



Risk screening of the potential invasiveness of non-native freshwater fishes in the River Ob basin (West Siberian Plain, Russia)

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Abstract

To inform regional managers of potentially invasive non-native (NN) freshwater fishes in the principal hydrosystem that drains the West Siberian Plain, the River Ob basin, 31 extant and potential future NN fish species were screened using the Aquatic Species Invasiveness Screening Kit (AS-ISK) with respect to current and projected future climate conditions. Calibration of the AS-ISK scores, using receiver operating characteristic curve analysis, identified ‘basic risk assessment’ and ‘climate change assessment’ threshold scores of 27.5 and 34.75, respectively, with which to distinguish species that pose a high risk of being invasive in the Ob basin and those that pose a low-to-medium risk. Of the species screened, 12 ranked as high risk (black bullhead *Ameiurus melas*, brown bullhead *Ameiurus nebulosus*, grass carp *Ctenopharyngodon idella*, common carp *Cyprinus carpio*, eastern mosquitofish *Gambusia holbrooki*, silver carp *Hypophthalmichthys molitrix*, oriental weatherfish *Misgurnus anguillicaudatus*, rainbow trout *Oncorhynchus mykiss*, Chinese (Amur) sleeper *Perccottus glenii*, topmouth gudgeon *Pseudorasbora parva*, brown trout *Salmo trutta*, pikeperch *Sander lucioperca* and rudd *Scardinius erythrophthalmus*). The remaining species ranked as medium or low risk. Although the risk scores increased in 68% of species under climate change conditions, this affected the risk rankings of only two species: *Salmo trutta* decreased in rank from high to medium and *Sander lucioperca* increased in rank from medium to high. The outcomes of the present study, which identified 12 species for which full risk assessments are recommended, serves to inform the development of NN species policy and management in Russia.

Keywords AS-ISK · Risk identification · Climate change · Decision-support tools · Asia

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Introduction

The West Siberian Plain is a region characterised by high native biodiversity (Solomeshch 2005) and aboriginal culture conservation value (Klubnikin et al. 2000), but threatened by indirect and direct human impacts, including climate change, habitat destruction and non-native (NN) species introductions. This is due to a lack of, or inadequately implemented, regional environmental management (Khitun and Rebristaya 2002). Over time, this has resulted in the region’s main drainage basin, the River Ob, receiving several NN species introductions without assessment of their potential impacts on the region’s native species and ecosystem nor their ecosystem services. And although there exists clear-cut evidence of highly adverse impacts by some invasive fish species (e.g. common carp *Cyprinus carpio*; Vilizzi et al. 2015), the threats posed by most invasive NN fishes remain largely unstudied (e.g. Crivelli 1995; Bogutskaya et al. 2001; Caiola and de Sostoa 2005; Sagoff 2005). This is especially notable for endemic

fishes of various regions across Europe (Kalogianni et al. 2014; Clavero et al. 2015; Glamuzina et al. 2017).

For river systems with high (or potentially unknown) endemism, it is essential to carry out a risk screening process to identify which NN fishes are likely to become invasive in the risk assessment (RA) area in question as well as to identify gaps in knowledge (Almeida et al. 2013; Simonović et al. 2013; Perdikaris et al. 2016; Piria et al. 2016). Assessment of NNS impacts on endemic fishes is due in large part to the limited knowledge of the environmental biology of many species, and this is particularly true for the West Siberian Plain (Bogutskaya et al. 2001; Romanov et al. 2017), where native fishes have been, or will be, affected by climate warming (Reist et al. 2006), habitat destruction (Klubnikin et al. 2000) and NN species introductions (e.g. Popov 2009; Interesova 2012, 2016). Such a risk screening study is needed for the Ob basin—a geographically extensive drainage basin that has at least one endemic fish species (Bogutskaya et al. 2001). However, given their later post-glacial colonisation by fishes, Siberian rivers such as the Ob are not expected to have as high a level of endemism as the later-colonised rivers of Western Europe (e.g. Iberia and Greece: Reyjol et al. 2007). That said, the taxonomic status of some of the known native freshwater fish species ($n = 41$) in the Ob basin (Popov 2009) requires further study (Dyldin et al. 2017; Levin et al. 2017; Romanov et al. 2017), potentially resulting in a revised list of endemic species in the near future. Of the 22 NN species of fish listed for Siberia, 17 have established self-sustaining populations in the Ob basin, which represents $\approx 32\%$ of all fish species.

Most of the NN fishes in the Ob basin were intentionally introduced (mainly for fishery enhancement), though some arrived accidentally as contaminants of authorised consignments of commercially valuable fish species. The vectors and pathways by which some of these NN fishes were introduced to the Ob basin remain largely unknown, though aquaculture and aquarium trade are both currently growing industries in Siberia, with an increasing number of NN fishes being imported. This increases the risks of NN fish introductions to the Ob basin, with their dispersal facilitated by the network of connected canals and reservoirs existing since the end of the 2000s that link the catchments of the rivers Ob and Volga, e.g. the rivers Miass and Ufa (Korlyakov and Nokhrin 2014).

Projections of future climate in Siberia for the end of the twenty-first century indicate temperature increases that are expected to be more pronounced in the cold season (up by $+8\text{ }^{\circ}\text{C}$ at higher latitudes) and less so in the warm season (up by $+5\text{ }^{\circ}\text{C}$ in southern Siberia) (Groisman et al. 2013). The potential effects of climate change on Arctic freshwater systems, and specifically the River Ob, are projected to be important at both local and basin scales (Prowse et al. 2006a). Indeed, the River Ob and its major tributary, the River Irtysh, are collectively considered a good example of the

‘worst-case scenario’ that would develop under future, warmer climate conditions due to the rivers being fed by poorly oxygenated groundwater on elevated contaminant inputs (Prowse et al. 2006b). Non-native fishes are another major form of ‘biopollution’ in Siberia that can affect native species and ecosystems (Popov 2009), and no risk analysis has been undertaken to identify their potential current and future impacts.

To address this lack of assessment of the potential adverse impacts of NN species on native species and ecosystems of the Ob basin, the aim of the present study was to identify which of the NN fishes in the Ob basin are likely to be invasive under current and predicted future climate conditions, which could contribute further to their wider dispersal. The outcome of this risk screening, which represents the first step in the NN species risk analysis process, will inform environmental managers and policymakers as to which NN species of fish warrant more comprehensive risk assessment. As such, the present study represents a crucial contribution towards the development of management strategies for NN fishes and to the implementation of management and conservation measures for native fishes and associated fisheries of the West Siberian region. This approach has the potential for wider application to other regions of Russia.

Study area, material and methods

The West Siberian Plain, which is the largest peatland in the world (Keddy et al. 2009), has been described as the world’s largest unbroken lowland (area $\approx 2.6\text{--}2.7$ million km^2), comprising about one-third of Siberia, with $> 50\%$ being below 100 m a.s.l. The Plain extends 2400 km from the Arctic Ocean to the foothills of the Altay Mountains in the South, and 1900 km from the Ural Mountains in the West to the River Yenisei in the East—it is comprised of eight distinct vegetation regions (tundra, forest-tundra, northern taiga, middle taiga, southern taiga, sub-taiga forest, forest-steppe and steppe), which are drained by the River Ob and its major tributary, the River Irtysh (https://en.wikipedia.org/wiki/Ob_River). The Ob basin, the RA area in the present study, represents the longest river system in Northern Asia (5410 km; ≈ 3 million km^2), crossing the climate zones ‘cold semi-arid’, ‘humid continental’ and ‘sub-arctic’. During its passage through Russia, Kazakhstan and China, the River Ob traverses temperate mountains, steppe, continental forest, boreal mountains, coniferous forest and tundra woodland, as well as polar ecological zones.

Each of the geographic regions of the West Siberian Plain possesses a specific ichthyofauna (Popov 2009), which as mentioned includes 17 established NN species of fish of which seven have formed local, self-reproducing populations in the Ob basin. However, none of these species has yet undertaken

natural spread, i.e. bighead carp *Aristichthys nobilis*, vendace *Coregonus albula*, grass carp *Ctenopharyngodon idella*, silver carp *Hypophthalmichthys molitrix*, channel catfish *Ictalurus punctatus*, bigmouth buffalo *Ictiobus cyprinellus*, European smelt *Osmerus eperlanus* and brown trout *Salmo trutta*. Whereas, the other nine established NN species of fish have begun to spread more widely, i.e. common bream *Abramis brama*, bleak *Alburnus alburnus*, *Cyprinus carpio*, sunbleak *Leucaspis delineatus*, Nikolsky's loach *Misgurnus nikolskyi*, Chinese (Amur) sleeper *Perccottus glenii*, topmouth gudgeon *Pseudorasbora parva*, southern ninespine stickleback *Pungitius platygaster* and pikeperch *Sander lucioperca* (Interesova 2016). Notably, *Pseudorasbora parva* and *Pungitius platygaster* arrived in the Ob basin from neighbouring regions, having been initially recorded in the River Ishim (part of the River Irtysh basin) and most likely migrated through the Nura-Ishim canal, which was constructed in the early 1970s. The other five NN species of fish that have failed to establish include: black buffalo *Ictiobus niger*, black carp *Mylopharyngodon piceus* and chum salmon *Oncorhynchus keta*—these species have not recently been found in water bodies of Western Siberia, whereas pink (humpback) salmon *Oncorhynchus gorbuscha* and rainbow trout *Oncorhynchus mykiss* have been reported in some waters of the Ob basin, but with no evidence to date of their ability to reproduce in the wild.

Risk screening

In total, 31 NN freshwater fish species were screened for their potential invasiveness in the RA area using the Aquatic Species Invasiveness Screening Kit (AS-ISK), which is available for free download at www.cefas.co.uk/nns/tools/ (Copp et al. 2016a). The AS-ISK is the next-generation decision-support tool of FISK, the freshwater Fish Invasiveness Screening Kit (Copp et al. 2009; Lawson Jr et al. 2013), which was adapted from the Weed Risk Assessment (WRA) of Pheloung et al. (1999). The AS-ISK was created by combining the questions from the generic screening module of the European Non-native Species in Aquaculture Risk Analysis Scheme (Copp et al. 2016b), which were adapted from the FISK v1 questions (Copp et al. 2009), within the architecture of the FISK v2 (Lawson Jr et al. 2013). In doing so, AS-ISK questions were formulated to comply with the 'minimum standards' (Roy et al. 2018) for the assessment of NN species under EC Regulation No. 1143/2014 on the prevention and management of the introduction and spread of invasive alien species (Council of the European Communities 2014). Similar to the FISK, which has been used globally (Vilizzi et al. 2019), applications of the AS-ISK include risk screenings of NN freshwater fishes for RA areas in China (Li et al. 2017), Great Britain (Dodd et al. 2019), Turkey (Tarkan et al.

2017a, b) and the southern Balkans (Glamuzina et al. 2017), of NN marine species for the Arabian/Persian Gulf and Sea of Oman (Clarke et al. 2020), for the coastal waters of southwestern Anatolia (Bilge et al. 2019), South Korea (Uyan et al. 2020) and of NN jellyfishes in the Mediterranean Sea (Killi et al. 2020).

Like the WRA and the FISK, the AS-ISK consists of 49 basic questions that examine the biogeographical and biological aspects of the taxon being screened, resulting in a Basic Risk Assessment (BRA) score. The AS-ISK has an additional six Climate Change Assessment (CCA) questions that require the assessor to evaluate how future climatic conditions are likely to affect the BRA score with regard to the risks of the taxon's introduction, establishment, dispersal and impact, resulting in a (combined) BRA + CCA score. To achieve a valid AS-ISK assessment, the assessor is required to provide for each question: a response, a justification for that response and a confidence rank for that response (see below). These three elements ensure that assessor responses are supported, where possible, by bibliographic sources and an explanation of their confidence in each response, which is a reflection of the available knowledge with which to answer the question. The resulting BRA score ranges from -20 to 68 , and the BRA + CCA score from -32 to 80 . Confidence in responses to questions are ranked using a 1–4 scale (1 = low; 2 = medium; 3 = high; 4 = very high) as per the Intergovernmental Panel on Climate Change (IPCC 2005; Copp et al. 2016a).

Fish species were selected for screening according to the following criteria: (1) extant species—those already recorded in the RA area ($n = 22$); and (2) horizon species, including (2a) potential entry via aquaculture ($n = 4$), (2b) existing in nearby river basins ($n = 3$) and (2c) currently sold in aquarium/pet shops ($n = 2$) (Table 1). Assessments were carried out by the first author, who is knowledgeable in the environmental biology of the fish species of the RA area, with GHC and LV overseeing construction of the species list and quality control of the generated AS-ISK database of assessments, respectively. Whilst replicated assessments (i.e. from two or more assessors) would have been preferable, this was not possible in the present study due to logistic constraints. However, risk assessments by a single assessor are not uncommon, both in the case of risk screenings (Vilizzi et al. 2019) and of full risk assessments (e.g. various assessments for Great Britain: www.nonnativespecies.org/index.cfm?pageid=143).

Statistical analysis

Following computation of the BRA and BRA + CCA scores, receiver operating characteristic (ROC) curve analysis (Bewick et al. 2004) was used to assess the predictive ability of AS-ISK to discriminate between NN freshwater fish

Table 1 Non-native freshwater fish species screened with the Aquatic Species Invasiveness Screening Kit (AS-ISK) for the River Ob basin. Provided for each species is the selection criterion (Crit.) (I, extant species; horizon species: 2a, potential entry via aquaculture; 2b, existing in nearby river basins; 2c, currently sold in aquarium/pet shops); the *a priori* invasiveness (Inv.) categorisation (N, non-invasive; Y, invasive); the Basic Risk Assessment (BRA) and BRA plus Climate Change Assessment (BRA + CCA) scores with corresponding risk outcomes; the difference (Delta) between BRA + CCA and BRA scores. The confidence level (CL) and the confidence factor (CF) (see

text for explanation) is given for all questions (Total) and separately for the BRA and CCA components of the risk assessment. Risk outcomes are based on a threshold of 27.5 for the BRA (low: score within interval [-20, 1]; medium [1, 27.5]; high [27.5, 68]) and of 34.75 for the BRA + CCA (low [-32, 1]; medium [1, 34.75]; high [34.75, 80]), using the statistically appropriate brackets (‘]’ and ‘[’) to present the intervals (see www.mathwords.com/i/interval_notation.htm). The receiver operating characteristic curves are given in Fig. 1 and the combined AS-ISK reports are given in Supplementary Table S1

Species name	Common name	Crit.	Inv.	Assessment component					Confidence					
				Score	Outcome	Score	Outcome	Delta	Total	BRA	CCA	Total	BRA	CCA
<i>Abramis brama</i>	common bream	1	N	27.0	Medium	33.0	Medium	6.0	3.0	3.1	2.8	0.76	0.77	0.71
<i>Alburnus alburnus</i>	bleak	1	Y	25.0	Medium	31.0	Medium	6.0	2.9	3.0	2.5	0.74	0.75	0.63
<i>Ameiurus melas</i>	black bullhead	2a	Y	39.5	High	51.5	High	12.0	2.8	2.8	2.7	0.70	0.71	0.67
<i>Ameiurus nebulosus</i>	brown bullhead	2a	Y	35.0	High	47.0	High	12.0	2.9	3.0	2.8	0.74	0.74	0.71
<i>Aristichthys nobilis</i>	bighead carp	1	Y	22.5	Medium	32.5	Medium	10.0	2.9	2.9	3.3	0.73	0.72	0.83
<i>Coregonus albula</i>	vendace	1	N	20.0	Medium	10.0	Medium	-10.0	2.8	2.9	2.0	0.71	0.73	0.50
<i>Ctenopharyngodon idella</i>	grass carp	1	Y	42.5	High	54.5	High	12.0	3.1	3.1	3.0	0.77	0.77	0.75
<i>Cyprinus carpio</i>	common carp	1	Y	37.5	High	49.5	High	12.0	3.0	3.0	3.0	0.75	0.76	0.75
<i>Gambusia holbrooki</i>	eastern mosquitofish	2c	Y	35.0	High	47.0	High	12.0	3.1	3.1	3.0	0.78	0.78	0.75
<i>Hypophthalmichthys molitrix</i>	silver carp	1	Y	36.5	High	48.5	High	12.0	3.1	3.1	3.0	0.77	0.78	0.75
<i>Ictalurus punctatus</i>	channel catfish	1	Y	25.0	Medium	33.0	Medium	8.0	2.7	2.7	2.3	0.66	0.67	0.58
<i>Ictiobus cyprinellus</i>	bigmouth buffalo	1	N	20.0	Medium	30.0	Medium	10.0	2.5	2.5	2.2	0.61	0.62	0.54
<i>Ictiobus niger</i>	black buffalo	1	N	12.5	Medium	22.5	Medium	10.0	2.5	2.5	2.5	0.62	0.62	0.63
<i>Leucaspius delineatus</i>	sunbleak	1	N	21.0	Medium	31.0	Medium	10.0	2.9	3.0	2.8	0.74	0.74	0.71
<i>Leuciscus aspius</i>	asp	2b	N	25.0	Medium	25.0	Medium	0.0	2.9	3.0	2.0	0.73	0.76	0.50
<i>Misgurnus anguillicaudatus</i>	Oriental weatherfish	2c	Y	34.5	High	46.5	High	12.0	2.8	2.8	2.8	0.70	0.70	0.71
<i>Misgurnus nikolskyi</i>	Nikolsky's loach	1	N	23.5	Medium	33.5	Medium	10.0	2.7	2.7	2.8	0.68	0.67	0.71
<i>Mylopharyngodon piceus</i>	black carp	1	Y	17.0	Medium	27.0	Medium	10.0	2.7	2.7	2.8	0.69	0.68	0.71
<i>Oncorhynchus gorbuscha</i>	pink (humpback) salmon	1	Y	12.0	Medium	12.0	Medium	0.0	2.7	2.8	2.0	0.68	0.70	0.50
<i>Oncorhynchus keta</i>	chum salmon	1	N	7.5	Medium	17.5	Medium	10.0	2.6	2.7	2.0	0.66	0.68	0.50
<i>Oncorhynchus mykiss</i>	rainbow trout	1	Y	44.0	High	40.0	High	-4.0	3.1	3.2	2.2	0.78	0.81	0.54
<i>Osmerus eperlanus</i>	European smelt	1	N	11.0	Medium	11.0	Medium	0.0	2.7	2.8	2.2	0.68	0.70	0.54
<i>Perccottus glenii</i>	Chinese (Amur) sleeper	1	Y	41.0	High	53.0	High	12.0	3.2	3.2	3.2	0.80	0.81	0.79
<i>Pseudorasbora parva</i>	topmouth gudgeon	1	Y	36.5	High	48.5	High	12.0	2.8	2.8	3.0	0.70	0.69	0.75
<i>Pungitius platygaster</i>	southern ninespine stickleback	1	N	6.5	Medium	12.5	Medium	6.0	2.7	2.7	2.5	0.66	0.67	0.63
<i>Salmo trutta</i>	brown trout	1	Y	35.0	High	27.0	Medium	-8.0	2.9	3.0	2.0	0.73	0.76	0.50
<i>Salvelinus fontinalis</i>	brook trout	2a	Y	27.0	Medium	21.0	Medium	-6.0	3.0	3.1	2.2	0.75	0.77	0.54
<i>Salvelinus namaycush</i>	lake trout	2a	Y	20.0	Medium	14.0	Medium	-6.0	2.9	3.0	2.2	0.73	0.75	0.54
<i>Sander lucioperca</i>	pikeperch	1	Y	28.0	High	36.0	High	8.0	2.8	2.9	2.5	0.71	0.72	0.63
<i>Scardinius erythrophthalmus</i>	rudd	2b	Y	44.0	High	44.0	High	0.0	2.8	2.9	2.5	0.70	0.71	0.63
<i>Squalius cephalus</i>	chub	2b	N	26.0	Medium	26.0	Medium	0.0	2.7	2.7	2.7	0.67	0.67	0.67

species posing a high risk and those posing a medium or low risk of being invasive for the RA area. For ROC analysis to be

implemented, species need to be categorised *a priori* in terms of their documented invasiveness (i.e. non-invasive or

invasive). To this end, *a priori* categorisation for invasiveness was based on a four-step approach: (i) similar to previous AS-ISK applications to fish (cited here above), a preliminary search was made of FishBase (www.fishbase.org) for any reference to the species' threat to humans, with the species categorised *a priori* as invasive if listed as 'potential pest' and as non-invasive if listed as 'harmless'; (ii) if the species was listed as either 'not evaluated' or was absent in the above database, then a search was made of the Global Invasive Species Database (GISD: <http://issg.org/database/welcome/aboutGISD.asp>), with the species categorised *a priori* as invasive if listed therein; (iii) if the species was absent from the GISD, then an additional search was made of the continental/country-level lists for invasive species in Africa, Asia, Europe and North America, whereby the species was categorised *a priori* as invasive if listed therein; finally, (iv) if the species was absent from any of the previous databases, then a Google Scholar (literature) search was performed to check whether at least one peer-reviewed reference in support for the species' invasiveness was found. The latter was then taken as 'sufficient evidence' for categorising the species *a priori* as invasive; whereas if no evidence was found, then the species was categorised *a priori* as non-invasive. Notably, in case a species was listed as harmless in FishBase, but found to be invasive in any of the other steps of the process, then the species was categorised *a priori* as invasive.

A ROC curve is a graph of sensitivity vs $1 - \text{specificity}$ (or alternatively, sensitivity vs specificity) for each threshold value, where in the present context, sensitivity and specificity will be the proportion of *a priori* invasive and non-invasive species, respectively, that are correctly identified by AS-ISK as such. A measure of the accuracy of the calibration analysis is the area under the curve (AUC), which typically ranges from 0.5 to 1.0, and the closer to 1.0, the better the ability to differentiate between invasive and non-invasive species. If the AUC is equal to 1.0, then the test is 100% accurate, because both sensitivity and specificity are 1.0, and there are neither 'false positives' (*a priori* non-invasive species classified as high risk, hence invasive) nor 'false negatives' (*a priori* invasive species classified as low risk, hence non-invasive). Conversely, if the AUC is equal to 0.5, then the test is 0% accurate as it cannot discriminate between 'true positives' (*a priori* invasive species classified as high risk, hence invasive) and 'true negatives' (*a priori* non-invasive species classified as low risk, hence non-invasive).

Following ROC curve analysis, the best AS-ISK threshold value that maximises the true positives rate and minimises the false positives rate was determined using Youden's J statistic, whereas a 'default' threshold of 1 was set to distinguish between low-risk and medium-risk species. ROC curve analysis was carried out with package pROC (Robin et al. 2011) for R x64 v3.2.0 (R Development Core Team 2018) using 2000 bootstrap replicates for the confidence intervals of

specificities, which were computed along the entire range of sensitivity points (i.e. 0 to 1, at 0.1 intervals). The threshold intervals are presented using the statistically appropriate brackets (']' and '['; www.mathwords.com/i/interval_notation.htm).

Based on the confidence level (CL) allocated to each response (see Risk screening), a confidence factor (CF) is obtained as:

$$CF = \sum(CL_{Q_i}) / (4 \times 55) \quad (i = 1, \dots, 55)$$

where CL_{Q_i} is the confidence level for Q_i , 4 is the maximum achievable value for confidence (i.e. very high: see above) and 55 is the total number of questions comprising the AS-ISK questionnaire. The CF ranges from a minimum of 0.25 (i.e. all 55 questions with confidence level equal to 1) to a maximum of 1 (i.e. all 55 questions with confidence level equal to 4). Two additional confidence factors were also computed, namely the CF_{BRA} and the CF_{CCA} , respectively based on the 49 Qs comprising the BRA and the six Qs comprising the CCA.

Differences between mean CL for the BRA (CL_{BRA}) and for the CCA (CL_{CCA}) were tested by permutational ANOVA based on a one-factor design (i.e. component, with two levels: BRA and CCA) (note that testing of the same differences for the CF leads to the same results as the two measures differ only by a constant). Analysis was carried out in PERMANOVA+ for PRIMER v6, with normalisation of the data and using a Bray-Curtis dissimilarity measure, 9999 unrestricted permutations of the raw data (Anderson et al. 2008), and with statistical effects evaluated at $\alpha = 0.05$.

Results

The ROC curve for the BRA scores resulted in an AUC of 0.8614 (0.7350–0.9877 95% CI) and that for the BRA + CCA scores in an AUC of 0.8273 (0.6839–0.9706 95% CI) (Fig. 1a, b). These AUCs were well above 0.5, indicating that AS-ISK was able to discriminate reliably between non-invasive (low-to-medium risk) and invasive (high risk) NN freshwater fishes for the RA area. Youden's J provided thresholds of 27.5 for the BRA and 34.75 for the BRA + CCA, which were used for calibration of risk outcomes. Accordingly, species within the calibrated BRA score threshold interval $[1, 27.5[$ ranked as posing a medium risk of becoming invasive in the RA area, and those attributed scores within the interval $]27.5, 68]$ ranked as posing a high risk. The BRA + CCA score threshold distinguished between medium-risk (score interval $[1.0, 34.75[$) and high-risk species (score interval $]34.75, 80]$). Whereas, species classified as low risk were those with BRA scores within $[-20, 1[$ and BRA + CCA scores within $[-32, 1[$.

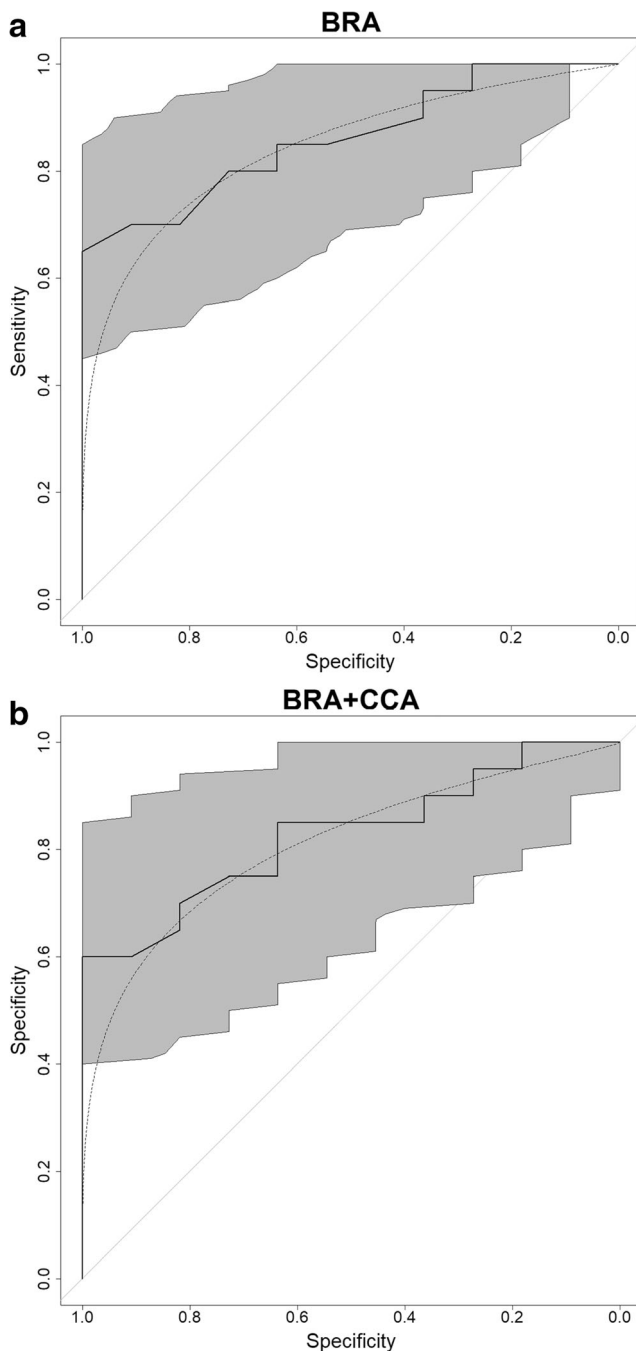


Fig. 1 Receiver operating characteristic curves for the assessment scores attributed to NN fish species screened for the River Ob basin (Table 1) using the Aquatic Species Invasiveness Screening Kit (AS-ISK): **a** BRA, scores from the Basic Risk Assessment (solid line); and **b** BRA + CCA, scores from the BRA plus Climate Change Assessment. Smoothing line and confidence intervals of specificities (grey area), which were computed (using 2000 bootstrap replicates) along the entire range of sensitivity points (i.e. 0 to 1, at 0.1 intervals), are also provided

Of the 31 freshwater fishes screened, based on both the BRA and BRA + CCA thresholds, 12 (38.7%) were classified as high risk and 19 (61.3%) as medium risk. Amongst the species categorised *a priori* as invasive, 12 were true positives. Of the 19 medium-risk species, eleven were categorised

a priori as non-invasive and eight as invasive (Table 1; see Supplementary information Table S1 for the species AS-ISK screening reports).

In the BRA, the highest-scoring species (score ≥ 40 , chosen as the ‘very high’ risk ‘sub-threshold’) were *Oncorhynchus mykiss*, rudd *Scardinius erythrophthalmus*, *Ctenopharyngodon idella* and *Perccottus glenii*, from higher to lower score. In the BRA + CCA (scores ≥ 46), this was true of the latter two species, but also for (in decreasing score) black bullhead *Ameiurus melas*, *Cyprinus carpio*, *Pseudorasbora parva*, *Hypophthalmichthys molitrix*, brown bullhead *Ameiurus nebulosus*, eastern mosquitofish *Gambusia holbrooki* and oriental weatherfish *Misgurnus anguillicaudatus* (Table 1).

The CCA resulted in an increase in risk ranking relative to the BRA score for 21 (67.7%) of the screened species, in a decrease in risk ranking for five (16.1%), and in no change for the remaining five (16.1%). Notably, all species classified as very high risk for the BRA + CCA also achieved the largest possible (positive) change in score of 12 (Table 1).

The CL values were the following: $CL = 2.85 \pm 0.03$ SE (all 55 Qs), $CL_{BRA} = 2.89 \pm 0.03$ SE and the $CL_{CCA} = 2.56 \pm 0.07$ SE (hence, in all cases indicating medium-to-high confidence). The CL_{BRA} was significantly higher than the CL_{CCA} ($F^{#}_{1,60} = 13.16$, $P < 0.001$; # = permutational value). Similarly, mean values for CF (all 55 Qs = 0.713 ± 0.008 SE) and CF_{BRA} (0.722 ± 0.009 SE) were higher than the mean value for the CF_{CCA} (0.641 ± 0.018 SE), and the mean CF_{BRA} was significantly higher than the mean CF_{CCA} (same significance values as for the CL_{BRA} vs CL_{CCA} comparison due to the two indices being related). In all cases, the narrow standard errors indicated overall similarity in CLs and CFs across the species screened.

Discussion

Of the NN freshwater fishes screened for the River Ob basin, 42% were classified as posing a high-to-very-high risk of being invasive, and all of these species have also attracted high-risk screening scores for RA areas in southern regions of Europe (FISK: Simonović et al. 2013; Perdikaris et al. 2016; Piria et al. 2016) and Asia (AS-ISK: Li et al. 2017; Tarkan et al. 2017a, b), whereas other species (i.e. *Ctenopharyngodon idella*, *Hypophthalmichthys molitrix*, *Oncorhynchus mykiss*) were classified by FISK as medium risk in Southern Finland (Puntilla et al. 2013), and some of these medium-risk species have been identified as posing medium- and moderately-high invasiveness risk in other RA areas. For example, *Aristichthys nobilis* and *Ictalurus punctatus* received higher risk rankings for the Ob basin than elsewhere. Similarly, *Abramis brama* and *Sander lucioperca*, both ranked as ‘medium risk’ in the present study, were classified as ‘medium-to-high risk’ for other RA areas with both FISK (Simonović et al. 2013;

Perdikaris et al. 2016; Piria et al. 2016) and AS-ISK (Li et al. 2017; Tarkan et al. 2017a, b). Of these two, *Abramis brama* has also received an AS-ISK high-risk ranking as a translocated species for those parts of Great Britain where the species is not native (Dodd et al. 2019). The differences in risk rankings of NN fishes in the Ob basin relative to other RA areas may be associated with the broader range of environmental conditions in the Ob basin. Also, species that have been introduced, but have not yet established self-sustaining populations, achieved lower risk rankings.

Of the highest BRA scoring species in the present study, only *Perccottus glenii* has established self-reproducing populations and begun to spread widely across the Ob basin. Following its appearance in the mid-1970s via an unknown introduction vector and pathway (Reshetnikov and Chibilev 2009), *P. glenii* was predicted to expand its range across the Holarctic region (Reshetnikov and Ficetola 2011). Consistent with this, the species has spread rapidly and is now widespread throughout the region (Reshetnikov et al. 2017) and considered to be one of the most invasive freshwater fishes in Russia (Dgebuadze et al. 2018). Despite the lack of documented evidence of current impacts on ecosystems of the Ob basin, *P. glenii* is thought to be responsible for a decline in the abundance of macro-invertebrates and amphibian larvae in small water bodies (Reshetnikov and Chibilev 2009).

Other species with high BRA scores included those not yet reported for the Ob basin (i.e. *Ameiurus melas*, *Ameiurus nebulosus*, *Ctenopharyngodon idella*, *Gambusia holbrooki*, *Misgurnus anguillicaudatus*, *Oncorhynchus mykiss* and *Scardinius erythrophthalmus*). Of these, *C. idella* and *O. mykiss* are of aquaculture interest in Siberia, but currently, there is no evidence of self-sustaining populations in the wild. *Ctenopharyngodon idella* and *P. glenii* are the two highest (i.e. risk) scoring species under future climate conditions. *Ctenopharyngodon idella* was first introduced in the Ob basin (Novosibirsk Reservoir) in 1958, into Bukhtarma Reservoir in 1968, and in the early 1970s into the Irtysh-Karaganda canal, lakes in the south of Western Siberia (e.g. Ubinskoye and Sartlan) and into the Belovsky Reservoir (River Inya, right-bank tributary of the Ob). Currently, *C. idella* has self-sustaining populations in Belovsky Reservoir only, where water is warmer as a result of heated water effluents (Tskhai et al. 2001). In addition, *C. idella* is currently farmed and sometimes caught in natural waters, probably as escapees from fish farms. Overall, *C. idella* can exert potentially negative impacts on the recipient ecosystems by over-consuming aquatic vegetation, which serves as a spawning substratum for native phytophilic fish species and as a refuge for their juvenile fishes and for amphibians.

Of the medium-risk NN species, five have established and spread within the Ob basin, six have formed self-reproducing populations at certain locations only, one is present but without evidence of natural reproduction, and seven of them are

horizon species. Many of these medium-risk species attracted AS-ISK scores near the upper limit of the medium-risk category (i.e. the threshold between medium- and high-risk species). Four of these high-scoring, medium-risk species are dispersing more widely in the Ob basin, predominantly by natural means, i.e. *Abramis brama*, *Alburnus alburnus*, *Leucaspius delineatus* and *Misgurnus nikolskyi*. Whereas, another two of these species (*Ictalurus punctatus* and *Aristichthys nobilis*) are established in one or a few locations only, with no evidence of wider dispersal within the West Siberian Plain.

Of particular concern is the potential effect of future climate conditions on potential invasiveness; this led to increased risk scores (i.e. BRA + CCA) in 68% of the screened species (Table 1), which suggests that more than half of the existing and potential future NN species are likely to pose an increased risk of being invasive under the future, warmer climatic conditions predicted for the Ob basin (Groisman et al. 2013). Notably, the species for which AS-ISK scores decreased, and thus their relative risk, were all salmonids. However, these climate-related increases in AS-ISK score resulted in changes of risk ranking (low, medium, high) in two species only (Table 1): *Salmo trutta* decreased in rank from high to medium and *Sander lucioperca* increased in rank from medium to high. The confidence levels for these assessments were higher for the BRA scores than for the BRA + CCA scores, which is not surprising given the uncertainty associated with climate forecasting (Mehta et al. 2019).

In conclusion, the present risk screening study has highlighted several gaps in knowledge with respect to both native and NN fish species in the Ob basin. The process of dispersal of NN fish species in the West Siberian Plain is currently being monitored, but documented data on the adverse impacts (ecological, socio-economic, ecosystem services) exerted by NN fishes remain scarce if not entirely lacking. In particular, little is known of the species' population dynamics, especially their population size and reproductive status in the Ob basin. Even less is known of socio-economic impacts that invasive NN fishes could cause and how this could affect the ecosystem services provided by the Ob basin's fishery resources to the various regions of the West Siberian Plain. The notable decrease in assessor confidence in their responses to the climate change (CCA) questions highlights an even greater uncertainty of how NN fishes will respond to the warmer climate and the projected increased runoff due to increased precipitation during winter and reduced river discharges in summer (Reist et al. 2006). The outcomes of the present study provide essential information for regional environmental managers, in particular the identification of high-risk species (13 under current and 12 under future climate conditions) for which full risk assessments are recommended (Table 1). As such, the present study serves to inform the process of developing effective NN fish species policy,

legislation and management in the various geographical regions of the West Siberian Plain and, ultimately, to other regions across Russia.

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