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RESEARCH PAPER

Risk of invasiveness of non-native fishes can dramatically increase in a changing climate: The case of a tropical caldera lake of conservation value (Lake Taal, Philippines)

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Abstract. In the Philippines, trade in non-native aquatic organisms for ornamental purposes and food consumption has been responsible for their large-scale importation since the 1940s. These non-native organisms, and especially invasive fishes, represent one of the major threats to global biodiversity. However, little is known of the potential threats they pose to native species and ecosystems in the Philippines, where a sound risk analysis strategy is needed to control and manage non-native species. As a case study, non-native freshwater fish species, both extant and horizon, were screened with the Aquatic Species Invasiveness Screening Kit (AS-ISK) for their risk of being or becoming invasive in Lake Taal – a volcanic crater lake of conservation value. Of the 45 species (13 extant and 32 horizon), 68.9% and 91.1% were ranked as high or very high risk, respectively under current and future climate conditions. This study, which provided evidence that led the Philippines government to adopt the AS-ISK decision-support tool for identifying potentially invasive aquatic species in other water bodies of the country, highlights the need for a comprehensive management strategy to avoid future non-native species introductions and mitigate adverse impacts from extant non-native species.

Key words: alien species, horizon scanning, risk screening, AS-ISK, decision-support tools

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Introduction

In view of the potential adverse impacts of biological invasions on aquatic ecosystems (e.g. Pimentel et al. 2005, Dudgeon et al. 2006, Vilà & Hulme 2017, Renault et al. 2022), the identification of potentially invasive non-native species, both extant and future, is crucial for informing stakeholders and environmental managers of the associated risks. This is necessary for informing policy and management decisions to protect inland waters and formulate rehabilitation and restoration strategies (D'Antonio & Meyerson 2002, Rahel & Olden 2008). Furthermore, measures to prevent the entry of non-native fishes into a new area, as well as strategies for rapid response and mitigation in the case of their entry, will be more effective if species likely to be invasive are identified prior to their introduction (Simberloff et al. 2013). To this end, several risk screening/identification and assessment methods have been developed, though it remains a difficult task to identify and assess the risks posed by many non-native species due to a lack of relevant information (Leung et al. 2012). Furthermore, the attitude towards non-native species is a continually evolving process that varies according to current societal values. At the same time, the public perception of risk is something that cannot be ignored by any government or ruling body. To gain public support in the fight for conservation of native biodiversity, the message needs to be clear, detailed and educational.

In Southeast Asia, the number of non-native fish species introduced and established over recent decades has increased considerably (De Silva 1989, Pallewatta et al. 2003, Welcomme & Chavalit Vidthayanom 2003), with 159 non-native fish species having been introduced into the Philippines alone since 1905 (Casal et al. 2007). The freshwater fish fauna of the Philippine archipelago is relatively depauperate due to biogeographic factors, with many freshwater habitats devoid of, or occupied by few, fish species. At the same time, information on the potential of non-native freshwater fishes to become invasive in the Philippines is currently limited to published reports; this despite the fact that the Philippines possesses more than 100 lakes, representing just over 0.5% (i.e. approx. 200,000 ha) of the country's surface area (Guerrero 2001, Mercene-Mutia 2001). Most of these water bodies consist of volcanic crater or tectonic lakes, which, despite their importance as natural resources, have received little study. The best known of the Philippines' crater lakes is Lake Taal (Fig. 1), due to its continued volcanic activity and its endemic freshwater sardinella ("tawilis") *Sardinella tawilis*. Despite the efforts of private and government agencies to protect Lake Taal, sustained adverse impacts on the lake's limnology have been exacerbated in recent years by an increasing presence of non-native species (Datinguinoo 2005, Mutia et al. 2013). This is of concern as endemic species tend to be most threatened by non-native species (Gurevitch & Padilla 2004), especially when invasive (e.g. Smith & Darwall 2006).

The decline of the endemic *S. tawilis* (Mutia et al. 2018, Santos et al. 2018) highlights the need to establish a non-native species risk management strategy to inform environmental protection policy, further research, and decisions on the formulation and strict implementation of conservation strategies. The aim of this study was to identify which of the extant and potential future (horizon) non-native freshwater fishes are likely to be, or to become, invasive in Lake Taal under current and future climate conditions. The outcomes of this study are intended to inform, and contribute to, the management and conservation of a critically threatened lake ecosystem in the Philippines. These outcomes will also serve as a reference point for similar future screening studies in other Philippine water bodies.

Methods

Lake Taal, the risk assessment area, is the third largest lake in the Philippines (area approx. 24,356 ha). Located in the caldera of an ancient volcano on Luzon Island, Lake Taal has an island at its centre and therefore consists of two basins, a shallower northern basin, where the practice of fish cage aquaculture is concentrated, and a deeper southern basin. Lake Taal provides numerous local ecosystem services, including aquaculture, recreational activities, navigation, tourism and water supply. Since the 1970s, aquacultural activities in the northern basin have been increasing annually at a rate of 9.2%. In addition to the endemic *S. tawilis*, important members of the fish fauna include the native tank goby *Glossogobius giuris* and two species for which native status is unconfirmed, namely the striped snakehead *Channa striata* and the bighead catfish *Clarias macrocephalus* (Corpuz et al. 2016, Mutia et al. 2018, Santos et al. 2018). A full description of the lake's catchment characteristics, hydrology, limnology and socio-economic features can be found in Perez et al. (2008).

To identify potentially invasive fishes for Lake Taal, the risk screening included 45 non-native taxa (hereafter referred to as "species" for simplicity) consisting of

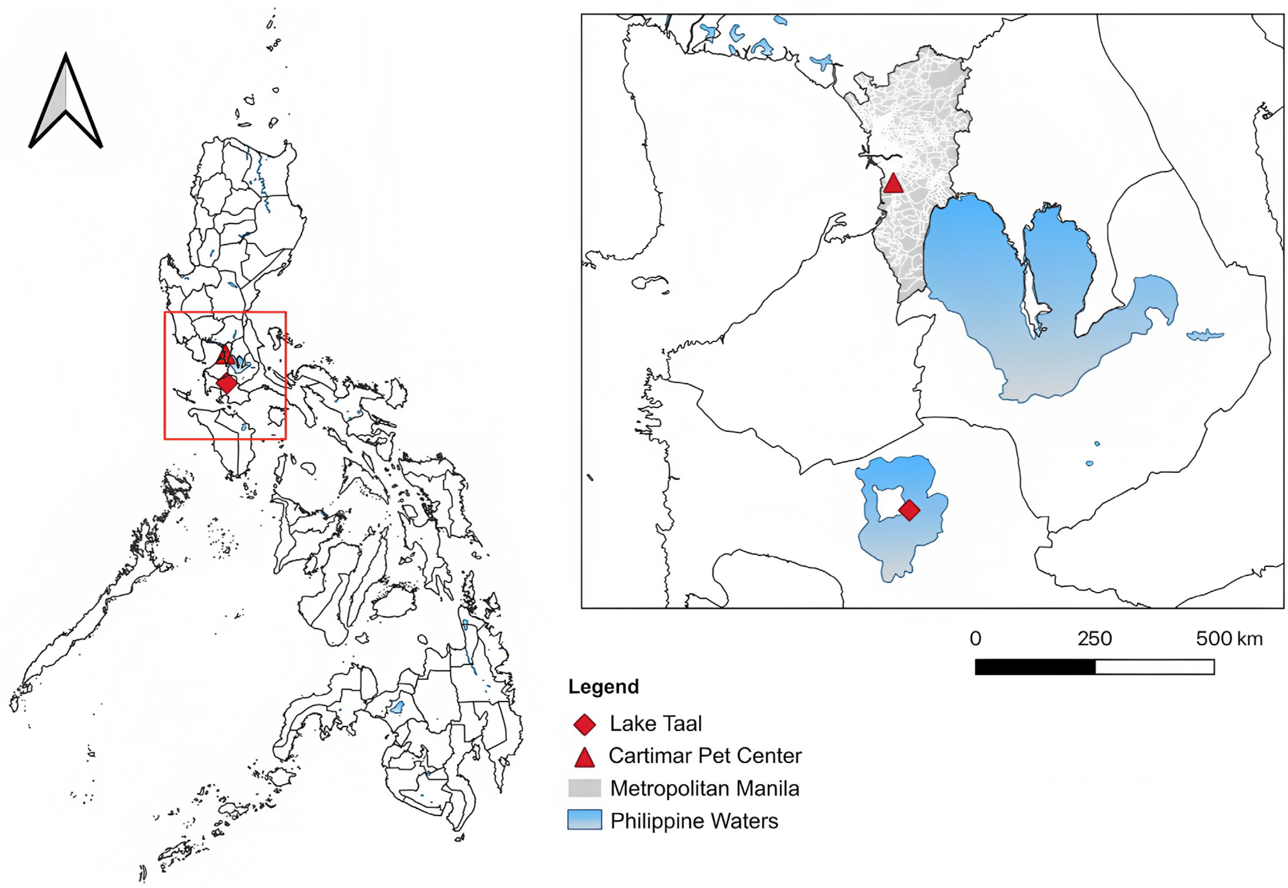

Fig. 1. Map of Lake Taal, Philippines, the risk assessment area for non-native freshwater fishes.

44 species and one hybrid (Table 1). The species were selected based on the following criteria: i) extant (n = 13), i.e. already present in the risk assessment area; and ii) horizon (n = 32), i.e. not yet reported in, but likely to enter, the risk assessment area in the near future. Horizon species were identified using the Centre for Agriculture and Bioscience International Invasive Species Compendium scanning tool (www.cabi.org/horizonscanningtool) together with expert knowledge of the potential introduction vectors that are likely to be relevant to the risk assessment area.

Risk identification was undertaken using the Aquatic Species Invasiveness Screening Kit v2.3.3 (AS-ISK: Copp et al. 2016b), which is available for free download at www.cefas.co.uk/nns/tools/ and offers users 32 languages, including Filipino (Copp et al. 2021). 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 alien species. The AS-ISK has been adopted by the Bureau of Fisheries and Aquatic Resources of the Philippines government to identify potentially invasive freshwater fish species (Republic of Philippines 2021). The AS-ISK consists of 55 questions of which 49 comprise the Basic Risk Assessment (BRA) and six the Climate Change Assessment (CCA). The latter component requires the assessor to predict how future predicted climatic conditions are likely to affect the BRA with respect to risk of introduction, establishment, dispersal and impact (Papa & Briones 2014, Mendoza et al. 2019, Volta & Jeppesen 2021).

To achieve a valid screening, a standard protocol was followed (Vilizzi et al. 2022a) whereby the assessor must provide for each question a response, confidence level and justification (e.g. Vilizzi & Piria 2022), with two score outcomes (BRA and BRA+CCA). Scores < 1 suggest a "low risk" of the species being or becoming invasive in the risk assessment area, whereas scores ≥ 1 indicate a "medium risk" or a "high risk". The distinction between medium and high risk is defined using a calibrated threshold obtained by Receiver Operating Characteristic (ROC) curve analysis (Vilizzi et al. 2022a, b). An additional *ad hoc* threshold was used to distinguish a "very high risk" category within fishes classified as high risk (as per Britton et al. 2011) to help prioritise allocation of resources for comprehensive (follow-up) risk assessment (Copp et al. 2016a, Vilizzi et al. 2022a).

Table 1. Freshwater fishes screened for their risk of invasiveness with regard to Lake Taal, Philippines. For the *a priori* categorisation (Outcome), the results of the protocol by Vilizzi et al. (2022a) are indicated: i) FishBase (www.fishbase.org); ii) Global Invasive Species Database (GISD: www.iucngisd.org) and Centre for Agriculture and Bioscience International Invasive Species Compendium (CABI: www.cabi.org/ISC); iii) Invasive and Exotic Species of North America list (IESNA: www.invasive.org); iv) Google Scholar (GScholar) literature search. N = no impact/threat; Y = impact/threat; "–" = absent; n.e. = not evaluated (but present in database); n.a. = not applicable.

		A priori categorisation					
Taxon name	Common name	FishBase	GISD	CABI	IESNA	GScholar	Outcome
Extant							
Carassius auratus	goldfish	Y	Y	Y	Y	n.a.	Invasive
Carassius carassius	crucian carp	Y	–	N	–	N	Invasive
Clarias batrachus	Philippine catfish	Y	Y	Y	Y	n.a.	Invasive
Colossoma macropomum	cachama	N	–	–	–	N	Non-invasive
Ctenopharyngodon idella	grass carp	Y	Y	Y	Y	n.a.	Invasive
Hypophthalmichthys nobilis	bighead carp	Y	Y	Y	Y	n.a.	Invasive
Oreochromis niloticus	Nile tilapia	Y	Y	Y	Y	n.a.	Invasive
Oreochromis niloticus × *Oreochromis urolepis*	Nile tilapia × wami tilapia	Y	–	Y	–	n.a.	Invasive
Pangasianodon hypophthalmus	striped catfish	N	–	–	–	N	Non-invasive
Parachromis managuensis	jaguar guapote	Y	–	n.e.	Y	n.a.	Invasive
Pterygoplichthys disjunctivus	vermiculated sailfin catfish	Y	Y	n.e.	Y	n.a.	Invasive
Sarotherodon melanotheron	blackchin tilapia	Y	–	–	–	N	Invasive
Trichopodus trichopterus	three spot gourami	N	–	–	–	N	Non-invasive
Horizon							
Acanthicus adonis	adonis pleco	N	–	–	–	N	Non-invasive
Amphilophus citrinellus	midas cichlid	N	–	–	Y	n.a.	Invasive
Austrolebias nigripinnis	blackfin pearlfish	N	–	–	–	N	Non-invasive
Balantiocheilos melanopterus	tricolour sharkminnow	N	–	–	–	N	Non-invasive
Barbonymus gonionotus	silver barb	N	–	–	–	N	Non-invasive
Baryancistrus xanthellus	golden nugget pleco	N	–	–	–	N	Non-invasive
Channa micropeltes	Indonesian snakehead	N	–	N	Y	n.a.	Invasive
Cichla temensis	speckled pavon	N	–	n.e.	–	N	Non-invasive
Cichlasoma bimaculatum	black acara	N	–	n.e.	Y	n.a.	Invasive
Cirrhinus cirrhosus	mrigal carp	N	–	–	–	N	Non-invasive

Table 1. continued

		A *priori* categorisation					
Taxon name	Common name	FishBase	GISD	CABI	IESNA	GScholar	Outcome
Coptodon zillii	redbelly tilapia	Y	–	Y	–	n.a.	Invasive
Cyprinus carpio	common carp	Y	Y	Y	Y	n.a.	Invasive
Gambusia affinis	western mosquitofish	Y	Y	Y	–	n.a.	Invasive
Hypophthalmichthys molitrix	silver carp	Y	Y	Y	Y	n.a.	Invasive
Micropterus floridanus	Florida largemouth bass	N	–	–	–	Y	Invasive
Misgurnus anguillicaudatus	oriental weatherfish	Y	Y	Y	Y	n.a.	Invasive
Oreochromis aureus	blue tilapia	Y	Y	Y	Y	n.a.	Invasive
Oreochromis mossambicus	Mozambique tilapia	Y	Y	Y	Y	n.a.	Invasive
Oreochromis urolepis	wami tilapia	N	–	–	–	N	Non-invasive
Osphronemus goramy	giant gourami	N	–	–	–	N	Non-invasive
Pangasius sanitwongsei	giant pangasius	N	–	–	–	N	Non-invasive
Pethia conchonius	rosy barb	N	–	N	–	N	Non-invasive
Piaractus brachypomus	pirapitinga	N	–	Y	Y	n.a.	Invasive
Poecilia latipinna	sailfin molly	Y	–	Y	–	n.a.	Invasive
Poecilia reticulata	guppy	Y	Y	Y	–	n.a.	Invasive
Poecilia sphenops	molly	N	–	–	–	Y	Invasive
Pterygoplichthys gibbiceps	leopard pleco	N	–	–	–	N	Non-invasive
Pterygoplichthys multiradiatus	Orinoco sailfin catfish	N	Y	n.e.	Y	n.a.	Invasive
Puntigrus tetrazona	Sumatra barb	N	–	–	–	N	Non-invasive
Trichopodus leerii	pearl gourami	N	–	–	–	N	Non-invasive
Trichopodus pectoralis	snakeskin gourami	Y	–	–	–	N	Invasive
Xiphophorus maculatus	southern platyfish	–	–	Y	–	n.a.	Invasive

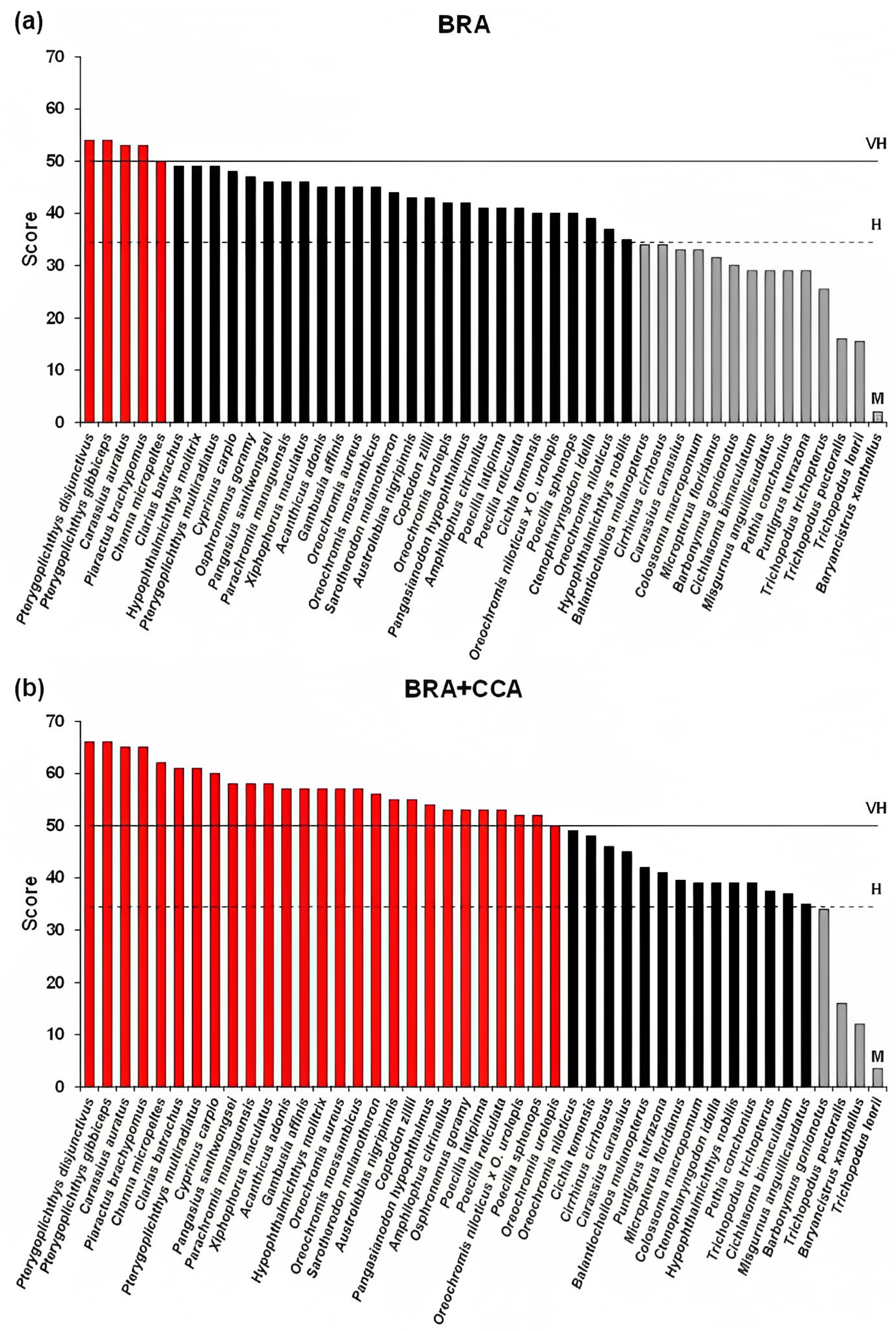

Fig. 2. Risk outcome scores for the non-native freshwater fishes screened with the Aquatic Species Invasiveness Screening Kit (AS-ISK) in Lake Taal. a) Basic Risk Assessment (BRA) scores; b) BRA + Climate Change Assessment (BRA+CCA) scores. Red bars = very high-risk species; black bars = high-risk species; grey bars = medium-risk species; solid line = very high-risk (VH) threshold; hatched line = high-risk (H) threshold; dotted line = medium-risk (M) threshold. Thresholds as per Table 2.

Table 2. Risk outcomes for the freshwater fishes screened with the Aquatic Species Invasivenss Screening Kit (AS-ISK) for Lake Taal. 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 34.5 (M = Medium; H = High; VH = Very high, based on an *ad hoc* threshold ≥ 50; see text for details), classification (Class: FP = false positive; TP = true positive; "–" = not applicable as medium-risk; see text for details), difference (Delta) between BRA+CCA and BRA scores, and confidence factor (CF). Risk outcomes for the BRA scores: M, with score within interval [1, 34.5[; H]34.5, 50[; VH [50, 72]. Risk outcomes for the BRA+CCA scores: M [1, 34.5[; H]38.5, 50[; VH [50, 82]. Note the reverse bracket notation indicating in all cases an open interval.

		BRA			BRA+CCA				CF		
Taxon name	*A priori*	Score	Rank	Class	Mean	Score	Class	Delta	Total	BRA	CCA
Acanthicus adonis	N	45.0	H	FP	57.0	VH	FP	12.0	0.87	0.86	0.96
Amphilophus citrinellus	Y	41.0	H	TP	53.0	VH	TP	12.0	0.85	0.86	0.75
Austrolebias nigripinnis	N	43.0	H	FP	55.0	VH	FP	12.0	0.83	0.83	0.79
Balantiocheilos melanopterus	N	34.0	M	–	42.0	H	FP	8.0	0.93	0.94	0.83
Barbonymus gonionotus	N	30.0	M	–	34.0	M	–	4.0	0.81	0.82	0.75
Baryancistrus xanthellus	N	2.0	M	–	12.0	M	–	10.0	0.75	0.74	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	M	–	45.0	H	TP	12.0	0.85	0.87	0.75
Channa micropeltes	Y	50.0	VH	TP	62.0	VH	TP	12.0	0.77	0.77	0.79
Cichla temensis	N	40.0	H	FP	48.0	H	FP	8.0	0.82	0.82	0.88
Cichlasoma bimaculatum	Y	29.0	M	–	37.0	H	TP	8.0	0.79	0.80	0.75
Cirrhinus cirrhosus	N	34.0	M	–	46.0	H	FP	12.0	0.86	0.85	0.96
Clarias batrachus	Y	49.0	H	TP	61.0	VH	TP	12.0	0.74	0.73	0.75
Colossoma macropomum	N	33.0	M	–	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
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
Gambusia affinis	Y	45.0	H	TP	57.0	VH	TP	12.0	0.85	0.85	0.83
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
Micropterus floridanus	Y	31.5	M	–	39.5	H	TP	8.0	0.80	0.81	0.71
Misgurnus anguillicaudatus	Y	29.0	M	–	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

Table 2. continued

		BRA			BRA+CCA				CF		
Taxon name	*A priori*	Score	Rank	Class	Mean	Score	Class	Delta	Total	BRA	CCA
Oreochromis niloticus × *Oreochromis urolepis*	Y	40.0	H	TP	52.0	VH	TP	12.0	0.89	0.89	0.88
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
Pangasianodon hypophthalmus	N	42.0	H	FP	54.0	VH	FP	12.0	0.88	0.88	0.88
Pangasius sanitwongsei	N	46.0	H	FP	58.0	VH	FP	12.0	0.76	0.77	0.75
Parachromis managuensis	Y	46.0	H	TP	58.0	VH	TP	12.0	0.84	0.84	0.88
Pethia conchonius	N	29.0	M	–	39.0	H	FP	10.0	0.79	0.78	0.88
Piaractus brachypomus	Y	53.0	VH	TP	65.0	VH	TP	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	Y	40.0	H	TP	52.0	VH	TP	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 gibbiceps	N	54.0	VH	FP	66.0	VH	FP	12.0	0.99	0.99	0.96
Pterygoplichthys multiradiatus	Y	49.0	H	TP	61.0	VH	TP	12.0	0.70	0.69	0.71
Puntigrus tetrazona	N	29.0	M	–	41.0	H	FP	12.0	0.67	0.66	0.75
Sarotherodon melanotheron	Y	44.0	H	TP	56.0	VH	TP	12.0	0.85	0.85	0.88
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
Xiphophorus maculatus	Y	46.0	H	TP	58.0	VH	TP	12.0	0.92	0.93	0.83

The *a priori* categorisation of species required for ROC curve analysis (Table 1) was implemented as per Vilizzi et al. (2022a). The ROC curve was fitted using pROC (Robin et al. 2011) for R x64 v4.0.5 (R Development Core Team 2022). Permutational ANOVA with normalisation of the data was used to test for differences in the confidence factor (CF; see Vilizzi et al. 2022a) between BRA and BRA+CCA, using a Bray-Curtis dissimilarity measure and 9,999 unrestricted permutations of the raw data, with statistical effects evaluated at α = 0.05. Following identification of the threshold score, evaluation of risk classifications to identify false-positive and false-negative rankings was not applied to medium-risk species as their further evaluation in a comprehensive risk assessment depends on policy/management priorities and/or the availability of financial resources.

Results

The ROC curve resulted in an AUC of 0.6765 (0.5086–0.8443 95% CI), and the threshold of 34.5 was used for calibration of the risk outcomes to distinguish between medium-risk and high-risk species (Table 2; refer to Table S1 for reports of the 45 screened species).

Based on the BRA scores (Table 2, Fig. 2a), 31 (68.9%) species were ranked as high risk and 14 (31.1%) as medium risk. Of the 28 species categorised *a priori* as invasive, 23 were ranked as high risk (true positives), whereas eight of the 17 species categorised *a priori* as non-invasive were ranked as high risk (false positives). Of the 14 medium-risk species, nine were *a priori* non-invasive and five invasive.

Based on the BRA+CCA scores (Table 2, Fig. 2b), 41 (91.1%) species were ranked as high risk and four (8.9%) as medium risk. Of the *a priori* invasive species, 27 were true positives, with 14 of the *a priori* non-invasive species being false positives. Of the four medium-risk species, three were *a priori* non-invasive and one invasive.

Based on an *ad hoc* threshold ≥ 50, there were five very high-risk species for both the BRA and BRA+CCA (i.e. vermiculated sailfin catfish *Pterygoplichthys disjunctivus*, leopard pleco *Pterygoplichthys gibbiceps*, pirapitinga *Piaractus brachypomus*, goldfish *Carassius auratus* and Indonesian snakehead *Channa micropeltes*), and an additional 22 for the BRA+CCA only (Table 2, Fig. 2). Overall, the combined number of high-risk and very high-risk species increased from 31 (68.9%) under the BRA to 41 (91.1%) under the BRA+CCA (Fig. 2). The CCA resulted in an increase in the BRA score (cf. BRA+CCA score) for 42 (93.3%) species, with no change for two (4.4%) and a decrease for one (2.2%), with 29 species achieving the maximum score increment of 12 and one the minimum score increment of −12 (Table 2).

Regarding the CF, mean CF_{Total} was 0.819 ± 0.012 SE, mean CF_{BRA} 0.820 ± 0.012 SE and mean CF_{CCA} 0.812 ± 0.012 SE, indicating high confidence in all cases. There was no difference between mean CF_{BRA} and mean CF_{CCA} ($F^{\#}_{1,88}$ = 0.20, $P^{\#}$ = 0.654; # = permutational value).

Discussion

Risk outcomes

To date, the calibrated threshold value of 34.5 recorded in this screening of non-native fishes with regard to a tropical volcanic lake of high conservation value is the highest found globally for identifying potentially invasive freshwater fishes (Vilizzi et al. 2022b). This large variation in threshold values for different risk assessment areas (Vilizzi et al. 2022b) may be attributed to factors such as number of translocated species, hydrological characteristics and climate conditions. Additionally, the dramatic increase in the number of high-risk, and especially very high-risk species, under predicted climate change conditions (Table 2) is a warning sign of the high susceptibility of Lake Taal to further invasions by non-native fishes.

The five species posing consistently a very high risk were *C. auratus*, *C. micropeltes*, *P. brachypomus*, *P. disjunctivus* and *P. gibbiceps.* The highest-scoring of these species, *P. disjunctivus* and *P. gibbiceps* (extant and horizon, respectively), are well-known invasive siluriforms, with non-native populations of the Genus currently found in 21 countries across five continents (Garcia et al. 2012, Orfinger & Goodding 2018). *Pterygoplichthys disjunctivus* has successfully established itself in the Philippines due to similar climatic conditions with its native range (To et al. 2022), whereas *P. gibbiceps* has yet to be recorded in the country. Siluriform fishes have been invading the Philippines for decades (Chavez et al. 2006a, Hubilla et al. 2007, Guerrero 2014) with a number of negative environmental and socio-economic consequences, including the displacement of endemic, native and economically important freshwater fishes, food and habitat competition, damage to fishing gear, disease introduction, bioaccumulation of coliform bacteria, soil erosion and increased water turbidity (Guerrero 2014, Hoover et al. 2014, Mutia et al. 2018, Orfinger

& Goodding 2018). The ability of these "plecos" to tolerate a wide range of environmental conditions thanks to their flexible biological and ecological traits is expected to facilitate their further establishment in, and wider dispersal into, other freshwater bodies of the Philippines (Chavez et al. 2006b, Brion et al. 2013, Kumar et al. 2018, To et al. 2022).

The extant *C. auratus* is native to China but has a long history of being imported as an ornamental and pet (aquarium) fish; consequently, it has been introduced worldwide into virtually all types of freshwater environment (Welcomme 1988, Lever 1996, Copp et al. 2005, 2006). The wide distribution of *C. auratus* has been facilitated by its hardiness, omnivory, low protein requirements, ornamental value and use in aquaculture (www.cabi.org/isc/datasheet/90563), allowing it to become invasive outside its native range. The association of *C. auratus* with detrimental changes in the environment include increased water turbidity, algal blooms and competition with native and endemic fish species (Richardson & Whoriskey 1992, Chavez et al. 2006b, Santos et al. 2018, To et al. 2022), and, in some cases, simply its co-occurrence with other non-native aquatic species (Copp et al. 2010). In the Philippines, *C. auratus* is well established in several types of fresh water, including the rivers Trinidad, Ambacan Layog and Leyte, as well as Lake Taal and Laguna de Bay (Mutia et al. 2018).

The horizon *P. brachypomus* (locally known as "pacu") is native to the Amazon basin (Angeles-Escobar et al. 2022) but is reported to have been introduced into Asia, including China, Malaysia and Taiwan, as an ornamental fish (Cagauan 2008, Chan et al. 2019). The species was introduced into the Philippines around the 1980s, where it has easily adapted and become established. The main purpose of introduction was as an ornamental species, alongside the increasing production of the species for capture fisheries and aquaculture. Additionally, there have been reports on the presence of *P. brachypomus* in some inland water bodies. Based on its potential to become an aggressive predator, the species is expected to become invasive once released and established in natural waters (Cagauan 2008).

One of the horizon species that obtained a very-high risk rank under both current (BRA) and climate change (BRA+CCA) conditions was *C. micropeltes*. This species is the largest channid, usually growing to 1 m and over 20 kg, and even as large as 1.5 m (Talwar & Jhingran 1992, Courtenay & Williams 2004). Usually found in large streams and canals with standing or slow-flowing waters (Cagauan 2008), *C. micropeltes* is a highly carnivorous fish that also feeds on some crustaceans. Its ability to breathe air and survive out of water for extended periods makes it a suitable candidate to become invasive once introduced outside its natural habitat (Cagauan 2008, Guerrero 2014). The species has been introduced into several countries apart from the Philippines, including China, Singapore, Thailand and the United States (Guerrero 2014, Lothongkham & Jaisuk 2020, Osathanunkul & Madesis 2022). Usually, *C. micropeltes* is used as a food fish, though it is occasionally used as an ornamental aquarium fish when very young and small (Osathanunkul & Madesis 2022). In the Philippines, the species has been found in the Pantabangan Reservoir (Nueva Ecija Province), where it is currently used by local fishers for food and as a sport fish (Guerrero 2014). The presence of an irrigation system for rice paddies and fishponds in lowland areas may act as a pathway, allowing the species to spread and establish itself more widely. Consequently, *C. micropeltes* should be studied and monitored closely to limit its invasive potential (Guerrero 2014). Currently, there is no report of *C. micropeltes* in Lake Taal or its tributaries (Corpuz et al. 2016, Mutia et al. 2018).

Climate change

For most of the fish species screened in this study, the perceived potential to become invasive increased dramatically (i.e. from medium-risk to high- or very-high risk) under the future climate conditions predicted for Lake Taal (Table 2, Fig. 2b). Overall, climate change in the Philippines is expected to result in a temperature increase of 0.9–1.4 °C alongside a change in weather patterns, i.e. an extended dry season from March to May and a wet season from July to November, with increased rainfall. In this regard, the United Nations Climate Summit in Copenhagen held in 2009 declared the Philippines as number eight in the top ten countries most vulnerable to future changes in climate. This suggests that the climate in the risk assessment area is likely to become even more suitable for sustaining a larger number of non-native fish species (Macusi et al. 2015, Chan et al. 2019, Mendoza et al. 2019). Importantly, the higher-risk species identified in this study can tolerate a wide range of aquatic environments and possess biological and ecological traits that facilitate their establishment and dispersal (Singh & Hughes 1971, To et al. 2022).

Among the species ranked as very-high risk in this study after accounting for climate change are the horizon Midas cichlid *Amphilophus citrinellus* and the extant Philippine catfish *Clarias batrachus*, along with the jaguar guapote *Parachromis managuensis* and the blackchin tilapia *Sarotherodon melanotheron* (Mutia et al. 2013, 2022). Annual capture fisheries production in Lake Taal was recently estimated at 1,004.14 MT of which approx. 47% consisted of the endemic *S. tawilis*, 31% of non-native species and 22% of migratory and/or native species (Aquilino et al. 2011, Mutia et al. 2022). *Amphilopus citrinellus*, *P. managuensis* and *S. melanotheron* were all included in the top ten fishes caught in Lake Taal (Araullo 2001, Rosana et al. 2006, Mutia et al. 2022), indicating the continuous proliferation of these non-native fishes in the risk assessment area; indeed, based on their high- to very-high risk ranking, they are expected to dominate and displace the native species soon. This is particularly evident with endemic *S. tawilis*, with recent data indicating that the Lake Taal population has been continuously declining due to illegal activities such as overfishing. However, other factors have also contributed to the species' decline, including increased pollution and the presence of non-native species (Santos et al. 2015, Mutia et al. 2018). For this reason, *S. tawilis* has been classified as endangered on the IUCN red list (Santos et al. 2018).

The extant Nile tilapia *Oreochromis niloticus* was introduced into the Philippines in the 1970s for aquacultural purposes, with farming of this economically valuable species in ponds and cages being popular amongst fish farmers across the country (Guerrero 2014). Recent data from the Bureau of Fisheries and Aquatic Resources (www.bfar.da.gov.ph/) indicate that *O. niloticus* is the second most important cultured species in the country, with Lake Taal as one of the species' major production areas (Araullo 2001, Rosana et al. 2006, Mutia et al. 2022). However, this study has revealed that, under predicted future climate conditions, *O. niloticus* is expected to pose a high (though not very high) risk of invasiveness due to its resilience.

Management considerations

This study has demonstrated that the lack of early detection measures and risk-screening studies can lead to the establishment of non-native species in Philippine fresh waters. As a signatory to the United Nations Convention on Biological Diversity (CBD; www.cbd.int/), the Philippines has adopted a series of "guiding principles" for the prevention, introduction and translocation of non-native species that are likely to threaten native species and ecosystems. Article 8 of the CBD provides a framework for national governments to establish their policies, guidelines and strategies for handling non-native species to prevent their entry, and minimise their spread and impact once introduced. In addition, the Republic Act No. 8550 Section 10 of the Philippines Fisheries Code of 1998 (www.fao.org/faolex/results/details/en/c/LEX-FAOC016098/) on the Introduction of Foreign Aquatic Species states that "No foreign finfish, mollusc, crustacean or aquatic plant shall be introduced in Philippine waters without a sound ecological, biological and environmental justification based on scientific studies subject to the bio-safety standard, as provided for by existing laws; provided, however, that the Department may approve the introduction of foreign aquatic species for scientific/research purposes".

Consequently, the importation of non-native species into the country is regulated by the Philippines Bureau of Fisheries and Aquatic Resources Regulatory and Fisheries Inspection and Quarantine Division five-step process. This is provided by Fisheries Administrative Order (FAO) No. 221, which includes an Import Risk Analysis for the evaluation of risk factors, such as environmental impact, disease risk and any effect on endemic species, which categorises the non-native species as "low risk", "medium risk", "high risk" or "prohibited". Despite current legislation, the overall status of non-native species in the country is poorly understood due to a lack of risk analysis studies and a failure to i) recognise their current and potential ecological and socio-economic impacts, ii) successfully implement species introduction laws, and iii) intervene in non-native species commerce and trade (Joshi 2006). This emphasises the need for risk screening to identify potentially invasive species and thereby inform implementation of management measures to mitigate their possible long-term impacts on native and, especially, endemic species. As an initial step towards addressing these issues, the Philippines Department of Agriculture adopted the AS-ISK in an amendment of its guidelines on the risk assessment for the introduction of new species (Republic of Philippines 2021).

Management recommendations derived from the present study include:

1) An introduction vector and pathway analysis is recommended to determine the various channels by which non-native species could be introduced into the Philippines. As prevention is cheaper and more effective than post-introduction control and eradication, vector and pathway analysis is an essential component of non-native species risk analysis.

2) Undertaking rapid and evidence-based risk assessment studies, essential for identifying potentially invasive species and their potential threats. This can be achieved using decision-support tools such as the AS-ISK, as adopted by the Philippines government (Republic of Philippines 2021) and used in this present study.
3) Undertaking a thorough risk assessment as conducted by the Import Risk Analysis Panel of BFAR in accordance with FAO 221. Priority should be given to those non-native species ranked as high- or very-high risk with the AS-ISK, with medium-risk species considered under a watching-brief given that some species go through a lag phase, appearing to be benign before becoming invasive.
4) Establishment of a comprehensive list or database of potentially invasive or prohibited species. This would provide accessible and updated information to national and regional policy-makers and stakeholders to help implement import, export, control or eradication measures for appropriate management, and to amend and reinforce non-native species legislation and regulations (Roy et al. 2018). Moreover, given that these non-native ornamental fishes pose comparable levels of risk within the same biogeographical region, it may also serve as a foundation for developing shared regulations to control the international trade of various non-native fish species among south-east Asian nations, particularly regarding highly marketable ornamental fishes (Chan et al. 2019, Wei et al. 2021).
5) Continuous monitoring and surveillance of establishments that promote the trade and commerce of high-risk non-native species by responsible government authorities, to ensure that no non-native species identified as high risk or prohibited are propagated in the country (Guerrero 2014).
6) Implementation of a comprehensive, government-led Information, Education, and Communication (IEC) campaign to inform the public and guide its perception of non-native fish species and their potential threats, thereby gaining public support to prevent further and future invasions.

As a final note, this risk screening study for Lake Taal using the AS-ISK decision-support tool is to be regarded as the most currently valid for the Philippines. In this respect, the recent paper by To et al. (2022), which aimed to evaluate the potential invasiveness of Siluriform species in the same risk assessment area using the AS-ISK, has some inconsistencies regarding the implementation of standard analytical protocols, which are discussed in Vilizzi & Piria (2022). The present "correction" is important, therefore, in setting the standard for the risk screening/assessment process of non-native (invasive) species in the Philippines. This will further support country-wide initiatives to mitigate the continuing proliferation of introduced species (Andersen et al. 2004). Furthermore, it is anticipated that this will also help inform policy-makers and stakeholders in the development of policies and guidelines for appropriate management of non-native and invasive species in the Philippines.

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Author Contributions

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Supplementary online material

Table S1. AS-ISK report for the 45 screened species (https://www.ivb.cz/wp-content/uploads/JVB-vol.-72-2023-Gilles-A.S.-Jr.-et-al.Tables-S1.pdf).