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Paddlefish (*Polyodon spathula*) in Europe: An aquaculture species and a potential invader

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Summary

The paddlefish (*Polyodon spathula*) was first introduced to Europe in 1974, mainly due to its potential for rearing in natural polyculture ponds and large temperate reservoirs. The information on the history of paddlefish aquaculture efforts in Europe is scarce, as well as data on current paddlefish aquaculture status and trends. In addition, there is a lack of data on its presence and potential establishment in the wild, while its invasive potential and associated risks and impacts are largely unknown. In order to evaluate its current status in Europe, we conducted a survey among scientists, aquaculture producers and other stakeholders, and reviewed literature and data on the Internet. Based on the results obtained, we discuss the potential and the challenges in European paddlefish aquaculture development, and analyze paddlefish invasive potential and risks associated with its naturalization. Paddlefish aquaculture is well established only regionally in Europe, but offers relatively high potential for further development in pond farms. Nevertheless, future development will require careful planning, especially regarding market development and improved marketing strategies. While paddlefish likely represents a low-risk invader, improved control and reporting on trade and intentional and unintentional releases will be required. Given the lack of knowledge on potential impacts following its introduction, due caution seems highly advisable.

1 | INTRODUCTION

The paddlefish (*Polyodon spathula*) is an acipenseriform species, native to the Mississippi–Missouri drainage in the US, and formerly also in the Great Lakes Basin in the US and Canada (Reid, Edwards, & Cudmore, 2007). It is a pelagic filter feeder, with sexual maturation at an age of 6–8 years. In its native range, the species was subjected to fisheries for both meat and roe, sold for caviar production. Paddlefish was first introduced to Europe in 1974, when hatched larvae were imported from Missouri to the former USSR (Vedrasco, Lobchenko, & Billard, 2001). Over the following decades, paddlefish was introduced in aquaculture in additional countries throughout Europe, such as Romania, Bulgaria, Hungary, Austria and Germany (Arndt, Gessner, & Raymakers, 2002; Hubenova, Zaikov, & Vasileva, 2007; Kottelat & Freyhof, 2007; Lenhardt et al., 2011). The main motivation behind its introduction was the potential for rearing in natural polyculture ponds and large temperate reservoirs due to its planktivorous feeding (Holčík, 2006; Lobchenko, Vedrasco, & Billard, 2002).

However, even though paddlefish aquaculture in Europe seems to have had a period of relative popularity, with widely distributed rearing facilities throughout the continent, there is an apparent scarcity of data on both past and present paddlefish aquaculture status in Europe. Furthermore, there are numerous reports on both intentional and unintentional paddlefish introductions across Europe, which leaves largely uncertain the actual level of paddlefish naturalization and establishment in the wild, as well as its invasive potential and negative impacts.

To overcome these data gaps, we reviewed literature and Internet sources, and conducted a survey among scientists, aquaculture

producers and other stakeholders potentially involved in paddlefish as an aquaculture species and/or potential invader. Based on the results obtained, we discuss the main challenges and potential for European paddlefish aquaculture development, and analyze paddlefish invasive potential and risks associated with its naturalization.

2 | MATERIALS AND METHODS

In order to obtain current information on paddlefish rearing and introductions in Europe, we contacted persons that were identified as potentially possessing relevant and reliable information. These were mainly European researchers dealing either with sturgeon ecology, management and aquaculture, or with freshwater fish invasions. They were identified either through personal contacts, or by being authors of key papers dealing with these topics. For countries characterized by a lack of data and contacts, or by their unresponsiveness, we also contacted researchers dealing with freshwater aquaculture and fish ecology in general, as well as aquaculture producers and representatives of relevant governmental institutions. Each person was sent a survey comprising 12 open ended questions on paddlefish aquaculture and introductions, distributed by E-mail (Appendix S1). The survey was provided either in English or Russian language, and focused on paddlefish presence in the respective country, time of import and country of origin, aquaculture production, rearing quantities, number of aquaculture facilities, quality of paddlefish market, expected production trends and plans, major observed problems and advantages in paddlefish rearing, paddlefish introductions and unintentional releases into the wild, presence of naturalized or established populations in the wild, effects on natural ecosystems and communities, personal opinions on paddlefish establishment and associated invasion risk, and relevant national legislation. In the last question, respondents were asked to suggest potential further contacts. The survey was distributed during November 2016 to May 2017 to 95 persons from 36 countries, with a response rate of 68% (i.e. 65 respondents from 34 countries).

As a complement to the survey data, a literature review was conducted, as well as a comprehensive search of information on the Internet. The Internet search was performed during January 2017 using the Google search engine in multiple languages. It was directed to information on market structure, commodities, prices and rearing facilities.

3 | RESULTS AND DISCUSSION

3.1 | Rearing history and current status

Paddlefish is cultivated in fish farms in a number of European countries (Hanel et al., 2011). Introduction of the paddlefish to Europe was driven by its intended use for aquaculture production, because of the quality of its meat and caviar (Holčík, 2006). Initial imports to Europe were 5,000 hatched larvae originating from the USA (Missouri) and introduced in the USSR in 1974, with further introductions in both 1976 and 1977 (Vedrasco et al., 2001). Paddlefish was subsequently imported to the Moldovan SSR (now Republic of Moldova) in 1978, to Hungary in 1986, to Germany in 1987, to Austria in 1990, to Romania and Slovakia in 1992, to Czech Republic and Poland in 1995, to Greece in 1997, to Belarus in 2001, and to Bulgaria in 2003 (Vedrasco et al., 2001; Holčík, 1991, 2006; Hubenova et al., 2007; Kottelat & Freyhof, 2007; Uzunova & Zlatanova, 2007; Nowak, Szczerbik, Tatoj, & Popek, 2008; Koščo, Košuthová, Košuth, & Pekárik, 2010; Lusk, Lusková, & Hanel, 2010; Mastitsky, Karatayev, Burlakova, & Adamovich, 2010; Musil, Jurajda, Adámek, Horký, & Slavík, 2010; Mims & Shelton, 2015; DAISIE, 2016; Perdikaris et al., 2016; Appendix S1). According to survey respondents, paddlefish aquaculture is absent from the UK, Ireland, France, Spain, Portugal, Italy, Switzerland, Albania, Macedonia, Montenegro, Netherlands, Serbia, Bosnia and Hercegovina, Sweden, Norway, Finland, Lithuania and Estonia. Available information also indicates that it is absent from the Latvia, Belgium and Luxembourg, although we did not manage to find respondents from those countries.

Paddlefish was imported with the aim to be reared in carp pond farms, motivated by its characteristics as a warm water species, filter feeder and economically valuable fish, which is able to adapt to conditions of intensive culture and reduce the amount of zooplankton in ponds (Musil et al., 2010; Nowak et al., 2008). The interest by European aquaculture was driven mainly by the high growth rate of paddlefish, the supplemental utilization of natural feed, potential for polyculture, and the potential of producing black caviar (Hubenova et al., 2007). The species was considered a good candidate for polyculture, as a complement to or even substitution for the less valuable carps (Lobchenko et al., 2002; Vedrasco et al., 2001).

There were significant research activities on paddlefish rearing carried out in Russia, Moldova and Romania, after which rearing commenced in commercial farms for meat production (Vedrasco et al., 2001). In Moldova it was reared in several fish farms in polyculture (at least until 2000; Lobchenko et al., 2002). Overall, paddlefish was reared only on a limited scale in central and western Europe (Williot et al., 2001). According to Kolman (2000 as cited in Nowak et al., 2008), in Poland it was an aquaculture species of rather low interest, although it was stocked in some farms, while Grabowska, Kotusz, and Witkowski (2010) reported that it is cultivated in Poland in many fish farms and privately owned recreational "put-and-take" waters for anglers. In Bulgaria, paddlefish is reared in regions of Plovdiv and Vidin (Hubenova et al., 2007). In the Russian Volga Delta, paddlefish was also reared to commercial size for meat production (Lobchenko et al., 2002). In Ukraine, it is reared in polyculture with common carp (*Cyprinus carpio*), Chinese carp (*Hypophthalmichthys molitrix*), pike (*Esox lucius*) and wels catfish (*Silurus glanis*; Mims & Shelton, 2015). In addition, aquarists occasionally rear this species as an ornamental fish, mostly for garden ponds (Holčík, 2006). According to Musil et al. (2010), it is cultivated in the Czech Republic in intensive and/or pond aquaculture, and its importance and use as an ornamental and game fish in private ponds continues to increase. In Denmark, several specimens have been introduced in several ponds for "put-and-take" recreational angling (Figure 1), which represents the northernmost documented location of paddlefish in Europe.

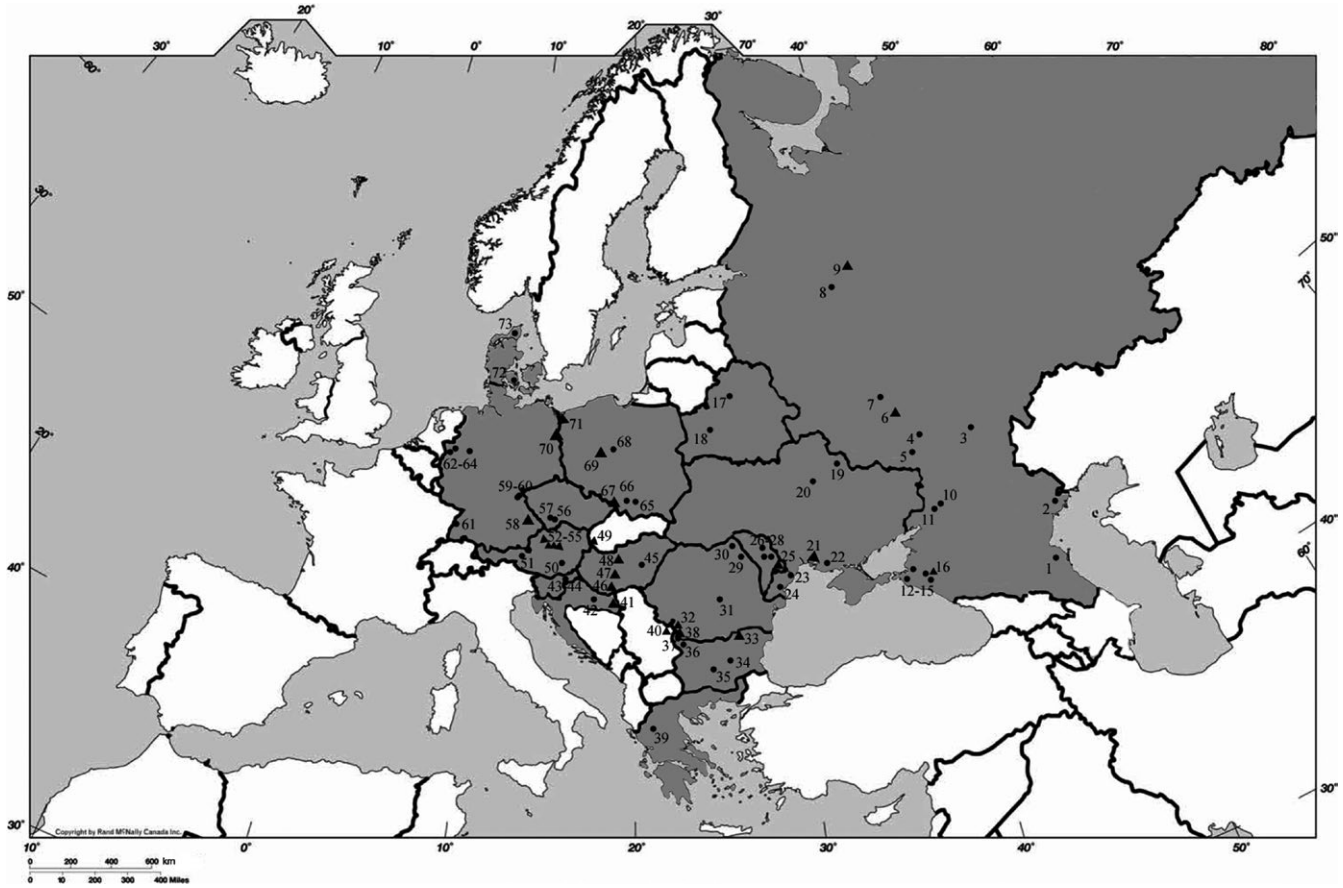

FIGURE 1 Presence of paddlefish in Europe. Countries with confirmed paddlefish rearing are marked in gray; circles—paddlefish aquaculture facilities, triangles—paddlefish records and introductions in open waters. For detailed location descriptions see Appendix S1

Results indicated that the European paddlefish aquaculture is still mainly located in Eastern and Central Europe (Figure 1; Appendix S1). Survey results, literature and Internet data revealed that specific paddlefish production characteristics differed among countries. However, as there were also some inconsistencies among survey respondents from the same country, survey results should be interpreted with due caution. The results can be compiled as follows:

- Paddlefish is currently reared in Europe mainly for meat production, and to a lesser extent for the production of ornamental fish or stocking material.
- Paddlefish meat is mostly sold regionally on domestic markets, refrigerated or as smoked or cured meat.
- Some of the countries, such as Czech Republic and Moldova, currently seem to rear it exclusively for ornamental purposes.
- Paddlefish caviar production in Europe is virtually absent, mainly due to poor market demand. On the other hand, Mims and Shelton (2015) reported presence of paddlefish caviar production in Russia, with exports into the European Union (EU).
- It is also popular as a game fish, and it is kept in Russia, Poland, Denmark, Czech Republic and Moldova in privately owned waterbodies under a "put-and-take" recreational angling.

3.2 | Production, quantities and prices

Information on production quantities is scarce and inconsistent, and should be therefore taken with due reservations. Historic production of paddlefish in Russia and Ukraine was about 70 and 20 tonnes/year, respectively. The survey data on current production in the two countries shows vast differences between assessments. Different respondents claimed that the current production in Ukraine ranges between 20 and 100 tonnes/year. According to Mims and Shelton (2015), the largest paddlefish farm in the Ukraine ("Cherkassyrybgosp farm") had a production of about 20–25 tonnes/year of processed paddlefish. However, current production in Ukraine is likely to be significantly lower, due to ongoing civil war. Other countries, such as Romania, Czech Republic and Poland had much lower production quantities (e.g., a few hundred kg/year in Poland during 2005–2007), while aquaculture is currently still in the establishment phase in Belarus and Croatia. The number of aquaculture facilities per country is relatively low, and currently ranges from 2 to 4 facilities in Romania, Belarus, Czech Republic, Slovenia, Austria, Moldova and Poland, up to 5–10 facilities per country in Ukraine and Russia.

Price of meat varied among countries. Quotes on the Internet ranged from 1 $/kg (Belarus) to 2–2.5 $/kg (Ukraine), and

occasionally prices up to 13 $/kg were observed (Russia). Fish in ornamental trade are sold at substantially higher price, between 75 and 320 $/specimen in Germany, and between 5 and 300 $/specimen in Russia, depending on the fish size. The price of paddlefish sold as stocking material to aquaculture facilities in Romania ranged from 0.12 $/specimen for larvae to 0.62 $/specimen for 5 cm fish.

Results of the survey indicated differing projections of future trends in paddlefish production. In Russia, production was predicted to remain stable, with the potential for 5%–10% annual growth, and the domestic market remaining open for larger quantities produced. In Belarus, there are plans for intensive development of both meat and caviar production, targeting both the domestic and international markets. Production in Ukraine is expected to stagnate due to the current economic and political situation, with a potential for increase in production up to 100 tonnes/year under positive development. According to Mims and Shelton (2015), production in Ukraine has a potential to reach production of up to 300–400 tonnes/year. Respondents differed in their predictions for Hungary, ranging from stagnation to growth in production, up to 5 tonnes/year by 2019. In Moldova, paddlefish broodstock is considered to be nearly lost, with only a few specimens left in several private ponds. Nevertheless, there are plans for rebuilding the broodstock. For the Czech Republic and Austria, decreasing trends are expected, while paddlefish aquaculture is in the establishment phase in Croatia, with no data on the planned production levels. Respondents indicated that there is currently no information on aquaculture development plans in other countries.

Based on feedback provided by survey respondents, potential major advantages of paddlefish aquaculture from the European perspective includes the possibility of rearing paddlefish in polyculture with carps, sturgeon, catfish and other species, the low rearing costs and the potential for high profits, the higher market price than for carp meat, simple rearing requirements, the use of natural forage base, the high growth potential, good meat quality, and hardiness of adults in pond rearing. This is however contrasted by reported drawbacks in paddlefish aquaculture, as described below.

3.3 | Drawbacks in aquaculture rearing

Major problems related to paddlefish aquaculture in Europe, according to survey respondents, are:

- High cost of stocking material due to demands related to juvenile feeding.
- Low survival of juveniles, especially due to predation by piscivorous birds, such as cormorants; a behavioural characteristic that makes them susceptible to predation are their feeding patterns, as they tend to remain close to the water surface.
- Acute lack of broodstock and stocking material in some countries, such as Ukraine and Moldova.
- Production prone to losses due to poaching.
- Aquaculture development hindrance by current legislation, such as regulation on invasive species in EU countries, and a lack of recognition of paddlefish as aquaculture species in national legislation in some countries (i.e. in Ukraine).
- Time needed for fish to reach maturity.
- Low rearing density in ponds, of about 30–50 individuals/ha.
- Unsuitability for intensive production; low success in feeding with formulated diets, while the maximum rearing density of 8–10 kg/m^3 in recirculating systems is not cost effective, when compared with both higher product price and higher output in sturgeon farming (e.g. approximately eight times higher rearing density in Siberian sturgeon, *Acipenser baerii*).

As outlined above, the main challenges faced by paddlefish aquaculture in Europe are related to the rearing of stocking material, which suffered from considerable losses of early life phases in the rearing process over the first summer, resulting in low volumes of the produced market-size fish (Hubenova et al., 2007). High broodstock mortality of unknown reasons sometimes led to the eradication of stocks, which occurred in Ukraine and Bulgaria (Mims & Shelton, 2015). Major factors for the low survival rates observed in paddlefish culture in ponds are declines in zooplankton, fluctuation of water temperature, and the presence of predators (i.e. birds, frogs, snakes, etc.; Hubenova et al., 2007). Poaching is recognized as another obstacle for paddlefish rearing in ponds and reservoirs in some countries (Mims & Shelton, 2015). According to respondents, susceptibility of paddlefish aquaculture to poaching is probably driven by their low density, high value, and high impact of poaching on standing stock.

Survey respondents were mostly unanimous that Europe represents relatively poor market for paddlefish meat. This holds true also for Central and Eastern Europe where it is mainly produced and paddlefish is considerably less expensive compared to sturgeon meat. The primary reason is traditional market, where customers prefer traditionally reared fish such as common carp. Despite the current market situation, respondents from Russia and Ukraine considered these two countries as unsaturated markets with good potential. Respondents from Hungary indicated that producers in this country are apparently planning to overcome the poor demand for paddlefish meat by processing it into convenience food products. As in the meat market, the interest in paddlefish caviar production in Europe is low, mainly due to a lack of market demand. Similarly as with meat, caviar markets are largely conservative, with customers preferring traditional sturgeon caviar. Moreover, paddlefish caviar ("Spoonbill") also reaches a comparatively lower price on market than the caviar of well established sturgeon species (Bronzi & Rosenthal, 2014).

According to the survey respondents, export of meat seems to be largely lacking, partly due to low production levels, with the exception of Hungary, where most of the production seems to be oriented towards the export. Exports are largely focused on fish for the pet trade. Fish are frequently exported to western European countries such as Belgium, France and Germany (Mims & Shelton, 2015).

3.4 | History of introductions in open waters

Most of the countries with paddlefish aquaculture have records of incidental paddlefish catches in natural waters (Jelkić & Opačak, 2013; Figure 1). In Poland it was introduced in natural waters in 1990s (Grabowska et al., 2010). It was occasionally recorded in open waters in Germany (Arndt et al., 2002), and since 1993 in Austria, as well as in Bulgaria in 2000 (Kutsarov, 2005), in Slovakia in 2004 (Holčík, Klindová, Masár, & Mészáros, 2006), in Serbia in 2006 (Lenhardt et al., 2006; Simonović, Marić, & Nikolić, 2006), and in Croatia in 2011 (Jelkić & Opačak, 2013). The primary vector of introduction was accidental releases from aquaculture (Grabowska et al., 2010; Hanel et al., 2011), and to a lesser extent intentional releases (Bogutskaya & Naseka, 2002). Trade by aquarists and rearing as ornamental fish in ponds represents another source of introductions (Gessner et al., 1999; Lelek, 1996). It is believed that all catches of paddlefish in the Upper Danube River originated from intentional introductions by aquarists, while those in Middle and Lower reaches of the river are attributed to accidental releases from aquaculture (Holčík, 2006; Lenhardt et al., 2011).

3.5 | Population establishment, status and invasiveness

In Russia, paddlefish was stocked in several water bodies where it is occasionally caught, but there is no evidence of establishment of reproducing populations (Holčík, 2006; Kottelat & Freyhof, 2007). Elvira (2000) suggested that specimens introduced in Russian rivers could have established natural populations, yet the evidence for natural reproduction is still lacking (Bogutskaya & Naseka, 2002). Some reports indicate that it has not established viable populations in several reservoirs in Russia and China, despite regular stocking (Holčík, 2006).

Occasional catches are reported from central European rivers, mostly originating from escapement due to flooding events in pond farms, or deliberate releases (Arndt et al., 2002; Czerniejewski, Keszka, & Rybczyk, 2008). In these rivers, paddlefish represented 0.32% of total sturgeon catches between 1991 and 2000 (Arndt et al., 2002).

Paddlefish is generally considered to have failed to establish viable populations in the Danube River so far (Jarić, Jaćimović, Cvijanović, Knežević-Jarić, & Lenhardt, 2015). This is supported by Holčík (2006), who claimed that its life history and the current deteriorated state of the Danube River environment and connectivity makes its establishment or naturalization highly unlikely. On the other hand, Simonović et al. (2006) claimed that its life history, including feeding and swimming capabilities, makes it particularly well adapted to the Danube River. Vassilev and Pehlivanov (2005 as cited in Jelkić & Opačak, 2013) reported observations of juvenile paddlefish found in the Lower Danube River. This finding was interpreted by some authors as a likely indication that they have passed through the acclimatization phase in that part of the Danube, as well as that a similar outcome could occur upstream (Zorić et al., 2014). Neverthless, without more substantial evidence, escapement from aquaculture or deliberate release can not be dismissed.

Paddlefish is considered to be an unlikely invader, with a low probability of establishing self-sustained populations in Europe, and this was consistent both within survey results and in literature. All respondents considered paddlefish as an unlikely invader based on the following arguments:

- It is considered to be a sensitive species that spawns under special conditions.
- It has a low population growth rate and long generation time.
- It is susceptible to predators during its early life, especially to piscivorous birds.
- Adults are easy to catch, due to large body size and pelagic feeding, so they are exposed both to commercial fishery and to poaching.

This point of view is supported by Bomford, Barry, and Lawrence (2010), who determined that paddlefish belongs to one of the least successful groups of fish regarding establishment in exotic ranges, and the studies involving Fish Invasiveness Scoring Kit (FISK) assessments consistently ranked it among the lowest scoring species, with low to medium invasiveness (Copp et al., 2009; Mastitsky et al., 2010; Perdikaris et al., 2016; Piria et al., 2016; Puntila, Vilizzi, Lehtiniemi, & Copp, 2013; Simonović et al., 2013). The main sources for unintentional introductions are escapement from farms and ponds with ornamental rearing. Since the species successfully reaches sexual maturity in aquaculture, it remains an unanswered question if it is able to reproduce successfully under natural conditions (Hanel et al., 2011; Lobchenko et al., 2002; Musil et al., 2010). Information on habitat conditions for spawning is presented by Mims and Shelton (2015). Some respondents indicated that the south of Russia has suitable conditions for population establishment, and that there are unconfirmed claims of established populations in some rivers in that region. Due to the potential that introductions have in some cases resulted in established natural populations, paddlefish occurrence should be watched closely (Elvira, 2000; Lenhardt et al., 2006).

3.6 | Potential impacts

There is little information available to predict potential impacts of this species in European natural waterbodies (Gollasch, Cowx, & Nunn, 2008; Lenhardt et al., 2011). Simonović et al. (2006) reported that paddlefish could have a negative impact on the already endangered natural sturgeon populations residing in the Danube. Gollasch et al. (2008) identified three types of potential impacts: competition with native fish species for food and critical habitat, such as spawning sites, introduction of novel parasites and diseases, and indirect environmental impact through habitat degradation, by effects on benthos and water turbidity through feeding.

Transfer of pathogens probably represents one of the more likely potential impacts, and there are reports that some newly introduced paddlefish specimens were infected with a bacterial agent (Uzunova

& Zlatanova, 2007). Disease transfer into wild populations is recognized as the most likely environmental risk of exotic sturgeon aquaculture (Arndt et al., 2002). As an example, the ship sturgeon (*A. nudiventris*) fishery in the Aral Sea crashed following an epizooty caused by *Nitzschia sturionis*, a gill trematode that was introduced with stellate sturgeon (*A. stellatus*; Zholdasova, 1997).

4 | CONCLUSIONS

Paddlefish culture represents a marginal aspect of aquaculture fish production in Europe, with a limited range to warm, large scale pond farming. In some countries a moderate to good potential for further development is noted, while in other areas only niche production for ornamental trade is a relevant market. Nevertheless, future development will require careful planning, especially regarding cost effectiveness, market development and improved marketing strategies. As a prerequisite, low juvenile survival must be resolved through development of novel rearing approaches, while predation control and stricter control of poaching seems to be a relevant issue locally. Broodstock husbandry, development and selection for aquaculture purposes should be targeted through cooperation with paddlefish managers, both in its native range in the United States and among European countries.

Paddlefish seems to represent a low-risk invader. Nevertheless, improved control and reporting on unintentional releases would be beneficial. It will also be important to enforce stricter regulation of the paddlefish aquarium trade throughout Europe, and increased scrutiny of imported and reared specimens to control the presence of and potential transfer of parasites and diseases (Arndt et al., 2002).

Some respondents expressed positive opinions regarding the effects of paddlefish introduction and establishment in natural waters, perceiving them as beneficial and having a desirable contribution to the native fauna and fishery stocks. A similar opinion can be also encountered in scientific literature (e.g. Mims & Shelton, 2015). Nevertheless, given our lack of knowledge on potential impacts following its introduction, a precautionary approach seems highly advisable (Jarić & Cvijanović, 2012), and intentional stocking of open water bodies should be discouraged.

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SUPPORTING INFORMATION

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