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HOW LIKELY IS *LEPOMIS GIBBOSUS* TO BECOME INVASIVE IN POLAND UNDER CONDITIONS OF CLIMATE WARMING?

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Background. Despite increasing reports of non-native freshwater fish dispersal in Poland, a risk identification and risk assessment (RA) of their current or future impacts has not been undertaken. In this study, to advise policy and management decisions the Aquatic Species Invasiveness Screening Kit (AS-ISK) was applied for the first time in Poland (the RA area) to identify whether or not non-native pumpkinseed, *Lepomis gibbosus* (Linnaeus, 1758), a freshwater sunfish, posed a high risk of being invasive in the RA area.
Material and methods. The AS-ISK was used to screen *L. gibbosus* for its potential invasiveness in the RA area under current climate conditions of the RA area (i.e. humid continental) and future predicted climate conditions (i.e. temperature increase by 1.5–3.0°C). The risk screening was based on available evidence of the species' life-history traits (LHT) from its introduced European range, including both ambient and artificially-heated environments.
Results. A LHT-based model for predicting *L. gibbosus* invasiveness revealed that the population in the Oder Canal, which receives heated-water discharge from the "Dolna Odra" electric power station, is amongst the most invasive in Europe. The basic AS-ISK score of 16.5 suggests the species already poses a risk of being invasive in Poland, and this risk is expected to increase under future, warmer climate conditions (AS-ISK Climate Change score = 28.5). Factors and traits affecting *L. gibbosus*' invasiveness were: current rate and range of spread, high climatic match, parental care, relatively small size at maturity, opportunistic foraging behaviour, and elevated likelihood of being illegally stocked.
Conclusion. Although *L. gibbosus* is known to cause adverse impacts in some circumstances, these are poorly understood for most of Europe, including the RA area, where the species is likely to disperse and establish new viable populations more widely, especially under future climate conditions. This first application of AS-ISK in Poland emphasises the need for national-level risk screening of non-native species in general, and freshwater fishes in particular, as part of Poland's non-native species management strategy for the control and containment of invasive species.

Keywords: AS-ISK, pumpkinseed sunfish, biological invasions, non-native species management, risk analysis

INTRODUCTION

A major challenge facing government agencies responsible for the environment is the prediction of which species are likely to become invasive under future (warmer) climatic conditions (e.g. Rahel and Olden 2008). In Europe, the likely response of freshwater fishes to climate change has been modelled for some countries (e.g. the UK and France), where the introduced freshwater sunfish, the pumpkinseed, *Lepomis gibbosus* (Linnaeus, 1758), is predicted to benefit from the warmer conditions (Buisson et al. 2008, Britton et al. 2010, Fobert et al. 2011). However, no such projections nor risk analysis (i.e. risk identification, assessment, management and communication) have been undertaken for any freshwater fishes in Poland, where an increase in mean annual temperature by 1.5–3.0°C, similar to the UK (Buisson et al. 2008, Britton et al. 2010), is predicted to occur by the end of the 21st century (Anonymous 2013).

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A warmwater fish indigenous to eastern North America (Scott and Crossman 1973), *L. gibbosus* has a native range that extends southward from temperate New Brunswick (Canada) to sub-tropical peninsular Florida (USA). Widely introduced in Europe (Copp and Fox 2007), *L. gibbosus* populations are also found in a few locations in Brazil (de Magalhães and Ratton 2005, Santos et al. 2012). The first *L. gibbosus* introductions into Europe, beginning at the end of the 19th century, originated from stocks in Canada and New York State (USA) exported to France (Arnold 1990), where the species' establishment was said to have been 'long and laborious' (Kunstler 1908). Imported to Germany from the USA in the early 1880s (Yavno et al. 2020) by Max von dem Born, who was a pioneer of non-native fish and crayfish importations for aquaculture (Copp et al. 2005, Kowarik and Rabitsch 2010), and in the same year to France (Yavno et al. 2020). *Lepomis gibbosus* was subsequently introduced to the Třeboňsko region of the Czech Republic in 1929 (Baruš and Oliva 1995). Since then, the species has established populations in at least 28 countries of Europe (Copp and Fox 2007), where the northernmost (known) reproducing population is situated in southern Norway (Cucherousset et al. 2009)—this believed to have been an unauthorised release of fish imported from the Czech Republic for the aquarium trade (Sterud and Jørgensen 2006).

The motivations for *L. gibbosus* introductions are varied, such as for aquaculture use in France (Kunstler 1908), as a forage fish for introduced piscivorous fishes in Iberia (Elvira and Almodóvar 2001), as an ornamental pond fish in England (i.e. an 18th century equivalent of 'koi carp': Copp et al. 2002), and as an aquarium fish in some countries (e.g. Tandon 1976, Sterud and Jørgensen 2006). However, in some cases, there have been inadvertent transfers between water bodies as a contaminant of intentional stocking of aquatic species, such as those of young-of-year (YoY) common carp, *Cyprinus carpio* Linnaeus, 1758 (see Tandon 1976), and native aquatic plants (Copp et al. 2017b). But, the reported, intentional (but illegal) introductions into lakes in Denmark, stocked along with rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792), were based on the presumption that *L. gibbosus* would free *O. mykiss* from the fish louse *Argulus foliaceus* (J.K. Jensen, pers. comm.). Notably, this same parasite-removal role of *L. gibbosus* has also been observed at a commercial angling venue (B. Brown, Tanyard Fishery: pers. comm.), in a region of England where the species has been present since at least as early as the 1910s (Wheeler and Maitland 1973).

The first records of *L. gibbosus* from the inland waters of Poland (i.e. including areas of former Germany and the Czech Republic) were in the 1920s–1930s. These refer to single individuals in the River Oder near Krosno Odrzańskie (Pappenheim 1927) and Słubice (Boettger 1934), as well as the River Nysa Łużycka near Gubin (Hoffman 1928). Rare reports refer also to the River Warta near Gorzów Wielkopolski (Thienemann 1950), Martwe Lake near Dziwnów (Wiktor 1959), the Pilchowice Reservoir on the River Bóbr near Jelenia Góra (Balon 1964), and to common carp aquaculture ponds 'Andrzej' and 'Grabownica' in Milicz on the River Barycz (Witkowski 1979). All of the above-mentioned records were of transient fish and all within the River Oder system. In the 1980s, a self-sustaining population was established in the lower River Oder, at a site influenced by warm water from a nearby "Dolna Odra" electric power station (Heese and Przybyszewski 1985). And in the following years, other self-sustaining populations appeared in adjacent water bodies of the city of Szczecin (Porębski and Małkiewicz 1995, Gruszka 1999, Zięba et al. 2016).

Currently, *L. gibbosus* is one of 37 alien fish species recorded in Polish waters (Witkowski and Grabowska 2012). Although *L. gibbosus* is considered a warm-water species, its native and introduced ranges include countries with cold climates (e.g. Canada, Norway, and Switzerland). And although the species' life-history traits are known to vary in response to temperature (Copp and Fox 2007, Masson et al. 2015), the role of local climate in the species' establishment success remains less well studied. Nonetheless, the populations reported to be the most invasive are mainly those located in the southern parts of Europe (Copp and Fox 2007, Almeida et al. 2014), but as mentioned here above, mean annual temperatures in Poland are expected to rise, by the end of 21st century.

The aim of the presently reported study was to assess the current and future invasiveness potential of *L. gibbosus* in Poland, and specifically to: 1) evaluate the existing published life history pertaining to *L. gibbosus* invasiveness potential within a wider European context; and 2) assess the species' invasiveness ranking using the Aquatic Species Invasiveness Screening Kit (AS-ISK) of Copp et al. (2016b). The outcomes of the presently reported study will serve to demonstrate to environmental managers and stakeholders in Poland the potential use of AS-ISK as a decision-support tool for informing legislation, policy and management (i.e. prevention, control, containment, eradication) of potential, existing and future undesired translocations of non-native fishes, such as *L. gibbosus*, in the country.

MATERIALS AND METHODS

The risk assessment (RA) area, the current territory of Poland, which includes the Polish part of the River Oder drainage area where *L. gibbosus* was first reported (Pappenheim 1927), has a humid continental climate (Köppen-Geiger type Dfb, defined as cold, without a dry season and with warm summers: Peel et al. 2007). According to Abell et al. (2008), the RA area falls within the freshwater ecoregion 'Central and Western Europe', which extends from England in the west to the western part of Belarus in the east. Data in published literature on *L. gibbosus* invasiveness potential were sourced for areas in the vicinity of Poland, with particular attention to those of close proximity and of same climate class (i.e. Köppen-Geiger class D: Peel et al. 2007). Because the growth and life-history traits (LHTs) of non-native populations of *L. gibbosus* in Europe respond to temperature in a similar manner (Copp and Fox 2007) as native populations (Fox

1994), the LHT-based model for predicting *L. gibbosus* invasiveness (Copp and Fox 2007) was employed. The most recent version of this model (Masson et al. 2015) was used because it is based on all European *L. gibbosus* populations for which both back-calculated total length (TL) at age and age at maturity have been published. This highly (statistically) significant model permits the mean age at maturity (in years) to be predicted from mean juvenile growth (i.e. TL at age 2). To predict the mean age at maturity for the RA area, the published TL at age 2 value for the core Polish population (data from Heese and Przybyszewski 1985, cited in table 1 in Copp and Fox 2007) was plotted on a re-drafted version of this model. Because heated-water populations of *L. gibbosus* are known to mature at age 1 (Dembski et al. 2006), the mean TL at age 1 of this core population was also plotted on the LHT model (for information purposes) because it inhabits a canal of the lower River Oder (53°12′50.34″N, 014°28′8.31″E) that receives heated-water effluent from the "Dolna Odra" electric power station. The water temperature therefore is by up to 8ºC higher than that of the river upstream and in the warmest months the water temperature reaches 26–30ºC (Domagała and Kondratowicz 2005, Domagała and Pilecka-Rapacz 2007).

To identify the invasiveness potential of *L. gibbosus*, the AS-ISK decision-support toolkit* was used. A direct derivative of FISK v2 (the Freshwater Fish Invasiveness Screening Kit: Lawson et al. 2013) and the generic screening module of ENSARS (the European Non-native Species in Aquaculture Risk Analysis Scheme: Copp et al. 2016a), AS-ISK consists of 49 questions (Qs) on the assessed species' LHTs, invasion and environmental biology, biogeography and history of introduction. Responses to these Qs provide a Basic Risk Assessment (BRA) score (Copp et al. 2016c), which is complemented by six additional 'climate change' questions that ask the assessor to foretell, based on their knowledge of the species, the likely effects of predicted future climate on the risk screening (specifically, the risks and magnitude of introduction, establishment and dispersal). Response scores to these six Climate Change Assessment (CCA) Qs are added to the BRA score, yielding a composite BRA + CCA score. To each question, the assessor must provide a response and a justification for their response (including bibliographic references) and then rank their confidence in that response. The confidence ranking categories are: 1 = low, 2 = medium, 3 = high, 4 = very high (Copp et al. 2016c). In all cases, an overall score < 1 assigns a status of 'low risk' (hence, not likely to be invasive), whereas values ≥ 1 identify alien species as potentially invasive and posing either a 'medium risk' or a 'high risk'. Importantly, it is advisable to identify a 'threshold' value for the RA area concerned by way of a 'calibration' process to distinguish between species of medium and high risk of invasiveness (Copp 2013, Hill et al. 2017).

Because there has been no calibration of either FISK or AS-ISK for (freshwater fish in) Poland and the only FISK application to round goby *Neogobius melanostomus* (Pallas, 1814) in the River Oder Estuary (Czerniejewski and Kasowska 2017) relied on the 'reference' UK threshold of 19 (Copp et al. 2009), which shares the same freshwater ecoregion as Poland (Abell et al. 2008), the choice of BRA and BRA + CCA thresholds to distinguish between medium *vs* high risk was based on the following three axioms:

1) Based on a global evaluation of 36 applications of FISK worldwide (Vilizzi et al. 2019), and noting that the AS-ISK BRA score is loosely equivalent to the FISK score being based on the original 49 LHT-related Qs (see *Introduction*), a FISK threshold of 8.2 has been identified for Köppen-Geiger climate class D, in which the country of Poland lies entirely.
2) In a recent worldwide application of the AS-ISK decision support tool (McKenzie 2019), led by L. Vilizzi and G.H. Copp, a comparison of the mean FISK (v2: Lawson et al. 2013) and AS-ISK (BRA) scores for the same set of species across six RA areas [i.e. Southern Finland: Puntila et al. (2013) vs. Vilizzi et al. (unpublished data); Anatolia and Thrace: Tarkan et al. (2014) vs. Tarkan et al. (2017b); River Neretva Basin: Simonović et al. (2017); Gangneungnamdae Stream Basin: Kim and Lee (2018) vs. Vilizzi et al. (unpublished data); Belarus: Rizevsky and Vintsek (2018) vs. Vilizzi et al. (unpublished data); Singapore: Yeo et al. (unpublished data) vs. Vilizzi et al. (unpublished data)] has resulted in a difference between the scores equal to −0.2.
3) The only comparative FISK vs. AS-ISK application on freshwater fishes providing both BRA and BRA + CCA thresholds (Glamuzina et al. 2017) has identified a BRA + CCA threshold of 12.62, hence 2.62 units higher than the BRA threshold of 10 for the same set of species.

In light of the above: (i) the threshold of 8.0 (i.e. 8.2 – 0.2) was used to distinguish between medium and high risk for the BRA score; and (ii) the threshold of 10.8 (i.e. 8.2 + 2.6) was used to distinguish between medium and high risk for the BRA + CCA score. Notably, the latter case, use of information from only one study to derive an estimate of the BRA + CCA threshold falls within the scope of Bayesian adaptive management practice (Hilborn and Mangel 1997, Prato 2005).

RESULTS

The re-drafted and updated LHT-based model with points plotted from the Heese and Przybyszewski (1985) values for TL at age (Copp and Fox 2007, Masson et al. 2015) revealed that, regardless of the mean age at maturity used (i.e. ages 1 and 2), the *L. gibbosus* population in the heated canal near the "Dolna Odra" electric power station (the most abundant and viable in Poland) is within the 'invasive' range for European populations (Fig. 1).

Based on the reference threshold score of 8.0, the BRA score for *L. gibbosus* in Poland (16.5) falls within the 'high risk' category (Table 1). When the potential effects of climate change on the risk screening

* *www.cefas.co.uk/nns/tools.*

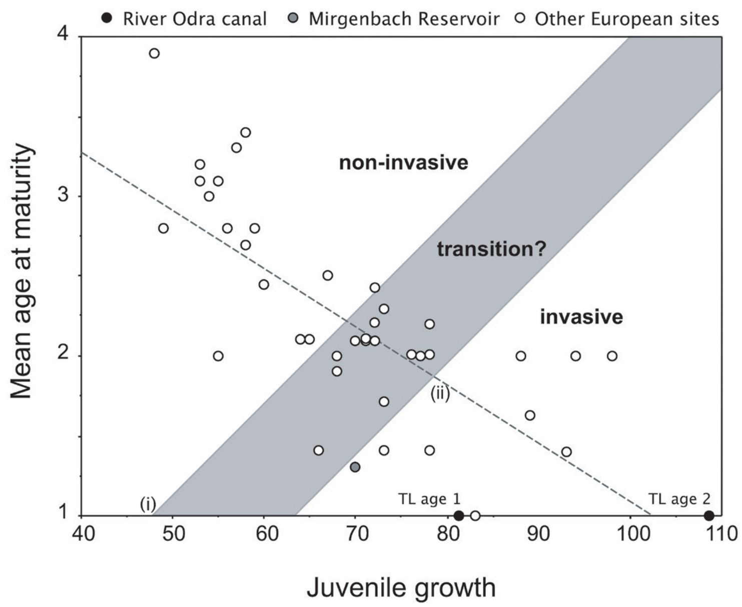

Fig. 1. Life-history-trait-based model for predicting *Lepomis gibbosus* invasiveness in Europe (Copp and Fox 2007), redrawn from Masson et al. (2015), presenting mean age at maturity (in years) as a function of mean juvenile growth (TL at age 2, in mm). The proposed physiological transition phase (shaded zone) between non-invasive and potentially invasive pumpkinseed populations is hypothesised as extending from the minimum age at maturity (the 45° line that traces from the intercept, at 'i') and the end of juvenile growth (which for many pumpkinseed populations is age 2; the 45° line that traces through the age 2 intercept with the regression slope, at 'ii'). Data points are given for the mean TL at ages 1 and 2 (filled circles) for the *L. gibbosus* population in the heated River Oder canal (from Table 1, Copp and Fox 2007) and that (shaded circle) for the Mirgenbach heated-water effluent reservoir in France (fig. 7, Masson et al. 2015) and other European populations (open circles)

responses are taken into consideration, *L. gibbosus*' BRA + CCA score increases to 28.5 (hence well above the 10.8 threshold) reflecting an even higher risk of the species being invasive in Poland in the future (Table 1). Factors and traits that increased *L. gibbosus*' AS-ISK score included a history of being invasive elsewhere, high climatic match, parental care, relatively small size at maturity, opportunistic foraging behaviour, and elevated likelihood of being illegally stocked. Traits that reduced the overall score included no likelihood of hybridisation with native species and low risks posed to native threatened or protected taxa (Table 1; Appendix 1). Overall, it is likely that *L. gibbosus* will continue to disperse and establish in the RA area under current climate conditions, and more likely under predicted future climatic conditions (Appendix 1). In the latter case, the risks of establishment and dispersal would increase the species' risk of invasiveness (Qs 50–52), and also the magnitude of future potential impacts (Qs 53–55).

The mean confidence levels for responses to Qs contributing to the BRA, CCA, and BRA + CCA scores for *L. gibbosus* in Poland were 2.45 (± 0.18 SE), 2.33 (± 0.61 SE) and 2.44 (± 0.17 SE), respectively, which suggests comparability among AS-ISK groups of Qs. Relative to *L. gibbosus* BRA and BRA+CCA scores published for other RA areas, those for Poland were consistently lower (Table 1) than for Lake Marmara (Turkey), River Neretva catchment (Bosnia and Herzegovina, and Croatia), and Thrace and Anatolia (Turkey).

DISCUSSION

The risk of invasiveness of *L. gibbosus* in Poland, such as revealed in this AS-ISK assessment, is a function of the species' probability to be introduced into, and to establish self-sustaining populations in novel environments (Copp and Fox 2007). This is evinced by the increasing number of populations reported in recent years (e.g. Graczyk et al. 2016, Zięba et al. 2016), including isolated water bodies where the releases were presumably the abandonment of unwanted pet fish (Zięba et al. 2016). Other accidental introductions have been as a contaminant of consignments of grass carp *Ctenopharyngodon idella* (Valenciennes, 1844), which were imported as 'fry' from Hungary (Graczyk et al. 2016). Similar accidental introductions as a contaminant have recently been reported in England, though the vector was water-filled trays of native plants stocked into a small angling water body for habitat enhancement (Copp et al. 2017b). In addition to natural spread, which is likely to be facilitated by the warmer temperatures and greater hydrological variability predicted for future climate conditions (Fobert et al. 2013, Zięba et al. 2016), *L. gibbosus* has a number of attributes that make it likely to be the target of intentional, future releases into new water bodies. Amongst these are the species' ease of capture by rod-and-line fishing (Evangelista et al. 2015), entrainment in landing and keep nets, its attractive coloration for ornamental purposes and aquarists (Copp et al. 2002), as well as its unusual (for Polish ichthyofauna) mating and nest-guarding behaviours (Scott and Crossman 1973, Almeida et al. 2012).

Table 1

AS-ISK scoring output for *Lepomis gibbosus* in some risk assessment (RA) areas within its non-native range of occurrence

Section/Category	Poland	Lake Marmara	River Neretva	Thrace and Anatolia
Biogeography/Historical	8.5	9.0	6.5	20.0
Domestication/Cultivation	2.0	1.0	0.0	4.0
Climate, distribution and introduction risk	2.0	0.0	1.0	2.0
Invasive elsewhere	4.5	8.0	5.5	14.0
Biology/Ecology	8.0	13.0	18.0	23.0
Undesirable (or persistence) traits	4.0	6.0	5.5	8.0
Resource exploitation	0.0	7.0	6.0	7.0
Reproduction	2.0	1.5	2.0	4.0
Dispersal mechanisms	2.0	−1.5	−1.5	2.0
Tolerance attributes	0.0	0.0	6.0	2.0
BRA Score	16.5	22.0	24.5	43.0
Climate change	12.0	6.0	11.0	10.0
BRA + CCA Score	28.5	28.0	35.5	53.0

Poland = RA area under study; Lake Marmara, Turkey = Tarkan et al. (2017a); River Neretva = Glamuzina et al. (2017); Thrace and Anatolia, Turkey = Tarkan et al. (2017b).

Regardless of the extent of the current non-native range of distribution, population density control for *L. gibbosus* should include both a reduction in the risk of escape of larvae and juveniles from semi-isolated water bodies (Fobert et al. 2013) and, where possible, eradication from isolated water bodies. Eradication may be possible by repeated depletion in small water bodies where only a few specimens are present; this was the case for the invasive, topmouth gudgeon, *Pseudorasbora parva* (Temminck et Schlegel, 1846), which was eradicated from a small pond by repeated electrofishing depletion (Copp et al. 2007). However, an attempt to remove *L. gibbosus* by intensive angling failed, and this led only to a decrease in maximal individual fish mass, which resulted in a population shift towards smaller size at maturity and overall slower growth (Evangelista et al. 2015). Whereas, repeated removals of *L. gibbosus* from isolated pond in the River Oder drainage resulted in reductions in spawning stock and in subsequent juvenile abundance in catches (Zięba et al. 2016). Also, introductions of native piscivores (especially northern pike *Esox lucius* Linnaeus, 1758), a species known to prey on introduced *L. gibbosus* (see Guti et al. 1991, Stakėnas et al. 2013), have proven effective to prevent *L. gibbosus* from becoming the dominant species thereby impacting on local biodiversity (van Kleef and Jongejans 2014). Other native piscivorous fishes known to prey on non-native *L. gibbosus* include brown trout, *Salmo trutta* Linnaeus, 1758, European eel, *Anguilla anguilla* (Linnaeus, 1758), and Eurasian perch, *Perca fluviatilis* Linnaeus, 1758 (see Stakėnas et al. 2013). Elsewhere, population expansion by *L. gibbosus* in the Mirgenbach Reservoir (France) coincided with the extinction of native population of *E. lucius* (see Masson et al. 2015), though this has been attributed to changes in water quality, such as increased temperature and copper concentrations (Masson et al. 2008).

For fish populations outside their native ranges, LHTs have proved to be particularly good predictors of non-native fish establishment success (e.g. Fausch et al. 2001, Marchetti et al. 2004, Vila-Gispert et al. 2005, Olden et al. 2006, Tarkan et al. 2016) and invasiveness (Copp and Fox 2007, Masson et al. 2015, Copp et al. 2016b). However, owing to the relation between latitude and temperature, intra-specific variation in LHTs at large spatial scales (cf. latitudinal clines) is also observed (e.g. Copp and Fox 2007, Fox and Copp 2014), including phenotypic plasticity and evolutionary adaptation (Muñoz et al. 2016). In the case of *L. gibbosus*, and similar to other species (Blanck and Lamouroux 2007), a decrease in growth and increase in age at maturity with latitude has been observed in non-native coolwater and warmwater populations of Europe (Copp et al. 2002, Cucherousset et al. 2009, Copp and Fox 2007), and this pattern is observed in both native and non-native populations (Fox and Copp 2014). In particular, significant variation has been found in adult *L. gibbosus* growth (age 2–3 increment in TL) and mean age at maturity with increasing latitude (Cucherousset et al. 2009). Under natural temperature conditions, juvenile growth rates (TL at age 2) in *L. gibbosus* appear to decrease significantly with increasing latitude, and differences in growth may extend into the adult stage resulting in stunted adult body size and regardless of lifespan (e.g. Copp and Fox 2007). Consequently, in case of ambient-temperature water bodies, invasiveness may reflect the thermal water regime. Within the more northerly part of its introduced range, such as the UK (Fobert et al. 2013) and the Netherlands (van Kleef et al. 2008), *L. gibbosus* is still not considered as being invasive, whereas in its southern range of distribution the species already shows traits testifying to its high invasiveness (Fobert et al. 2013).

Results of studies on *L. gibbosus* LHTs in artificially-heated water bodies provide further evidence that shifts in growth rate, age at maturity or YoY survival are a likely response to climate change (e.g. Dembski et al. 2006, Masson et al. 2015, Zięba et al. 2015). The exceptional water temperature regimes in the centre of *L. gibbosus* distribution in Poland are caused by the continuous inflow of post-cooling water from the Electric Plant "Dolna Odra" into an adjacent canal, which results in water temperature increases of ≈8°C in summer and up to 15°C in winter relative to the adjacent River Oder (Domagała and Kondratowicz 2005, Domagała and Pilecka-Rapacz 2007). As a result, the *L. gibbosus* population from the heated Oder Canal can be considered to possess LHTs that place it amongst the most invasive of all known populations of *L. gibbosus* in Europe (Fig. 1). In warmer water bodies, this phenomenon could result in more protracted spawning in some (Fox and Crivelli 2001) but not all circumstances (Zięba et al. 2010), with possible earlier onset of the juvenile period (Zięba et al. 2010). This would ultimately favour the growth and survival of age-1 individuals (Masson et al. 2015, Zięba et al. 2015), thereby increasing food intake and assimilation efficiency but also reducing energy expenditure (Cucherousset et al. 2009). As a result, contrary to ambient water sites, YoY individuals from warmwater populations are known to suffer lower mortality in their first winter of life (Zięba et al. 2015), and whilst facing a physiological trade-off between maturation and continued juvenile growth, they tend to mature earlier (Masson et al. 2015). Apart from a shift in the range of distribution, which is an expected response to climate change conditions (Parmesan 2006), LHTs adjustments allow the species to increase their overall survival (Zięba et al. 2015) and colonisation rate (Fobert et al. 2013). So, once relocated to warmer water bodies, *L. gibbosus* are expected to experience an increase in both recruitment and propagule pressure (Fobert et al. 2013).

In conclusion, this first application of AS-ISK in Poland emphasises the need for a more extensive risk screening of non-native aquatic species in general and non-native fishes in particular in the RA area. This will require reliable assessment and computation of AS-ISK BRA and BRA + CCA reference thresholds in order to provide environmental managers and stakeholders in Poland with the knowledge of potential adverse impacts of non-native aquatic species, both under current and predicted climatic conditions. In fact, this represents a crucial step for planning control and containment of invasive species as part of environmental management initiatives. With specific regard to *L. gibbosus* in Poland, the most viable and abundant population occupies an environment that is warmer than natural water bodies in its native range and relative to most non-native locations within Europe, including other infested waters in Poland. Being that *L. gibbosus* in both its native and introduced ranges occupies water bodies across broad climatic gradients (Fox and Copp 2014), this species' phenotypic plasticity renders it capable of expanding its range in Poland under both current and future climate conditions. However, despite the BRA and BRA + CCA scores, which classify *L. gibbosus* as likely to pose a high risk of invasiveness, the species' known adverse impacts are not yet fully understood for the RA area, and the evidence from other northerly parts of Europe is equivocal. For example, studies in southern England of the species' microhabitat and trophic interactions with native fishes found limited or no evidence for adverse impacts (Stakėnas et al. 2013, Jackson et al. 2016, Copp et al. 2017a), whereas impacts have been recorded in managed ponds in the Netherlands (van Kleef et al. 2008) and in natural streams of the Iberian Peninsula (Almeida et al. 2014). In fact, the bulk of evidence for *L. gibbosus* impacts in Europe comes from the Iberian Peninsula, where the species is invasive mainly in human-degraded environments (e.g. Ferreira et al. 2007, Almeida et al. 2009), though impacts in at least one 'natural' water course have been documented (Almeida et al. 2014). As such, further research is needed in Poland to assess the potential impact of *L. gibbosus* on this country's native species and ecosystems.

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APPENDIX 1

AS-ISK v2 output report for *Lepomis gibbosus* assessed for Poland

		Question	Response	Justification	Confidence
A. Biogeography/Historical					
1. Domestication/Cultivation					
1	1.01	Has the taxon been the subject of domestication (or cultivation) for at least 20 generations?	Yes	*L. gibbosus* has established populations in at least 28 European countries, and has been the subject of both intentional and incidental introductions (Copp and Fox 2007). This species is known to be easily reared in captivity, and was introduced in 1927 into the RA area for the purpose of keeping ornamental fish in ponds (Witkowski and Grabowska 2012)	Very high
2	1.02	Is the taxon harvested in the wild and likely to be sold or used in its live form?	Yes	*L. gibbosus* was reported as by-catch from commercial fishers operating in the RA area and is also the target of rod-and-line fishing. This species is also known to be illegally stocked in isolated ponds nearby the RA area (Zięba et al. 2016)	Very high
3	1.03	Does the taxon have invasive races, varieties, sub-taxa or congeners?	No	*L. gibbosus* can hybridise with most other lepomid species, especially with *L. cyanellus*, which is also introduced in some European countries	High
2. Climate, distribution and introduction risk					
4	2.01	How similar are the climatic conditions of the RA area and the taxon's native range?	Medium	Based on Köppen-Geiger climate classification system (Peel et al. 2007), the RA climate type is Dfb and covers the species' entire area of introduction. Whereas, Dfb covers ≈1/3 of the species' native range	Medium
5	2.02	What is the quality of the climate matching data?	Medium	Based on the comparison of Köppen-Geiger climate classification system (Peel et al. 2007)	Medium
6	2.03	Is the taxon already present outside of captivity in the RA area?	Yes	See e.g. Gruszka (1999), Domagała et al. (2014), Zięba et al. (2016)	Very high
7	2.04	How many potential pathways could the taxon use to enter in the RA area?	>1	See Zięba et al. (2016)	High
8	2.05	Is the taxon currently found in close proximity to, and likely to enter into, the RA area in the near future (e.g. unintentional and intentional introductions)?	Not applicable	See e.g. Gruszka (1999), Zięba et al. (2016)	Very high
3. Invasive elsewhere					
9	3.01	Has the taxon become naturalised (established viable populations) outside its native range?	Yes	See Jordan et al. (2009)	Very high
10	3.02	In the taxon's introduced range, are there known adverse impacts to wild stocks or commercial taxa?	Yes	See van Kleef et al. (2008)	Very high
11	3.03	In the taxon's introduced range, are there known adverse impacts to aquaculture?	No	To the best of the Assessor's knowledge, there are no adverse impacts to aquaculture	Low
12	3.04	In the taxon's introduced range, are there known adverse impacts to ecosystem services?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Low

		Question	Response	Justification	Confidence
13	3.05	In the taxon's introduced range, are there known adverse socio-economic impacts?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Low
B. Biology/Ecology					
4. Undesirable (or persistence) traits					
14	4.01	Is it likely that the taxon will be poisonous, or pose other risks to human health?	No	*L. gibbosus* is the subject of recreational fishing and is known to have excellent taste, to be low in fat and high in protein (Jordan et al. 2009)	Very high
15	4.02	Is it likely that the taxon will smother one or more native taxa (that are not threatened or protected)?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Low
16	4.03	Are there threatened or protected taxa that the non-native taxon would parasitise in the RA area?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Low
17	4.04	Is the taxon adaptable in terms of climatic and other environmental conditions, thus enhancing its potential persistence if it has invaded or could invade the RA area?	Yes	See Domagała et al. (2014)	High
18	4.05	Is the taxon likely to disrupt food-web structure/function in aquatic ecosystems it has or is likely to invade in the RA area?	No	Zięba et al. (2018) indicate that the taxon should not disrupt food-web structure in the RA area	Low
19	4.06	Is the taxon likely to exert adverse impacts on ecosystem services in the RA area?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Medium
20	4.07	Is it likely that the taxon will host, and/or act as a vector for, recognised pests and infectious agents that are endemic in the RA area?	No	See Pilecka-Rapacz and Sobecka (2008), Piasecki and Falandysz (1994)	Low
21	4.08	Is it likely that the taxon will host, and/or act as a vector for, recognised pests and infectious agents that are absent from (novel to) the RA area?	Yes	See Pilecka-Rapacz and Sobecka (2008), Piasecki and Falandysz (1994)	High
22	4.09	Is it likely that the taxon will achieve a body size that will make it more likely to be released from captivity?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Low
23	4.10	Is the taxon capable of sustaining itself in a range of water velocity conditions (e.g. versatile in habitat use)?	Yes	See e.g. Gruszka (1999), Masson et al. (2015), Valente et al. (2016), Zięba et al. (2016)	Very high
24	4.11	Is it likely that the taxon's mode of existence (e.g. excretion of by-products) or behaviours (e.g. feeding) will reduce habitat quality for native taxa?	No	To the best of the Assessor's knowledge, no published data are available on such impacts	Low
25	4.12	Is the taxon likely to maintain a viable population even when present in low densities (or persisting in adverse conditions by way of a dormant form)?	Yes	Personal observations	Medium
5. Resource exploitation					
26	5.01	Is the taxon likely to consume threatened or protected native taxa in RA area?	No	No published data are available on the diet of *L. gibbosus* for the RA area. However, unpublished data suggest no impact on threatened or protected native taxa	Low
27	5.02	Is the taxon likely to sequester food resources (including nutrients) to the detriment of native taxa in the RA area?	No	To the best of the Assessor's knowledge, no published data are available in regard	Low

Table continues on next page.

Table cont.

		Question	Response	Justification	Confidence
6. Reproduction					
28	6.01	Is the taxon likely to exhibit parental care and/or to reduce age-at-maturity in response to environmental conditions?	Yes	See Masson et al. (2015), Valente et al. (2016)	Very high
29	6.02	Is the taxon likely to produce viable gametes or propagules (in the RA area)?	Yes	See Domagała et al. (2014)	Very high
30	6.03	Is the taxon likely to hybridise naturally with native taxa?	Yes	*L. gibbosus* can hybridise with other species in the genus, such as redbreast sunfish, *L. auritus*, green sunfish, *L. cyanellus*, longear sunfish, *L. megalotis*, orangespotted sunfish, *L. humilis*, and warmouth, *L. gulosus* e.g. Scott and Crossman (1973)	Very high
31	6.04	Is the taxon likely to be hermaphroditic or to display asexual reproduction?	No	Pumpkinseed is a dioecious species with no asexual reproduction (Froese and Pauly 2017)	High
32	6.05	Is the taxon dependent on the presence of another taxon (or specific habitat features) to complete its life cycle?	Yes	Pumpkinseed prefers to spawn on sand or gravel substrata, where males before reproduction construct small, circular nests (McPhail 2007)	Medium
33	6.05	Is the taxon known (or likely) to produce a large number of propagules or offspring within a short time span (e.g. <1 year)?	Yes	See Zięba et al. (2010, 2015)	Very high
34	6.06	How many time units (days, months, years) does the taxon require to reach the age-at-first-reproduction? [In the Justification field, indicate the relevant time unit being used.]	2	See Masson et al. (2015), Valente et al. (2016)	Medium
7. Dispersal mechanisms					
35	7.01	How many potential internal pathways could the taxon use to disperse within the RA area (with suitable habitats nearby)?	>1	Intentional (illegal) stocking by anglers; natural drift from warm water canals (centre of occurrence) (Zięba et al. 2016)	Medium
36	7.02	Will any of these pathways bring the taxon in close proximity to one or more protected areas (e.g. MCZ, MPA, SSSI)?	No	No such sites are known in close proximity to the current centre of occurrence	Low
37	7.03	Does the taxon have a means of actively attaching itself to hard substrata (e.g. ship hulls, pilings, buoys) such that it enhances the likelihood of dispersal?	No	To the best of the Assessor's knowledge, no such means of attachment exist	Very high
38	7.04	Is natural dispersal of the taxon likely to occur as eggs (for animals) or as propagules (for plants: seeds, spores) in the RA area?	No	To the best of the Assessor's knowledge, such displacement mechanism is not present in the RA area	Low
39	7.05	Is natural dispersal of the taxon likely to occur as larvae/juveniles (for animals) or as fragments/seedlings (for plants) in the RA area?	Yes	Possible from the warm water outflow canal of the Dolna Odra Power Plant into the Oder River	Low
40	7.06	Are older life stages of the taxon likely to migrate in the RA area for reproduction?	Yes	Unpublished data (G. Zięba) on the migratory behaviour of *L. gibbosus* in the warm-water outflow canal of the Dolna Odra Power Plant	Very high
41	7.07	Are propagules or eggs of the taxon likely to be dispersed in the RA area by other animals?	No	To the best of the Assessor's knowledge, such means of dispersal does not exist	Low
42	7.08	Is dispersal of the taxon along any of the pathways mentioned in the previous seven questions (7.01–7.07; i.e. both unintentional or intentional) likely to be rapid?	Yes	See Zięba et al. (2016)	Low
43	7.09	Is dispersal of the taxon density dependent?	Yes	See Fobert et al. (2013)	Medium

		Question	Response	Justification	Confidence
8. Tolerance attributes					
44	8.01	Is the taxon able to withstand being out of water for extended periods (e.g. minimum of one or more hours) at some stage of its life cycle?	No	No	Low
45	8.02	Is the taxon tolerant of a wide range of water quality conditions relevant to that taxon? [In the Justification field, indicate the relevant water quality variable(s) being considered.	Yes	*L. gibbosus* can tolerate a wide range of environmental conditions (Vila-Gispert et al. 2002). Optimum temperature is 24–32°C, and lower oxygen levels than bluegill, *L. macrochirus*, can be tolerated (Holtan 1998). *L. gibbosus* is negatively affected when pH drops to 5.2–5.3 (Sun and Harvey 1986)	Very high
46	8.03	Can the taxon be controlled or eradicated in the wild with chemical, biological, or other agents/means?	Yes	See van Kleef et al. (2008)	High
47	8.04	Is the taxon likely to tolerate or benefit from environmental/human disturbance?	Yes	See Fobert et al. (2013)	Very high
48	8.05	Is the taxon able to tolerate salinity levels that are higher or lower than those found in its usual environment?	No	To some extent, though not as high as 15‰ (Keup and Bayless 1964)	High
49	8.06	Are there effective natural enemies (predators) of the taxon present in the RA area?	Yes	Northen pike *Esox lucius* (see van Kleef et al. 2008)	Medium
C. Climate change					
9. Climate change					
50	9.01	Under the predicted future climatic conditions, are the risks of entry into the RA area posed by the taxon likely to increase, decrease or not change?	Increase	See Zięba et al. (2015)	High
51	9.02	Under the predicted future climatic conditions, are the risks of establishment posed by the taxon likely to increase, decrease or not change?	Increase	See Zięba et al. (2010, 2015)	Very high
52	9.03	Under the predicted future climatic conditions, are the risks of dispersal within the RA area posed by the taxon likely to increase, decrease or not change?	Increase	See Fobert et al. (2013)	Very high
53	9.04	Under the predicted future climatic conditions, what is the likely magnitude of future potential impacts on biodiversity and/or ecological integrity/status?	Higher	To the best of the Assessor's knowledge, future climate change within the RA area may influence *L. gibbosus* potential impact on biodiversity and/or ecological integrity/status, becoming e.g. subdominant, competing for space and/or food, with commercial species	Low
54	9.05	Under the predicted future climatic conditions, what is the likely magnitude of future potential impacts on ecosystem structure and/or function?	Higher	To the best of the Assessor's knowledge, future climate change within the RA area may influence *L. gibbosus* potential impact on ecosystem structure and/or function, becoming e.g. subdominant, competing for space and/or food, with commercial species	Low
55	9.06	Under the predicted future climatic conditions, what is the likely magnitude of future potential impacts on ecosystem services/socio-economic factors?	Higher	To the best of the Assessor's knowledge, future climate change within RA area may influence *L. gibbosus* potential impact on ecosystem services/socio-economic factors by e.g. changing the attractiveness of angling venues, reducing nature reserve purity, consequently leading even to penalties from the EU	Low