yangtze River Basin and Pearl River Basin (Figure 1I). In total, 20 Chinese provinces were identified as being at risk of Alligator gar invasion, with Guangxi, Jiangxi, Hunan, Hubei, Anhui, Jiangsu, and Guangdong containing larger high-risk areas (Figure 1J). High-risk areas were concentrated along the middle and lower reaches of the Yangtze and Pearl rivers.

The identification of potential IAS invasion areas enables more targeted and cost-effective monitoring. Based on the native model, the Alligator gar showed a strong preference for lower elevations and less seasonal waters, typically found in subequatorial offshore water systems in the Northern Hemisphere (Figure 1F). Our model predicted a total potential invasion area of approximately 3.0×10^5 km of rivers and 5.6×10^4 km^2 of lakes, with high-risk areas accounting for nearly 10%. In those high-risk areas, introduction and dispersal could be caused by fish transport or human release, and therefore strict regulation is urgently needed.

The reported distribution patterns of Alligator gar in China (Figure 1F) suggest that invasion is at an early stage. Of concern, however, several reported southern sites are in high-risk waters, which could mean that the invasion process has already commenced in nearby areas.

The Yangtze River Basin and Pearl River Basin are of particular concern (Figure 1J) given their high proportion of high-risk areas. Compared with the Yellow River Basin, the middle and lower reaches of the Yangtze River and Pearl River are more suitable for Alligator gars. Thus, systematic field studies and corresponding actions are required to quantify the potential dispersal patterns in these basins. Therefore, we recommend the following:

(1) Region- and watershed-specific management and mitigation measures should be implemented following predicted invasion risk evaluation. For high-risk areas, such as Guangxi, Jiangxi, Hunan, Hubei, Anhui, Jiangsu, and Guangdong, and aquatic biodiversity repositories, more

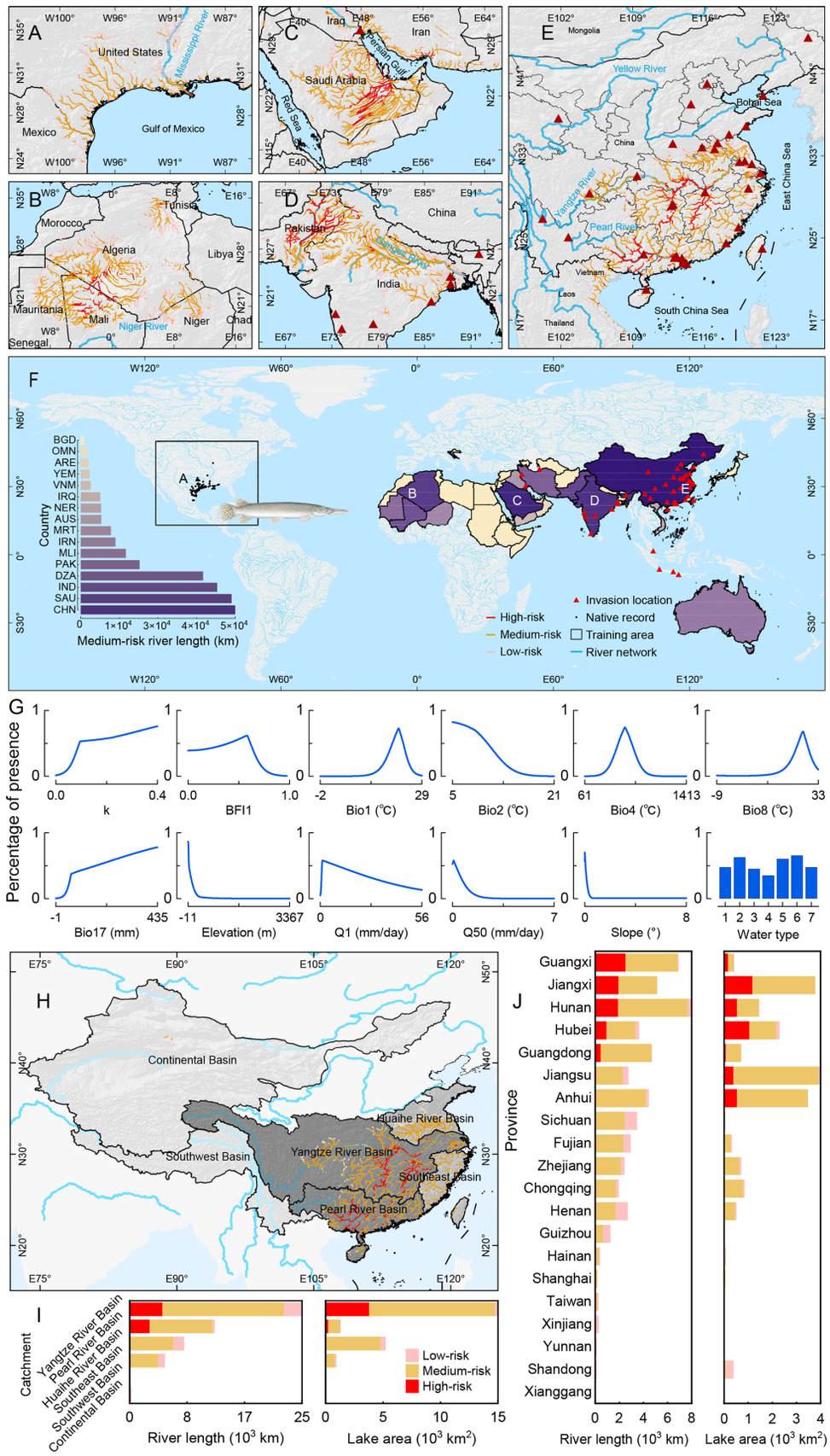

Figure 1 Global invasive risk assessment of Alligator gar and environmental variable responses

advanced technologies are needed for systematic assessment and to determine response mechanisms (Yin et al., 2020). Furthermore, based on our model predictions, the Alligator gar should be included in more comprehensive risk scoring systems (Li et al., 2021).

(2) The original rules and regulations for IAS in China, such as the Biosecurity Act, Law of PRC on the Protection of Wildlife, Law on the Quarantine of Animals and Plants Brought into or Taken Out of the Chinese Territory, and Measures for the Administration of Invasive Alien Species, should be amended to accelerate and strengthen the mitigation of Alligator gar invasion, especially regarding fishery and aquatic biodiversity conservation.

(3) More resources should be devoted to public education regarding inappropriate release of captive animals, which is likely to be the main source of Alligator gars in China. Relevant authorities should advocate for the establishment of a list of alien species deemed harmful to the environment for public education and guidance. The public should also be able to act in a timely manner after encountering the species, given the risk of ecological damage when the population shifts from settlement to range expansion.

In this study, we assessed the global invasion risk of the freshwater Alligator gar. By training a native model combining native population occurrence data and different environmental variables, we projected the native model to a global scale and predicted four potential invasion hotspots in North Africa, West Asia, South Asia, and East Asia, involving more than 40 countries and regions. China showed the largest water system with invasion risk, with high-risk areas concentrated in the Yangtze River Basin and Pearl River Basin. The worldwide invasion report suggests that Alligator gar invasion is at an early stage and greater focus on early prevention and immediate response is critical.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

Conceptualization: Y.H.S., Y.F., and B.C.G.; Data analysis: W.D.X., Z.X.W., and K.S.; Writing: W.D.X., Z.X.W., and Y.H.S.; Supervision & funding acquisition: Y.H.S., Y.F., and B.C.G. All authors read and approved the final version of the manuscript.

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