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Risk Assessment

Current and future risk of invasion by non-native freshwater fishes in a mega-biodiversity country: the Philippines

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Abstract

The Philippines is a mega-biodiversity country hosting a vast number of aquatic species of which most are endemic. With over 7,100 islands making up its territory, the Philippines are home to a remarkable array of fish species. These play a vital role in enriching the country's inland waters biodiversity and some of them are of high economic and commercial value. However, this extremely rich biodiversity is on the brink of collapse. Research in the Philippines has primarily focused on marine and terrestrial ecosystems, highlighting a significant gap in the study of inland waters and its freshwater fishes. In total, 374 freshwater fish species belonging to 29 orders and 78 families have been documented in the Philippines. This large number of fish species faces high extinction risks due to various human-induced impacts including habitat destruction, overfishing and the presence of introduced species. This study investigates the risk of invasiveness of all 64 introduced freshwater fish species currently present in the Philippines. Of these species, 65.6% and 70.3% were ranked as carrying a high or very high risk of invasiveness under current and future climate conditions, respectively. The highest risk species were goldfish *Carassius auratus*, Indonesian snakehead *Channa micropeltes*, largemouth black bass *Micropterus salmoides*, pirapitinga *Piaractus brachypomus*, vermiculated sailfin catfish *Pterygoplichthys disjunctivus* and Amazon sailfin catfish *Pterygoplichthys pardalis*. Given the high conservation value of Philippine freshwater ecosystems, efforts are needed from stakeholders and environmental managers in the mitigation and prevention of the detrimental impacts of the invasive fish species already present, and preventative measures are required to counteract the introduction of any additional non-native species. The results of this study, which represents the first comprehensive risk screening for a specific group of organisms in a country, will serve as a foundation for developing shared regulations to control the international trade of the non-native fish species at higher risk of invasion.

Key words: introduced species, invasive species, risk screening, AS-ISK, climate change

Introduction

The Philippines is a mega-biodiversity country (Mittermeier et al. 2004; Carpenter and Springer 2005) renowned for its abundant terrestrial and marine plant and animal species (Myers et al. 2000; Heaney et al. 2013).

The archipelagic geography of the Philippines encompasses over 406,328 hectares of ecologically and socio-economically important inland waters, including eight RAMSAR-recognised wetlands (Sespeñe et al. 2016; Guerrero 2021). Its freshwater ecosystems are home to hundreds of species, contributing to the country's rich inland water biodiversity (Herre 1953; Lynch et al. 2016; Papa and Briones 2017). These water bodies also provide valuable goods and services to the country's inhabitants (Magbanua et al. 2023). However, the Philippines is also often seen as a country of ecological ruin, with its biodiversity teetering on the brink of collapse (Posa et al. 2008). Philippine freshwater ecosystems confront numerous threats and challenges due to environmental and human-induced pressures, including nutrient enrichment, over-extraction of water sources and the alarming spread of invasive species exacerbated by climate change (Palmer et al. 2015). Among these threats, the introduction of invasive species ranks as the second-highest cause of biodiversity loss in the country after habitat destruction (Guerrero 2021).

In the Philippines, non-native freshwater fishes have been commonly introduced for aquaculture, ornamental trade, recreational fishing and biological control. A recent study documented a total of 374 freshwater fish species, with 64 of these recorded as introduced (Jamandre 2023). The prevalence of negative effects from these non-native species introductions outweighs the beneficial ones (Guerrero 2021). For instance, in Laguna de Bay (Luzon Island) highly cultured fish such as bighead carp *Hypophthalmichthys nobilis* (Richardson, 1845) and Nile tilapia *Oreochromis niloticus* (Norman, 1922), along with ornamental species such as clown featherback *Chitala ornata* (Gray, 1831) and sailfin catfishes *Pterigoplichthys* spp. Gill, 1858, have adversely impacted the native biodiversity of the lake (Bagarinao 2001). Overall, lack of knowledge regarding invasive fish species in the Philippines, combined with the absence of country-wide risk screening studies, poses an underlying threat to this mega-biodiversity country (To et al. 2022; Guerrero 2021; Pagad et al. 2018).

The Philippine government actively addresses the threat of non-native species. For instance, the Wildlife Conservation and Protection Act of 2001 (Section 13) prohibits the introduction of non-native aquatic species to Philippine waters without proper risk evaluation and clearance by the authorities. In addition, government agencies concerned with aquatic wildlife conservation, such as the National Fisheries Research and Development Institute, have adopted the Aquatic Species Invasiveness Screening Kit (AS-ISK: Copp et al. 2016b, 2021) as the officially approved risk screening tool to regulate aquatic wildlife introductions in the country. Further, the Bureau of Fisheries and Aquatic resources, under the Fisheries Administrative Order No. 233, has upheld several mitigation and control measures of aquatic wildlife conservation, which strictly manages the introduction and utilization of non-native species in the country.

In the Philippines, research has primarily focused on marine and terrestrial ecosystems, leaving a notable gap in freshwater ecosystem studies (Bagarinao 2001; Ong et al. 2002). This lack of attention to freshwater fish species has hindered research efforts for the management and conservation of inland waters. This is despite the awareness that many native (endemic) species, some of which remain undiscovered, face high extinction risks due to various human-induced impacts (Posa et al. 2008). In response to this pressing issue, our study aims to address this research gap by conducting a thorough screening of non-native freshwater fish species in the Philippines. By doing so, we seek to provide critical insights for stakeholders and policymakers to develop effective management and conservation strategies tailored to the unique challenges of Philippine inland waters. Moreover, our findings hold broader implications, serving as a model for country-wide screening approaches that can be adapted and applied in other regions grappling with invasive species in freshwater ecosystems.

Materials and methods

Risk screening involved the 64 non-native freshwater fish species recently identified for the Philippines (Jamandre 2023) (Table 1). The AS-ISK v2.3.3 was used to conduct the screenings. This taxon-generic decision support tool complies with the minimum standards for screening non-native species under EC Regulation No. 1143/2014 on the prevention and management of the introduction and spread of invasive species (Roy et al. 2018). This toolkit was recently adopted by the Philippine government, Bureau of Fisheries and Aquatic Resources (Republic of the Philippines 2021). The AS-ISK consists of 55 questions. The first 49 questions comprise the Basic Risk Assessment (BRA) dealing with the biogeographical, historical, biological and ecological traits of the screened species. The last six questions comprise the Climate Change Assessment (CCA). The latter component requires the assessor to identify how projected future climatic conditions are likely to affect the BRA with respect to risks of introduction, establishment, dispersal and impact.

Screenings were conducted by the first author (the assessor) who is knowledgeable of the biology and ecology of the screened species in the Philippines – the risk assessment area. The assessor, who is an expert in invasion biology, conservation biology and ichthyology, has several years' experience in the risk screening of non-native fish species in the Philippines (Gilles et al. 2023). He is also part of the technical working group of the Bureau of Fisheries and Aquatic Resources of the Philippines, which drafted the newly approved fishery order requiring the risk screening of all non-native aquatic species prior to their introduction in the inland waters of the country. For the CCA component, a number of relevant references were consulted (Papa and Briones 2014; Mendoza et al. 2019; Volta and Jeppesen 2021). Screening followed the standard protocol described in Vilizzi et al. (2022a), with the assessor providing

Table 1. Non-native freshwater fish species screened with the Aquatic Species Invasiveness Screening Kit (AS-ISK) for the Philippines. *A priori* categorisation (Outcome: N = non-invasive; Y = invasive) follows the four-step protocol described in Vilizzi et al. (2022a): (1) FishBase (www.fishbase.org); (2) Global Invasive Species Database (GISD: www.iucngisd.org); (3) European Alien Species Information Network (EASIN: https://easin.jrc.ec.europa.eu/easin); (4) Google Scholar literature search. N = no impact/threat; Y = impact or threat; '–' = absent; n.a. = not applicable.

		A priori categorisation				
Species name	Common name	FishBase	GISD	EASIN	Google Scholar	Outcome
Amatitlania nigrofasciata (Günther, 1867)	convict cichlid	Y	–	–	n.a.	Y
Ameiurus catus (Linnaeus, 1758)	white catfish	N	–	N	N	N
Anabas testudineus (Bloch, 1792)	climbing perch	N	–	–	Y	Y
Aplocheilus panchax (Hamilton, 1822)	blue panchax	N	–	–	N	N
Arapaima gigas (Schinz, 1822)	arapaima	N	–	–	N	N
Austrolebias nigripinnis (Regan, 1912)	blackfin pearlfish	N	–	–	N	N
Barbonymus gonionotus (Bleeker, 1849)	silver barb	N	–	–	N	N
Bidyanus bidyanus (Mitchell, 1838)	silver perch	N	–	–	N	N
Carassius auratus (Linnaeus, 1758)	goldfish	Y	Y	N	n.a.	Y
Carassius carassius (Linnaeus, 1758)	crucian carp	Y	–	Y	n.a.	Y
Channa micropeltes (Cuvier, 1831)	Indonesian snakehead	N	–	N	N	N
Channa striata (Bloch, 1793)	striped snakehead	Y	–	–	n.a.	Y
Chitala chitala (Hamilton, 1822)	clown knifefish	N	–	–	N	N
Chitala ornata (Gray, 1831)	clown featherback	N	–	–	Y	Y
Cichla ocellaris Bloch & Schneider, 1801	peacock cichlid	Y	Y	–	n.a.	Y
Cirrhinus cirrhosus (Bloch, 1795)	Mrigal carp	N	–	–	N	N
Cirrhinus mrigala (Hamilton, 1822)	Mrigal carp	N	–	–	N	N
Clarias gariepinus (Burchell, 1822)	North African catfish	Y	Y	N	n.a.	Y
*Colossoma macropom*um (Cuvier, 1816)	cachama	N	–	N	N	N
Coptodon zillii (Gervais, 1848)	redbelly tilapia	Y	–	N	n.a.	Y
Corydoras aeneus (Gill, 1858)	bronze corydoras	N	–	–	N	N
Ctenopharyngodon idella (Valenciennes, 1844)	grass carp	Y	Y	Y	n.a.	Y
Cyprinus carpio Linnaeus, 1758	common carp	Y	Y	N	n.a.	Y
Danio rerio (Hamilton, 1822)	zebra danio	N	–	–	N	N
Fundulus heteroclitus (Linnaeus, 1766)	mummichog	N	–	Y	n.a.	Y
Gambusia affinis (Baird & Girard, 1853)	western mosquitofish	Y	Y	Y	n.a.	Y
Helostoma temminckii Cuvier, 1829	kissing gourami	N	–	–	N	N
Hemichromis bimaculatus Gill, 1862	Mexican mojarra	N	–	–	N	N
Hypophthalmichthys molitrix (Valenciennes, 1844)	silver carp	Y	Y	Y	n.a.	Y
Hypophthalmichthys nobilis (Richardson, 1845)	bighead carp	Y	Y	Y	n.a.	Y
Hypostomus plecostomus (Linnaeus, 1758)	suckermouth catfish	N	–	N	N	N
Ictalurus punctatus (Rafinesque, 1818)	channel catfish	Y	–	N	n.a.	Y
Labeo catla (Hamilton, 1822)	catla	N	–	–	N	N
Labeo rohita (Hamilton, 1822)	roho labeo	N	–	–	N	N
Lepomis cyanellus Rafinesque, 1819	green sunfish	N	–	Y	n.a.	Y
Lepomis macrochirus Rafinesque, 1819	bluegill	Y	–	N	n.a.	Y
Mayaheros urophthalmus (Günther, 1862)	blue tilapia	N	–	–	N	N
Melanotaenia nigrans (Richardson, 1843)	blackbanded rainbowfish	N	–	–	N	N
Micropterus salmoides (Lacepède, 1802)	largemouth black bass	Y	Y	Y	n.a.	Y
Misgurnus anguillicaudatus (Cantor, 1842)	oriental weatherfish	Y	Y	Y	n.a.	Y
Oreochromis aureus (Steindachner, 1864)	blue tilapia	Y	Y	N	n.a.	Y
Oreochromis mossambicus (Peters, 1852)	Mozambique tilapia	Y	Y	Y	n.a.	Y
Oreochromis niloticus (Linnaeus, 1758)	Nile tilapia	Y	Y	Y	n.a.	Y
Oreochromis spilurus (Günther, 1894)	Sabaki tilapia	N	–	–	N	N
Oreochromis urolepis (Norman, 1922)	wami tilapia	N	–	N	N	N
Osphronemus goramy Lacepède, 1801	giant gourami	N	–	–	N	N
Osteochilus vittatus (Valenciennes, 1842)	Sumatra barb	N	–	–	N	N
Osteoglossum bicirrhosum (Cuvier, 1829)	arawana	N	–	–	N	N
Pangasianodon hypophthalmus (Sauvage, 1878)	striped catfish	N	–	N	N	N
Parachromis managuensis (Günther, 1867)	jaguar guapote	Y	–	–	n.a.	Y
Piaractus brachypomus (Cuvier, 1818)	pirapitinga	N	–	N	N	N
Poecilia latipinna (Lesueur, 1821)	sailfin molly	Y	–	–	n.a.	Y

Table 1. (continued).

		A priori categorisation				
Species name	Common name	FishBase	GISD	EASIN	Google Scholar	Outcome
Poecilia reticulata Peters, 1859	guppy	Y	Y	Y	n.a.	Y
Poecilia sphenops Valenciennes in Cuvier and Valenciennes, 1846	molly	N	–	N	N	N
Pterygoplichthys disjunctivus (Weber, 1991)	vermiculated sailfin catfish	Y	Y	–	n.a.	Y
Pterygoplichthys pardalis (Castelnau, 1855)	Amazon sailfin catfish	N	Y	N	n.a.	Y
Puntigrus tetrazona (Bleeker, 1855)	Sumatra barb	N	–	–	N	N
Pygocentrus nattereri Kner, 1858	red piranha	N	–	–	N	N
Rasbora borapetensis Smith, 1934	blackline rasbora	N	–	–	N	N
Sarotherodon melanotheron Rüppell, 1852	blackchin tilapia	Y	–	–	n.a.	Y
Scleropages formosus (Müller & Schlegel, 1840)	Asian bonytonque	N	–	–	N	N
Trichopodus leerii (Bleeker, 1852)	pearl gourami	N	–	–	N	N
Trichopodus pectoralis Regan, 1910	snakeskin gourami	Y	–	–	n.a.	Y
Trichopodus trichopterus (Pallas, 1770)	three spot gourami	N	–	–	N	N

for each question a response, confidence level and justification (Vilizzi and Piria 2022). This results in two outcome scores: BRA and BRA+CCA. A score < 1 categorises the species as carrying a "low risk" of invasiveness in the risk assessment area. A score ≥ 1 categorises the species as "medium risk" or "high risk". The distinction between medium and high risk is defined using a calibrated threshold that is obtained by Receiver Operating Characteristic (ROC) curve analysis (Vilizzi et al. 2022a, 2022b). An *ad hoc* threshold was also used to distinguish "very high risk" species within those classified as high risk (cf. Gilles et al. 2023).

The *a priori* categorisation of species required for ROC curve analysis was implemented as per the standard protocol (Vilizzi et al. 2022a) (Table 1). Fitting of the ROC curve was with pROC (Robin et al. 2011) for R x64 v4.3.2 (R Development Core Team 2024). Permutational ANOVA with normalisation of the data was used to test for differences in the confidence factor (CF: see Vilizzi et al. 2022a) between the BRA and BRA+CCA. This used a Bray-Curtis dissimilarity measure, 9999 unrestricted permutations of the raw data, and with statistical effects evaluated at α = 0.05. Following identification of the threshold score, evaluation of the risk classifications to identify false-positive and false-negative rankings was not applied to the medium-risk species because their further evaluation in a comprehensive risk assessment depends on policy and management priorities and the availability of financial resources (Copp et al. 2016a).

Results

The ROC curve resulted in an AUC of 0.7681 (0.6518–0.8845 95% CI) and the threshold of 27.5 was used for calibration of the risk outcomes to distinguish between medium-risk and high-risk species (Table 2; refer to the Supplementary online material Appendix 1 for reports of the 64 screened species).

Based on the BRA scores (Table 2, Figure1a, c), 42 (65.6%) species were ranked as high risk, 21 (32.8%) as medium risk and 1 (1.6%) as low risk. Of the

Table 2. Risk ranks and outcomes for the non-native freshwater fish species screened with the AS-ISK for the Philippines. For each species, the following information is provided: *a priori* categorisation of invasiveness (N = non-invasive; Y = invasive: see Table 1), Basic Risk Assessment (BRA) and BRA + Climate Change Assessment (BRA+CCA) scores with corresponding risk ranks based on a calibrated threshold of 27.5 (L = Low; M = Medium; H = High; VH = Very high, based on an *ad hoc* threshold ≥ 50), classification (Class: FP = false positive; TN = true negative; TP = true positive; '–' = not applicable as medium-risk: see text for details), CCA as difference between BRA+CCA and BRA scores, and confidence factor (CF). Risk outcomes for the BRA scores (intervals): L [−20, 1[; M, [1, 27.5[; H]27.5, 50[; VH [50, 72]. Risk outcomes for the BRA+CCA scores: L, [−32, 1[; M [1, 34.5[; H]27.5, 50[; VH [50, 82]. Note the reverse bracket notation indicating an open interval.

		BRA			BRA+CCA				CF		
Species name	*A priori*	Score	Rank	Class	Score	Rank	Class	CCA	Total	BRA	CCA
Amatitlania nigrofasciata	Y	39.0	H	TP	49.0	H	TP	10.0	0.75	0.78	0.58
Ameiurus catus	N	13.5	M	–	11.5	M	–	−2.0	0.66	0.67	0.58
Anabas testudineus	Y	18.0	M	–	24.0	M	–	6.0	0.81	0.82	0.71
Aplocheilus panchax	N	−2.0	L	TN	0.0	L	TN	2.0	0.63	0.64	0.50
Arapaima gigas	N	27.0	M	–	39.0	H	FP	12.0	0.67	0.66	0.75
Austrolebias nigripinnis	N	43.0	H	FP	55.0	VH	FP	12.0	0.83	0.83	0.79
Barbonymus gonionotus	N	30.0	H	FP	34.0	H	FP	4.0	0.81	0.82	0.75
Bidyanus bidyanus	N	7.0	M	–	7.0	M	–	0.0	0.73	0.73	0.75
Carassius auratus	Y	53.0	VH	TP	65.0	VH	TP	12.0	0.87	0.88	0.79
Carassius carassius	Y	33.0	H	TP	45.0	H	TP	12.0	0.85	0.87	0.75
Channa micropeltes	N	50.0	VH	FP	62.0	VH	FP	12.0	0.77	0.77	0.79
Channa striata	Y	28.0	H	TP	36.0	H	TP	8.0	0.87	0.86	0.96
Chitala chitala	N	41.0	H	FP	41.0	H	FP	0.0	0.73	0.72	0.75
Chitala ornata	Y	41.0	H	TP	41.0	H	TP	0.0	0.75	0.74	0.75
Cichla ocellaris	Y	32.0	H	TP	36.0	H	TP	4.0	0.70	0.70	0.67
Cirrhinus cirrhosus	N	34.0	H	FP	46.0	H	FP	12.0	0.86	0.85	0.96
Cirrhinus mrigala	N	5.0	M	–	7.0	M	–	2.0	0.65	0.67	0.54
Clarias gariepinus	Y	43.5	H	TP	51.5	VH	TP	8.0	0.70	0.69	0.71
Colossoma macropomum	N	33.0	H	FP	39.0	H	FP	6.0	0.85	0.86	0.83
Coptodon zillii	Y	43.0	H	TP	55.0	VH	TP	12.0	0.82	0.83	0.75
Corydoras aeneus	N	25.0	M	–	29.0	H	FP	4.0	0.70	0.69	0.75
Ctenopharyngodon idella	Y	39.0	H	TP	39.0	H	TP	0.0	0.87	0.86	0.96
Cyprinus carpio	Y	48.0	H	TP	60.0	VH	TP	12.0	0.86	0.86	0.83
Danio rerio	N	45.0	H	FP	49.0	H	FP	4.0	0.67	0.68	0.63
Fundulus heteroclitus	Y	22.0	M	–	22.0	M	–	0.0	0.70	0.72	0.50
Gambusia affinis	Y	45.0	H	TP	57.0	VH	TP	12.0	0.85	0.85	0.83
Helostoma temminckii	N	7.0	M	–	11.0	M	–	4.0	0.65	0.66	0.58
Hemichromis bimaculatus	N	15.0	M	–	19.0	M	–	4.0	0.65	0.66	0.58
Hypophthalmichthys molitrix	Y	49.0	H	TP	57.0	VH	TP	8.0	0.88	0.88	0.88
Hypophthalmichthys nobilis	Y	35.0	H	TP	39.0	H	TP	4.0	0.85	0.85	0.88
Hypostomus plecostomus	N	19.5	M	–	11.5	M	–	−8.0	0.60	0.61	0.58
Ictalurus punctatus	Y	39.0	H	TP	51.0	VH	TP	12.0	0.87	0.88	0.75
Labeo catla	N	16.0	M	–	16.0	M	–	0.0	0.68	0.70	0.50
Labeo rohita	N	5.0	M	–	9.0	M	–	4.0	0.70	0.71	0.63
Lepomis cyanellus	Y	46.0	H	TP	52.0	VH	TP	6.0	0.83	0.85	0.63
Lepomis macrochirus	Y	44.0	H	TP	48.0	H	TP	4.0	0.83	0.86	0.63
Mayaheros urophthalmus	N	48.0	H	FP	58.0	VH	FP	10.0	0.80	0.79	0.92
Melanotaenia nigrans	N	5.0	M	–	−3.0	L	TN	−8.0	0.70	0.66	0.96
Micropterus salmoides	Y	53.0	VH	TP	61.0	VH	TP	8.0	0.90	0.89	1.00
Misgurnus anguillicaudatus	Y	29.0	H	TP	35.0	H	TP	6.0	0.75	0.76	0.75
Oreochromis aureus	Y	45.0	H	TP	57.0	VH	TP	12.0	0.92	0.92	0.88
Oreochromis mossambicus	Y	45.0	H	TP	57.0	VH	TP	12.0	0.88	0.88	0.88
Oreochromis niloticus	Y	37.0	H	TP	49.0	H	TP	12.0	0.87	0.87	0.88
Oreochromis spilurus	N	17.0	M	–	17.0	M	–	0.0	0.71	0.68	0.92
Oreochromis urolepis	N	42.0	H	FP	50.0	VH	FP	8.0	0.86	0.86	0.88
Osphronemus goramy	N	47.0	H	FP	53.0	VH	FP	6.0	0.77	0.78	0.75
Osteochilus vittatus	N	12.0	M	–	22.0	M	–	10.0	0.64	0.63	0.71
Osteoglossum bicirrhosum	N	7.0	M	–	11.0	M	–	4.0	0.62	0.63	0.54

Table 2. (continued).

		BRA			BRA+CCA				CF		
Species name	*A priori*	Score	Rank	Class	Score	Rank	Class	CCA	Total	BRA	CCA
Pangasianodon hypophthalmus	N	42.0	H	FP	54.0	VH	FP	12.0	0.88	0.88	0.88
Parachromis managuensis	Y	46.0	H	TP	58.0	VH	TP	12.0	0.84	0.84	0.88
Piaractus brachypomus	N	53.0	VH	FP	65.0	VH	FP	12.0	0.71	0.70	0.75
Poecilia latipinna	Y	41.0	H	TP	53.0	VH	TP	12.0	0.86	0.87	0.79
Poecilia reticulata	Y	41.0	H	TP	53.0	VH	TP	12.0	0.62	0.62	0.63
Poecilia sphenops	N	40.0	H	FP	52.0	VH	FP	12.0	0.85	0.86	0.79
Pterygoplichthys disjunctivus	Y	54.0	VH	TP	66.0	VH	TP	12.0	0.80	0.81	0.75
Pterygoplichthys pardalis	Y	54.0	VH	TP	66.0	VH	TP	12.0	0.77	0.77	0.75
Puntigrus tetrazona	N	29.0	H	FP	41.0	H	FP	12.0	0.67	0.66	0.75
Pygocentrus nattereri	N	36.0	H	FP	38.0	H	FP	2.0	0.67	0.68	0.58
Rasbora borapetensis	N	9.0	M	–	9.0	M	–	0.0	0.63	0.63	0.67
Sarotherodon melanotheron	Y	44.0	H	TP	56.0	VH	TP	12.0	0.85	0.85	0.88
Scleropages formosus	N	14.0	M	–	18.0	M	–	4.0	0.61	0.63	0.50
Trichopodus leerii	N	15.5	M	–	3.5	M	–	−12.0	0.63	0.62	0.75
Trichopodus pectoralis	Y	16.0	M	–	16.0	M	–	0.0	0.85	0.85	0.88
Trichopodus trichopterus	N	25.5	M	–	37.5	H	FP	12.0	0.65	0.65	0.67

30 species categorised *a priori* as invasive, 27 were ranked as high risk (true positives), and of the 34 species categorised *a priori* as non-invasive, 15 were ranked as high risk (false positives). Of the 21 medium-risk species, 18 were *a priori* non-invasive and three invasive.

Based on the BRA+CCA scores (Table 2, Figure 1b, d), 45 (70.3%) species were ranked as high risk, 17 (26.6%) as medium risk and 2 (3.1%) as low risk. Of the *a priori* invasive species, 27 were ranked as high risk (true positives), and of the *a priori* non-invasive species, 18 were ranked as high risk (false positives). Of the 17 medium-risk species, 14 were *a priori* non-invasive and three invasive.

Based on an *ad hoc* threshold ≥ 50, there were six very high-risk species for both the BRA and BRA+CCA [i.e. from higher to lower score: Amazon sailfin catfish *Pterygoplichthys pardalis* (Castelnau, 1855), vermiculated sailfin catfish *Pterygoplichthys disjunctivus* (Weber, 1991), largemouth bass *Micropterus salmoides* (Lacepède, 1802), goldfish *Carassius auratus* (Linnaeus, 1758), pirapitinga *Piaractus brachypomus* (Cuvier, 1818) and Indonesian snakehead *Channa micropeltes* (Cuvier, 1831)] and an additional 19 for the BRA+CCA only (Table 2, Figure 1a, c). The number of high-risk species increased from 42 (65.6%) under the BRA to 45 (70.3%) under the BRA+CCA and that of the very high-risk species increased from 6 (9.4%) to 25 (39.1%). The CCA resulted in an increase in the BRA score (cf. BRA+CCA score) for 51 (79.7%) species, in no change for 9 (14.1%) and in a decrease for 4 (6.3%) (Table 2).

The mean CF_{Total} was 0.763 ± 0.012 SE, the mean CF_{BRA} 0.765 ± 0.012 SE and the mean CF_{CCA} 0.745 ± 0.016 SE, hence in all cases indicating high confidence. There was no difference between mean CF_{BRA} and mean CF_{CCA} ($F^{\#}_{1,126} = 0.94$, $P^{\#} = 0.333$; # = permutational value).

Discussion

Risk outcomes

This study is the first comprehensive risk screening of all non-native freshwater fish species in the Philippines and at the global level is the first study of this kind for a specific group of organisms. The six species consistently posing the highest risk of invasion (*Carassius auratus*, *Channa micropeltes*, *Micropterus salmoides*, *Piaractus brachypomus*, *Pterygoplichthys disjunctivus* and *Pterygoplichthys pardalis*) indicate the need for appropriate investigation into measures for their management and control. This is even more crucial in view of climate change and the high likelihood of increased risk of invasiveness for an additional 19 species.

Carassius auratus is native to China and has been introduced to freshwater environments worldwide (Lever 1996; Copp et al. 2008; Takada et al. 2010). In the Philippines, it has been imported as an ornamental or pet fish, commonly used in aquariums (Gilles et al. 2023). The species' widespread distribution across the country has been aided by its resilience, omnivorous diet, minimal protein requirements, aesthetic appeal and use in aquaculture. Its omnivorous diet allows it to consume a wide range of food sources, as commonly observed in successful long-term invasions (Tonella et al. 2017). Furthermore, its minimal protein requirements allow it to thrive in nutrient-poor waters, enhancing its invasive potential. The presence of *C. auratus* has been linked to detrimental effects on the environment such as increased water turbidity, algal blooms, competition with indigenous fish species, and in some cases cohabitation with other non-native aquatic species (Richardson and Whoriskey 1992; Copp et al. 2010; Santos et al. 2018; To et al. 2022). In the Philippines, *C. auratus* has established itself in various freshwater habitats, including the rivers Ambacan, Layog, Leyte and Trinidad, as well as Lake Taal and Laguna de Bay (Mutia et al. 2018).

Channa micropeltes, locally known as "black mask", is native to Thailand. Its economic significance stems mainly from capture fisheries in many parts of Asia, including the Philippines. This species has been reported from Lake Taal and Pantambangan Reservoir (Guerrero 2014; Gilles et al. 2023). Limited information is available regarding the specific diet of *Channa micropeltes* or channids in general. However, this species is widely recognised as a highly predatory piscivore and is considered the "most ravenous" of all channids (Ng and Lim 1990). Furthermore, *C. micropeltes* may attack and kill fish without consuming them (Roberts 1989). This species possesses enlarged, knife-like canine teeth with two cutting edges arranged perpendicular to the body axis, allowing it to shear sections of flesh from large prey (Courtenay and Williams 2004). This is a potential threat to local ecosystems if introduced outside its native range (Gilles et al. 2023). *Channa micropeltes* is an obligate air-breather found in lowland rivers and swamps, typically associated with deep water bodies (Courtenay and Williams 2004). It inhabits large streams and canals with standing or slowly flowing water, its diet primarily consists of fish, although it also consumes some crustaceans, and breeding occurs in small streams with dense vegetation (Kottelat and Widjanarti 2005). In the Philippines, because of its adaptability and ability to thrive in various aquatic environments, *C. micropeltes* has been identified as an invasive species in several regions where it has been introduced (Osathanunkul and Minamoto 2021; To et al. 2022). This species should therefore be closely monitored to limit its invasive potential, especially under climate change conditions.

Micropterus salmoides is considered one of the 100 worst invasive species in the world (Costantini et al. 2023). In the Philippines, this species was introduced (reportedly in 1985) for recreational or sport fishing and is thought to have successfully established itself in Lake Caliraya (Laguna). Currently, there is no report on the invasiveness of this species. *Micropterus salmoides* exhibits broad environmental adaptability, enabling its survival in diverse native habitats as well as ecosystems where it has become invasive. It usually inhabits various aquatic environments such as lakes, ponds, swamps and backwaters, as well as pools within creeks and rivers (Page and Burr 2011). It is typically found in areas with muddy or sandy substrata and frequently encountered in reservoirs (Page and Burr 2011). It tends to favour calm, clear waters with dense vegetation along the banks. *Micropterus salmoides* is a generalist carnivore primarily feeding during the day and consuming mainly nearshore organisms found frequently in freshwater habitats. Young individuals primarily eat invertebrates, but their diet shifts to being dominated by fish as they age. Cannibalism can occur, particularly among age-0 individuals with significant variability in growth rate (Scott and Crossman 1973). During spawning, and when water temperatures fall below 5 °C or rise above 37 °C, individuals cease feeding (Costantini et al. 2023; Díaz et al. 2007). Nest construction occurs at depths ranging from 25 mm to 203 mm and males become aggressive and territorial building their nests on muddy bottoms of shallow water (Page and Burr 2011; Costantini et al. 2023). *Micropterus salmoides* has been introduced widely as a game fish in many countries. The detrimental effects of this species on host ecosystems result from its predation and competition with respect to the native fauna. These negative consequences are strongly dependent on the nature of the environment and the biological characteristics of other species (Costantini et al. 2023).

Piaractus brachypomus, locally known as "pacu", originates from the Amazon basin (Escobar et al. 2019). Records indicate its introduction to Asia, including China, Malaysia and Taiwan, primarily for ornamental purposes (Cagauan 2007; Chan et al. 2019). In the Philippines, there are reports of *P. brachypomus* being present in various inland water bodies since the 1980s (Cagauan 2007; To et al. 2022; Gilles et al. 2023; Jamandre 2023). Initially introduced for ornamental purposes due to its wide tolerance to environmental changes, this species has successfully adapted and thrived in the Philippines. *Piaractus brachypomus* mainly feeds on plants and detritus, zooplankton, insects, snails and decaying plants. Some individuals are carnivorous and possess a powerful dentition that can crush hard food and cause serious harm to humans (Cagauan and Joshi 2002; Velasco-Hogan et al. 2021). Morphologically, *P. brachypomus* can attain a maximum length of 45 cm and an average weight of 25–30 kg, making it a candidate for displacing other species (Cagauan 2007). Due to its potential as an aggressive predator, there are concerns about its becoming further invasive if released and established in other water bodies of the country (Cagauan 2007; Gilles et al. 2023).

Pterygoplichthys disjunctivus and *P. pardalis* are considered among the most successful freshwater invasive species worldwide (Hubilla et al. 2008; To et al. 2022). They have spread to 21 countries in five continents, leading to various negative impacts on the environment with severe socio-economic consequences. Documented impacts include displacement of native and economically important species, soil erosion, increased water turbidity, damage to fishing gear, competition for food, introduction of parasites, and accumulation of coliform bacteria and heavy metals (Chavez et al. 2006a; Hubilla et al. 2008; Orfinger and Goodding 2018). The successful introduction and invasion of these two species are largely attributed to their biological characteristics, with high fecundity, parental care, rapid growth and a long lifespan, which contribute to their reproduction, survival and dispersal (Orfinger and Goodding 2018; To et al. 2022; Gilles et al. 2023). *Pterygoplichthys disjunctivus* and *P. pardalis* also possess broad physiological tolerance to factors like salinity, pH levels and hypoxia, enabling them to thrive in polluted and high salinity environments (To et al. 2022). Their enlarged, hyper-vascularised stomach allows them to breathe air and survive out of water for extended periods, while their armoured plates and strong spines provide protection from predators (Orfinger and Goodding 2018). Additionally, their popularity in the ornamental trade and aquaculture contributes to their high propagule pressure, increasing the likelihood of their introduction into new habitats. Similar climatic conditions between their native and introduced ranges also play a significant role in their successful establishment and invasion (Orfinger and Goodding 2018; To et al. 2022; Gilles et al. 2023). In the Philippines, these two species have spread throughout the country for decades, including Laguna de Bay and its surrounding lakes and rivers in Luzon Island, as well as the Agusan Marsh in Agusan del Sur (Mindanao), Lake Paitan in Nueva Ecija and Marikina River in Metro Manila (Chavez et al. 2006a; Hubilla et al. 2008; Guerrero 2014).

Climate change

Climate change is predicted to drive significant changes across the Philippines in the near future (Gilles et al. 2023). The consistent increase in the number of high-risk species observed in this study after accounting for projected climate conditions indicates that these species must be subjected to strict management and control across Philippine inland waters. However, there remains a notable scarcity of literature regarding the influence of climate change on future invasions by these freshwater fish species.

On a broader scale, climate change can impact on the invasiveness of freshwater fish (Vilizzi et al. 2021). An increase in temperature has been shown to influence the extent of recruitment in various fish species, particularly warm water ones such as *Micropterus salmoides*. Studies have shown that this species can thrive in water temperatures ranging from 10 to 32 °C (Díaz et al. 2007). Similarly, *Pterygoplichthys disjunctivus* and *P. pardalis* have a wide tolerance to changing temperatures (Guerrero 2014; To et al. 2022; Gilles et al. 2023). This is evident as this Genus is thought to be one of the most successful freshwater invasive taxa worldwide, with several occurrences of various negative environmental and socio-economic impacts (Orfinger and Goodding 2018; To et al. 2022).

Close climate matching was generally found in this study for the higher risk species between their native range and the risk assessment area. A similar projected response to extreme temperatures and climate matching is expected for *Carassius auratus*, *Channa macropeltes* and *Piaractus brachypomus*. Specifically, increased risks of entry, establishment and dispersal are predicted for these species (Courtenay and Williams 2004; Di Santo et al. 2018; Carosi et al. 2019; Jia et al. 2019; Giao et al. 2022). It is also anticipated that climate change will impact their introduction pathways (Costantini et al. 2023). Areas conducive to their aquaculture are projected to shift, potentially altering the regions where these species are cultivated and consequently facilitating new introductions (Rahel and Olden 2008).

Overall, climate change is expected to open up new ecological niches for invasive species (Vilizzi et al. 2021). In inland waters of the Philippines, these shifts in ecological niches could also lead to new possibilities for hybridisation (Muhlfeld et al. 2017). Such scenarios may ultimately result in biodiversity loss (i.e. species displacement and extinction), ecosystem destruction (i.e. habitat degradation and functional feeding group shifts) and compromised ecosystem services (i.e. poor social, economic and cultural provisions).

Understanding the impact and future implications of invasive species under climate change needs a comprehensive and holistic approach. Based on the results of this study, future research should investigate the following ecological aspects:

1) Temperature change and fish physiology – This will investigate how rising temperatures under climate change predictions affect the metabolism, growth rate and reproductive cycle of invasive fish species compared to native species. This will also allow to determine if warmer waters can create more favourable conditions for invasive species to outcompete native species.
2) Range shifts and habitat suitability – This will evaluate how changing climate conditions influence the geographical range shifts of invasive fish species. Furthermore, this will assess alterations in habitat suitability for both invasive and native fish species due to changes in water temperature, oxygen levels and salinity.
3) Impact on ecosystem dynamics – This will explore the cascading effects of fish invasiveness on food webs, nutrient cycling and ecosystem stability in the context of climate change. It will also investigate how invasive species may disrupt predator–prey relationships and the overall biodiversity of aquatic ecosystems.
4) Interactions with other stressors – This will investigate the combined effects of climate change and other human-induced stressors, such as pollution and habitat fragmentation, on fish invasiveness. It will also help understand how these interactions might exacerbate the spread and impact of invasive species.
5) Predictive modelling – This will utilise predictive models to forecast future invasions under various climate change scenarios as well as identify potential hotspots for future invasions so as to prioritise areas for monitoring and management efforts.
6) Adaptation and mitigation strategies – This will develop adaptive management strategies to mitigate the impacts of climate change on fish invasiveness, explore the potential for using native species restoration, habitat modification and targeted removal of invasive species as mitigation measures.

By focusing on the above aspects, future studies will be able to provide a comprehensive understanding of the interactions between climate change and fish invasiveness, ultimately aiding in the development of effective management and conservation strategies.

Management considerations

Invasive fish species in Philippine freshwater ecosystems have resulted in various impacts including siltation and destruction of riverine habitats as well as declines in native, endemic and economically important fishes (Cuvin-Aralar 2016; Santos et al. 2018; Jumawan et al. 2011). This has involved economic losses to local fisherfolk trough damage of gill nets and fish corrals (Guerrero 2014; Chavez et al. 2006b; Casal et al. 2007; Hubilla et al. 2008). Given these threats, the Philippines: (i) has an existing Fisheries Code from 1998 (i.e. Republic Act No. 8550) that prohibits the introduction of non-native aquatic species without sound ecological, biological and environmental justification; and (ii) has recently adopted the AS-ISK in the amended Fisheries Office Order series of 202 of the Bureau of Fisheries and Aquatic Resources (FOO No. 043: Republic of Philippines 2021) that provides guidelines on risk screening before introduction of any new species.

Despite existing policies and guidelines, the proliferation and impact of invasive species across the country has been extensibely documented (Bradecina 2008; Lam and Sia 2009; Guerrero 2014, Briones et al. 2016; To et al. 2022; Gilles et al. 2023). The present study underscores actions needed to prevent further ecological and economic harm caused by non-native freshwater fish species in the Philippines. To meet this objective, it is imperative to enhance current regulations and procedures governing the importation of live fish. This can be achieved by adopting appropriate measures as part of an overall, multi-faceted strategy that would include: (i) further utilisation of the AS-ISK for accurate evaluation of the risks associated with the introduction and spread of potentially invasive species; (ii) establishment by the Bureau of Fisheries and Aquatic Resources of a permanent Import Risk Analysis Panel to evaluate applications for the importation of live fish together with dedicated screening and quarantine facilities at international points of entry (Republic of the Philippines 2003); (iii) prevention of unauthorised spread of freshwater fish species by conducting rigorous and consistent monitoring of aquarium pet shops nationwide; (iv) implementation of ecological impact studies and research, in collaboration with local government units, academia, local communities including fisherfolks, and aquatic resources management councils, aimed at identifying mitigation measures to control and prevent the spread of invasive fish species across the country; (v) establishment of a comprehensive Information, Education, and Communication campaign via mass media platforms to highlight the detrimental effects of invasive fish species and raise public awareness regarding the importance of responsible care for aquarium fish pets and environmental conservation.

Author contributions

Study conceptualisation: A.S. Gilles Jr, L. Vilizzi; Data preparation: A.S. Gilles Jr, J.M. Bate; Data analysis: L. Vilizzi; Writing the article: A.S. Gilles Jr, J.M. Bate, E.M Peralta, R.T.B. Pavia Jr., L. Vilizzi.

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Data availability statement

All required data/information are provided in the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Appendix 1. AS-ISK report for the 64 screened species.

This material is available as part of online article from:
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