Int Aquat Res (2021) 13:89–107
https://doi.org/10.22034/IAR.2021.1920885.1129

REVIEW

Paddlefish, *Polyodon spathula*: Historical, current status and future aquaculture prospects in Russia

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Received: 16 January 2021 / Accepted: 31 March 2021 / Published online: 25 June 2021

Abstract In the wild, overfishing, habitat loss, industrial and agriculture activity has led to the degradation of freshwater habitats and, therefore, dramatically declines the Mississippi paddlefish (*Polyodon spathula*) stocks (Stone 2007). Paddlefish gain a growing commercial interest in the USSR/Russian Federation due to its ability to produce high-quality caviar. Also, it can be reared in polyculture ponds and a wide range of temperate reservoirs. Therefore, aquaculture of these valuable fish is necessary to meet consumer demand in Eastern European markets with flesh and caviar. Published information about the culture of paddlefish in the USSR/Russian Federation is scarce and not permanently available. Regarding our study, data were collected from English reports and translated Russian official statistics and studies. Also, FAO fisheries data from 1880 up to 2010 for paddlefish were included. Moreover, caviar production data and prices were surveyed from companies. The collected data could briefly represent the historical and current status of paddlefish aquaculture and provide insight into the expected future production in the Russian Federation. Besides, it investigates the drawbacks of paddlefish aquaculture development and the potential challenges in Russian territories. Also, it discusses potential impacts related to the preservation of the breeding stocks, population naturalization and invasiveness of the species in the southern parts of Russia (*i.e.*, in the Volga-Caspian basin): Saratov, Rostov, Astrakhan Oblast and Krasnodar regions. Furthermore, this review aimed to gather the available data and the latest final findings that may address the welfare of paddlefish data to fill the knowledge gap towards improving the management of this species. In addition, future development prospects can be supported by government oversight through accurate accounting and financing for private farm activity.

Keywords Paddlefish . Cultivation . Meat . Caviar production . Sustainability

Introduction

The Mississippi paddlefish, *Polyodon spathula* (Walbaum 1792), is an endangered (Grady 2004; Graham 1986) Acipenseriformes species belonging to the family Polyodontidae and endemic to the Northern Hemisphere. It is distributed in 26 contiguous states in North America and south of Canada in the riverine streams such as the Great Lakes Basin (Jarić et al. 2019; Parker 1987; Parker 1988; Reid et al. 2008), as well

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as in different types of broad rivers and backwater areas. Also, it was found in Mississippi, Ohio, tributaries of Arkansas rivers, and Missouri drainage (Page and Burr 2011; Reid et al. 2008). It is a potamodromus-pelagic species that has been adopted into aquaculture as a filter feeder in mono or polyculture farming systems. Late sexual maturity occurs at seven up to 14 years, and at a size of 10-15 kg, it can reach up to 55 years old (DeVries et al. 2009; Mims and Shelton 2015; Elnakeeb et al. 2020). In the wild, habitat destruction and river modification are the most prevalent changes influencing *P. spathula* distribution and abundance (Graham 1997). Thereby, broodstocks have diminished in most United States freshwater streams since the beginning of the last decade (Graham 1997).

Based on the culture strategies organized by VNIRO, specifically at the beginning of the 1970s, the Soviet Union started several remarkable developmental efforts towards sustaining the aquaculture industry. One of them was initiated with the import of the *Polyodon spathula*, one of the leading representatives of the sturgeon-feeding in the world (Burtsev and Gershanovich 1976; Reshetnikov 1997; Vinogradov et al. 2005). Likewise, Eastern European countries started to shed light on paddlefish aquaculture. In response to its farming potential in polyculture, it would make it possible to utilize the enormous bio-energetic resources of inland water bodies and to obtain valuable products in a relatively short time-period (2-3 years). In addition, the natural climate changes prevalent in Russia are suitable as feeding habits for planktivorous species (Holčík 2006; Lobchenko et al. 2002).

In 1974, the Soviet Union was the first country which imported fertilized eggs from Missouri, U.S to the Krasnodar oblast experimental fish ponds "Goryachi Klyouch farm". Consequently, paddlefish cultivation was widely practiced in many USSR/Russian farms to produce caviar and spread to many countries all over Eurasia, especially in the EU and China (Melchenkov et al. 1996; Vasetskiy 1971;Vedrasco et al. 2001). Since 1993, 15 countries in Europe, such as Germany, Hungary, Romania, Austria, and Bulgaria developed the cultivation of paddlefish with secondary introductions of hatched larvae from the former USSR or directly from the USA to support meat and caviar production (Holcík 1991; Arndt et al. 2002; Hubenova et al. 2007; Kottelat and Freyhof 2007; Lenhardt et al. 2011).

The successful trials achieved in paddlefish naturalization by the egress from the culture system facilities had been first progressed in the southern Russian territories to establish in the Volga-Caspian basin (*i.e*., Saratov, Rostov, Astrakhan Oblast and Krasnodar regions) (Holčík 2006). Despite the wide spread of paddlefish farms in most European countries, there is a lack of informative data about paddlefish aquaculture and marketing. Moreover, most studies have focused on biological characterization, ecological diversity, reproductive behavior, partial genome sequencing, phenotype-to-habitat relations, seasonal growth patterns, *etc*. Such studies do not shed light on possible risks and the potential for paddlefish development.

Over the last 40 years, the leading role of Soviet scientists have emerged in making fruitful scientific efforts to study the biological aspects of the spawning process and the acclimatization behavior. Nevertheless, the attempts did not succeed in adapting paddlefish to the wild, even though the species has been repeatedly stocked/released into the Russian fresh water streams for nearly fifty years. Also, paddlefish fisheries data from the Volga River and the Volga-Caspian delta are insufficiently available. Furthermore, there is a lot of evidence confirming the failure of all attempts to establish paddlefish stocks in an open water streams in Russian territory, in addition to their negative invasive impact on the equilibrium of aquatic-systems (Bogutskaya and Naseka 2002; Holčík 2006; Kottelat and Freyhof 2007; Ponomareva et al. 2014). Besides, extensive dam building in the mid 1900's significantly reduced the extent of the paddlefish movements. However, a recent screening for invasiveness placed the paddlefish in the medium-risk category (Vilizzi et al. 2019).

There is still a very limited market for the flesh, and their market price per ounce is still significantly low compared to caviar (Reed and Drabelle 2019). Also, any aquaculture facilities remain entirely tied to the caviar as their sole money-making product. On the other hand, paddlefish adult males and females do not spawn annually (Jennings and Zigler 2000). Besides, American paddlefish populations have declined dramatically, primarily due to overfishing and natural habitat destruction (Bettoli et al. 2009). Hence, artificial reproduction, caviar and fry production and aquaculture practices will resolve the reduction induced by high fishing pressure and lead to the rehabilitation of wild stocks (Billard and Lecointre 2000).

To overwhelm the data scarcity, we collected available literature review revisions and data from the translation of paddlefish aquaculture literature in the Russian language, original articles, dissertations in Russian publications, and state registry. Besides that, information was obtained through pilot studies surveying commercial farms and contacting scientists working at the KaspNIPKH Institute. The available data approved an apparent scarcity of data on both past and present paddlefish aquaculture status in Russia. Furthermore, it was hard to obtain accurate production data from the private sector. For these abovementioned reasons, the Federation registry merges Russian flesh and caviar production for all ten cultivated sturgeon species, hybrids and paddlefish (Abrosimova and Vasilyeva 2016).

According to the results obtained, we defined the main obstacles that faced paddlefish aquaculture. Also, we shed light on the expected opportunities for the development of European paddlefish aquaculture and examine the invasive potential and risks associated with its naturalization.

History and the role of Russian policies towards sustainability of paddlefish culture

After the post-WWII reconstruction and development, the history of paddlefish culture began with rapid unforeseeable events and radically changed the fish production sector. Hence, after World War II (WWII) ended in the USSR, most governmental efforts were directed towards the industrial revolution by adopting the idea of establishing giant projects (*e.g.*, dam constructions; hydroelectric power stations and establishment of internal water ways). Moreover, after 1991, the Russian Federation has built 34 dams, ranked second behind the United States (50 dams) (McCully 1996). Therefore, sturgeon and paddlefish habitats changed dramatically, since dams were quickly built-up on the main river channels and their tributaries. Also, they blocked access to breeding grounds for the wild sturgeon population into the southern regions. Thereby, to replenish the broodstock of diadromous fish species, it was necessary to develop managed breeding and rearing technologies (Kokoza 2004).

The Annual Ministerial Review issued a clear statement that all attempts should be undertaken to achieve the primary goal of environmental sustainability (FAO 2000). Ultimately, there were two parallel development strategies to compensate for deterioration in the aquatic ecosystem: fisheries and aquaculture. The "Concept of development of fisheries in the period 1950-2020" and the "Development Strategy for Russian Aquaculture and Fisheries," attained to develop fish by-products throughout increasing the actual production (Dvoryaninova and Sokolov 2014; Dvoryaninova and Syanov 2013; Naiel et al. 2020). Overfishing and poaching during the last three decades generated a catastrophic decline in natural stocks of almost all sturgeon species in the Azov-Black Sea and Caspian basin and many species have been threatened with extinction (Magomaev et al. 2017). Accordingly, all sturgeon species were included in the IUCN red list of threatened species (Hilton-Taylor 2000) and their exports are subjected to the CITES restrictions (CITES 2002).

The USSR tended to used paddlefish in polyculture systems as one of the most promising sturgeon species feeding on plankton. Besides, the main advantages of the polyculture technique were the highly efficient use of reservoir systems and the increase, the quantity of the marketable products and the reduction of the pressure on natural sturgeon populations (Holčík 2006). Moreover, a numerous spacious concept "Aquaculture" for strengthening production policies has begun to be applied, which means the activity of rearing and controlled propagation of fish under commercial farming conditions (Fedyaev 2003). Furthermore, the importance of supplying larvae to enhance stocking programmes, including aquaculture products and other features related to the encouragement of imports and exports of fish and fishery products for different regions and decreased catches, was recognized by the central government (Minselkhoz 2015). The following points briefly describe the historical sequence of paddlefish breeding and rearing development in USSR/Russian Federation:

1. On August 6, 1950 Joseph Stalin authorized industrialization efforts so-called "Great Construction Projects of Communism" proposed by the Council of the USSR to construct dams to generate energy at the north of Stalingrad "Volga Hydroelectric Station". Subsequently, free movement of sturgeons during the spawning migration season was impeded (Mettee et al. 2009).

2. In the mid-20th century, the predominant trend of this era was the growth of USSR long-range fisheries that relied upon commercial harvesting of marine stocks and kept away from inland fishery resources. Maintaining sturgeon stocks at an optimal level was only a part of the solution to the problem of rational management issues. It was also necessary to ensure that there were adequate markets for meat and caviar, mainly due to increasing turnout on the Russian sturgeon markets.

3. From 1949 to 1969, the global scientific community has noted the successful activities of the Soviet

scientists towards developing sturgeon broodstocks and particularly the production of the new 'bester' hybrid (*Huso huso* × *Acipenser ruthenus*) by Prof. Nikolai I. Nikolyukin and Nina Timofeeva. Also, Andrew N. Derzhavin, Vladimir V. Milstein, Igor A. Burtsev, Sergei A. Doroshev, Alevtina A. Popova, Nina A. Abrosimova, Valentina N. Shevchenko, Lev F. Lvov and Vladimir P. Mikheev developed hatching techniques, biotechnological procedures and pond construction systems for rearing sturgeon larvae (Vasilyeva et al. 2019).

4. During the same period (from 1950 to 1970), Soviet scientists proposed paddlefish as a sturgeon-alternative species for meat and caviar, based on its unique characteristics such as, planktivorous feeding mode by filtering suspended zooplankton and its high growth rates (Arkhangelsky and Vikhlyaev 1999; Bagrov and Melchenkov 2001; Shapovalova 2005).

5. At the end of April 1974, fertilized eggs of paddlefish were imported from the USA. Then, hatched pre-larvae were reared in recirculated tanks located in the Southern European territories of the Soviet Union. Melchenkov and Kanidieva (2015) indicated that imported fertilized eggs from Missouri State in the US, were allocated directly into three locations; 1- Ukraine (Donrybkombinat, VNIRO, r/z); 2- the North Caucasus- Krasnodar Oblast (Goryachi Klyouch experimental fish breeding plant, VNIIPRH); 3- Lower Volga region (Astrakhan Oblast, Ikryaninsky experimental sturgeon fish breeding factory, ORZ - TsNIORH). The total exports of about half a million fertilized eggs and the same number of live fish were imported under the agreement (partial scientific collaboration) among Wildlife Service organizations in the USA and the former USSR (Hanel et al. 2011; Hoover 1999; Jarić et al. 2019; Melchenkov et al. 2009; Raymakers 2002; Vedrasco et al. 2001). Under this agreement, 330,000 juveniles were also exported to Russia through new shipments during the next four years (Graham 1986; Mims et al. 2009; Simonović et al. 2006). On the other hand, many reports indicate that paddlefish accidentally entered into European countries, causing in some cases several adverse effects on the already endangered natural sturgeon populations residing in the Danube (Jarić et al. 2015; Kolar et al. 2007). Three categories of possible impacts may be identified; 1) competition with native fish species for natural food and critical habitat, such as spawning sites, 2) introduction of novel parasites and diseases, 3) indirect environmental impact through habitat degradation, by effects on benthos and water turbidity through feeding (Jarić et al. 2019; Mehana et al. 2020).

6. During 1974-1978, the first successful artificial propagation of the initial paddlefish shipment (specifically in early 1974) was achieved in the experimental fishponds of 'Hotkey' farm located in the Krasnodar Oblast. Thus, the species was found in low-quantities in the wild in the Krasnodar reservoir and the Kuban River tributaries (Moskul 1994).

7. In the mid-1970s, the VNIRO Acclimatization Laboratory received the first small batch of paddlefish embryos from North America. Approximately 100 larvae were able to survive and grow until puberty (Melchenkov et al. 1996; Vasetskiy 1971;Vedrasco et al. 2001).

8. In 1975, paddlefish were cultured in the Krasnodar, Astrakhan and the Voronezh reservoirs. The first capture of paddlefish in the lake of the Great Kostroma region in the Far East Russian water bodies was noted, representing the first collected sample from the paddlefish in the natural Russian water streams (Kharin and Cheblukov 2009).

9. In the spring of 1984, scientists and fishers (Dr. Vinogradov and his team) performed several research efforts to transport the first offspring, which served as the basis for establishing the native paddlefish broodstocks and the organization of artificial propagation and conservation programmes (Lobchenko et al. 2002). After the success of the Soviet experiments, the first paddlefish generation was disseminated to southern regions. Based on Soviet expertise, broodfish were transported from Krasnodar and Astrakhan experimental hatcheries into Moldavia, Ikreanoe, Romania, Hungary and China (Ji and Wang 2009; Vedrasco et al. 2001).

10. In 1987, the first field trial was conducted to acclimatize the paddlefish offspring derived from Goryachi Klyouch into the Russian open water streams, mainly in the Cuban and Volga rivers (Bogutskaya and Naseka 2004; Holčík 2006; Melchenkov and Kanidieva 2015; Reshetnikov et al. 2003).

11. In 1993, after successful domestication, the Russian Federation listed paddlefish and three other domesticated species of sturgeons (Danube sturgeon *Acipenser gueldenstaedtii*, Brandt & Ratzeburg, 1833, Beluga sturgeon and Sterlet sturgeon *Acipenser ruthenus* Linnaeus, 1758) (Bogeruk et al. 2001; Romanov 2019). Also, the Registers of the State of Selection Achievements involved paddlefish as a breed of animals (2001) under ID No. 9357555 and permitted for farming.

12. In 1994, the paddlefish cultivation became widespread under different culture systems, whether in mono or polyculture with sturgeon and carp species in commercial farms in Dagestan Big Fish Company and Shirokolsky fish factory (Alieva et al. 2016a). Moreover, paddlefish were stocked in governmental fish ponds following aquaculture research and production in the center 'BIOS', subsequently named 'KaspNIPKH' Institute in 2008, in Astrakhan Oblast under the supervision and management of Lydia M. Vasilyeva (Vasilyeva et al. 2019; Vasilyeva and Elnakeeb 2019).

13. Since April 1998, the paddlefish was categorized as one of the endangered species on the International Union for Conservation of Nature (IUCN 2013). Also, it was banned from international trade and listed in Appendix 2 of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (Ludwig 2008; CITES 2012; Raymakers 2002).

14. In 2008, two other hatcheries beside Krasnodar were established in the southern regions near the Black Sea (Astrakhan and Rostov Oblasts), to produce paddlefish larvae (Melchenkov et al. 2009).

15. From 1974 until 2019, Russian researchers and farmers worked together for almost 45 years for the acclimatization and establishment of paddlefish broodstocks in Russia (Table 1). Nowadays, there are many commercial and governmental paddlefish farms, mainly for meat and grayish-black caviar production. Also, the species is kept in private fishing clubs for "put-and-take" recreational angling (Dvoryaninova et al. 2016; Jarić et al. 2019; Ponomareva et al. 2014).

16. After the USSR subversion, specifically from 2000 up to early 2015, the private sector attained paddlefish stocks despite the apparent rarity of sufficient information about the relation between paddlefish production capacity and local Russian market requirements. There have also been trends towards supplying European countries and China with Russian caviar, fertilized eggs, fry, larvae and fingerlings (Jarić et al. 2019; Mims and Shelton 2015).

Methodology for data collection

Despite the limited available knowledge on paddlefish cultivation in Russia, obtained data must be preserved in an appreciable procedure (Jarić et al. 2019). Data collected during the current review mainly refer to English or Russian official statistics and reports (FAO 1994; FAO 2001; FAO 2015). The paddlefish catch data (commercial harvest only) and statistics from 1880 up to 2010 have been embedded (Pikitch et al. 2005). Likewise, caviar production and prices were surveyed from companies such as Caviar direct, Caviar express, Caviar Russe, Marky's caviar, Mackenzie limited, Petrossian, Plaza de Caviar, The Golden Egg, and Tsar Nicoulai (Carlson and Bonislawsky 1981; CITES 2001).

Differences between the current data and other studies may be attributed to the combination of available information on paddlefish and sturgeon species in the Soviet Union era. Moreover, the state-owned and the collectively-run farms ("Sovkhoz" and "Kolkhoz" farms, respectively) were dismantled after the subversion of the USSR and then sold to the private sector. Thus, the paddlefish government expenditure and farming statistics have been restricted owing to a lack of economic interest. The farmers mainly reveal their accurate production statistics based on confidentiality reasons (Golovina et al. 2019). Previously, the Codex Alimentarius organization excluded the paddlefish from the global production (flesh fish and caviar) of the Acipenseridae family. Therefore, world statistics vary given the lack of statistics from the Russian Federation (Bronzi et al. 2019).

The Russian Federation regulation laws for cultivated paddlefish

During the 1970-1980s, world-fisheries experienced a decline. Therefore, aquatic biological resources in the USSR/Russian Federation increasingly rely on fresh water fish farming not only in reservoirs but also in fish farms. Thus, the aquaculture industry has been developed rapidly, despite the absence of an appropriate regulatory framework in the USSR era (Devine et al. 2020; Hupfeld and Phelps 2018; Kramer et al. 2019). In 1974, the USSR imported the first batch of paddlefish fertilized eggs through scientific exchange agreement between the Bureau of Sports Fishing (BSF) and the US Environmental Protection Agency (EPA). The cooperation aimed to use paddlefish for scientific purposes, such as broodstock establishment and sustainability, artificial propagation, and ecological balanced nutritional studies under different farming conditions, such as in earthen ponds and reservoirs estuaries and floating cages (Melchenkov 1987;

Table 1 The leading role and research efforts of Russian scientists related to paddlefish aquaculture

Scientific efforts	Date and location of the experiments	Findings	References
Attempts to acclimatize the paddlefish under conditions of USSR	In the 1970s–1980s, VNIIPRH, "Goryachi Klyouch" experimental fish breeding plant, Krasnodar Oblast.	Paddlefish exhibit low salinity tolerance. Therefore, the expected area of its distribution will be limited to river segments above the estuaries.	Vinogradov and Erokhina (1975); Vinogradov et al. (1986) and Melchenkov (1987, 1988)
Dissemination paddlefish as a promising aquaculture fish in the USSR governmental farms.	In 1974-2000. Goryachiy Klyuch and the Ikryaninsky sturgeon fish-breeding plant, Astrakhan Region.	Introduction of paddlefish into the southern rivers basins helped in the development of fisheries due to the limited potential for natural spawning.	Melchenkov (2001) and Vinogradov et al. (2003)
Studies of paddlefish growth variation in monoculture for the stages Phase-I and Phase-II.	In 1974-2000, at the central research units of the Goryachiy Klyuch farm and the Ikryaninsky sturgeon-ponds plant.	The existence of a hierarchic size structure and competition for "free water space" in monoculture of farmed paddlefish Phase-II stocks in the earthen ponds, were emphasized.	Vinogradov et al. (1986)
Using morphological and environmental features to discriminate individuals of Acipenseriformes	From 1974 and research is still ongoing, at various farming locations in the former USSR and the Russian Federation.	The influence of environmental factors on the results of population studies based on morphological heterogeneity within genera and species has been proven.	Kalmykov et al. (2009) and Kolpanosova et al. (2011)
Artificial spawning of paddlefish under Russian culture conditions.	In 1984-1987, at the research institutes in Dagestan Republic, Krasnodar, Astrakhan Oblast, Rostov, and Saratov.	The first Russian offspring were obtained from paddlefish by Dr. Vinogradov and his team.	Vedrasco et al. (2001); Lobchenko et al. (2002); Melchenkov & Kanidieva (2015)
Hematological studies for pre-larvae, larvae and post-larvae of farmed paddlefish.	In 2005-2006, at the Astrakhan State Technical University and the Kuban State University, Krasnodar.	An inverse correlation was observed between the number of abnormal forms of red blood cells (degenerative) and Phase-stage of the paddlefish.	Shapovalova (2005); Kudrenko & Lysenko (2007)
The developmental anomalies of paddlefish larvae stages and the beginning of active feeding.	In 2006, KaspNIPKH institute, "BIOS" experimental Sturgeon fish breeding plant, Astrakhan Oblast.	The identified developmental anomalies during the spring-season in the paddlefish larvae stage do not rely on environmental stressors.	Nikolskaya et al. (2006)
Study of the daily feeding patterns for paddlefish larval stages.	In 2007, at the fish farm of Russian Miroshnichenko (Minsk region).	Almost all zooplankton representatives found in samples captured from the pond of the paddlefish larvae.	Konchits et al. (2009)
Comparison of paddlefish parasitofauna in Russia and USA under different cultural systems.	In 2008, samples were collected from private farms, Krasnodar region.	Russian scientists recorded nine types of parasites compared to six species found in the native ranges (Northern America).	Kudrenko et al. (2008)
Nutrition and survival rates studies in the initial stages of paddlefish life.	In 2009-2010, KaspNIPKH, "BIOS- research institute" experimental fishpond, Astrakhan Oblast.	Feeding on the third day after hatching of paddlefish larvae using a commercial diet helped to increase survival and growth rate.	Vasilieva & Nekrasova (2010)
Comparative molecular genetic studies on sturgeon and paddlefish stocks	In 2010, by the Southern Scientific Center of the Russian Academy of Sciences (SSC-RAS), Rostov-on-Don.	Sturgeons formed a monophyletic branch, separate from paddlefish and/or other fish. However, these sequences turned out to be useless for the identification of species or interspecific relationships.	Timoshkina et al. (2011)
Attempt to accelerate production by using artificial feed for paddlefish juveniles.	In 2012, at the scientific-experimental base of FSUE "CaspNIRKH" - in the Center "BIOS."	Paddlefish initially prefer feeding on microorganisms and then artificial feed.	Anatolievna & Vyacheslavovich (2012)
Studies of carcass characteristics and chemical composition of the paddlefish.	In 2011-2013, at the laboratories at Voronezh State Technological Academy and private farm "Pavlovskrybkhoz"	Compared with silver carp, paddlefish muscles are characterized by a high level of protein, fat, and manganese.	Kolpanosova et al. (2011) and Puntila et al. (2013)

Table 1 Continued

Tracing the trace elements and their accumulation in the muscle of paddlefish.	In 2015-2016, KaspNIPKH institute, experimental fishponds "BIOS," Astrakhan Krai.	The nature of the accumulation of trace elements is due to the environmental and physiological-biochemical characteristics of fish in this farming area.	Terpugova et al. (2016)
Influence of chlorella supplementation on the paddlefish production	In 2017, at LLC Semikarakorskaya Ryba, Rostov Region.	The introduction of *Chlorella vulgar is* into the pond had a positive effect on the productive qualities of paddlefish and water quality.	Frolova et al. (2019)
Paddlefish culture with different fish species.	In 2018, at experimental fish farms, Saratov State Agrarian University (SSAU).	Paddlefish can be farming together with herbivorous fish. However, due to possible competition in nutrition, it is advisable to exclude silver carp from the polyculture or reduce the density of both species.	Ilyichev & Gurkina (2018)
Study of seasonal changes and their impact on growth performance	In 2018, at KaspNIPKH institute (experimental fishponds), Astrakhan Oblast.	Although low temperatures in winter, it considered the most stable period over the year in which the fish is subject to less environmental stresses.	Vasilyeva & Elnakeeb (2019)
Studies of transverse skin folds in the early paddlefish stages and the kinematics of the jaw apparatus.	In 2018-2019, at the aquarium units of the Institute of Ecological and Evolution Problems. Severtsov, Russian Academy of Sciences, Moscow.	The first evidence in the presence of transverse skin folds in the larvae and post-larvae stages of paddlefish in the upper jaw, which disappear during development. Also, there can be considered as a functional component of the provisional jaw mechanism that operates in the early stages of active nutrition.	Tsessarsky (2019)

Melchenkov 1988; Vinogradov and Erokhina 1975).

Before the Soviet Union subversion in 1991, the official site of Rosrybolovstvo reported that the highest peak of aquaculture development was observed during the early 1990s. Total aquaculture production in the Soviet Union was about 254,347 tonnes in 1990 (FAO 1994). The highest aquaculture production level was achieved after applying advanced aquaculture technologies both in principles and farming practices. The annual increase in fish production was 10-15%, one of the highest in aquaculture production. Whereas, from 1989 to 1996, fish production from natural fisheries resources decreased by four times.

In 2001, the Russian Federation endorsed law No.22-OZ, which regulated the establishment of a specific aquaculture program entitled "Development of Russian fisheries and aquaculture in inland waters for the period 2001-2005". This law led to the development of fisheries and aquaculture facilities in regions with rich inland water resources (FAO 2001).

In 2004, the Interparliamentary Assembly of the Commonwealth of Independent States confirmed the modification of the aquaculture law for use in national legislation. In 2005, a draft of a specific federal law was prepared, which was put up for public discussion and continued until September 6, 2011. On July 24, 2013, the Federal Law No. 148-F3 on Aquaculture was approved by the Russian Federation. The law was issued to establish a comprehensive legislative framework regulating the legal framework in aquaculture (fish farming, provision of feed ingredients, technical and other products), as well as to sustain the biodiversity of inland waters.

At the end of 2016, the Russian Federation yielded 173,900 tonnes of fishery products including 31,300 tonnes from the fish farm. In mid-2017, the volume of aquaculture output surpassed 71,000 tonnes, which is 12% higher than the same period of the previous year (Rosrybolovstvo 2018). Legislative frameworks and cooperation in law enforcement accompanied such increases in overall fish production. Moreover, it was necessary to meet aquaculture production requirements by constructing more hatcheries following the aquaculture sector development. The incremental stabilization of the aquaculture sector proceeded from mid-2015 up to the present. According to the Federal program No. 314 entitled "Development of the fishery complex," which was approved by Decree of the Government of the Russian Federation of May 15, 2014, the volume of commercial aquaculture production by 2020 should reach 232.300 tonnes (Andronova et al. 2019).

In April 25, 2017, the Federal State Statistics Service (Rosstat) approved the law (No. 291) that regulates the paddlefish capture from the wild and it is commercial aquaculture practices under code 140 (according to this law, the paddlefish was recommended as a commercial fish farming species under code 1513) (ROSSTAT 2017).

To date, the Russian Federation stated that there were 4,491 fish farms established on 544,000 hectares (ha). Also, 3,151 hatcheries planned to be built on 434,000 ha (*i.e.* covering more than 70% of the total available inland resources). Before the aquaculture law approval, the hatcheries were established on a total area of 354,200 ha. Then, after passed the law, 2,615 hatcheries were constructed on total area of about 190,000 ha. Thus, Rosrybolovstvo and its regional departments purchased about 79,800 ha to established 1,275 hatcheries. According to auction estimates, the development budget of hatcheries passed 430 million rubles.

The Ministry of Agriculture of the Russian Federation (Minselkhoz) approved an animal list of species used in culture and experimental trials including paddlefish and other species. The Ministry of Agriculture officially published order No. 369 of July 1, 2019, "On the approval of the list of botanical and zoological genera and species provided for in Article 1413 of the Civil Code of the Russian Federation" (Center 2007).

Russian research efforts and paddlefish farming facilities

After the subversion of the Soviet Union, the total fish production from fisheries declined during the late 1980s and 1990s (Bertrand et al. 2010). Following the prohibition of the selling of wild black caviar in local markets in 2007, there was a continuous increase to fulfill the demands of the local markets, driving the federal organizations to develop the aquaculture sector, with a special focus on breeding of both sturgeons and paddlefish (Vasilyeva and Elnakeeb 2019). As a result of the regulatory acts, the Federation set a major goal to increase the number of paddlefish farms and significantly improve the facilities technology, based on the Federal program No. 314 which was approved on May 15, 2014.

Soviet scientists in the southern regions of the Volga River, northern Caucasus and Ukraine, were interested over the period from 1974 through 1984 in achieving the proposal introduced by Professor B.S. Ilyin in 1960. He referred to introducing a non-indigenous paddlefish as a promising species into the southern reservoirs of the European part of the Soviet Union (Melchenkov and Kanidieva 2015). At that time, numerous studies by Russian scientists and fishers were performed on the biological aspects ranging from the egg stage to sexual maturity and broodfish development (Table 1). Subsequently, the species was introduced and widely dispersed in European countries and China (Ji and Wang 2009; Mims and Shelton 2015; Vedrasco et al. 2001).

For several objective and subjective reasons, it was impossible to preserve the experimental batch of paddlefish until adulthood at that time. The tasks assigned to the researchers were successfully solved by the team of the acclimatization laboratory of VNIIIPRH located in the base of Goryachiy Klyuch. The main work carried out was to study the biological aspects of paddlefish. It began with the acclimatization and broodstock establishment in open waters and observation culture rearing behavior in fish ponds based on monitoring/recording nutrition, growth performance, water quality, and environmental stressors. Ultimately, successful artificial propagation via hormonal induction, spawning, hatching and larval rearing was investigated in the early years of research (Burtsev and Gershanovich 1976; Gershanovich 1983; Gershanovich 1984; Gershanovich and Nikolaev 1984; Gershanovich et al. 1987; Vinogradov 1978). The hormonal stimulation depended on ambient temperatures close to ranges optimal for egg incubation, which vary for different sturgeons (Mañanós et al. 2008). Among gonadotropins, the most frequently used preparations that can be applied for stimulation of spawning in sturgeon broodstock are: acetone-dried sturgeon pituitary (SP); acetone-dried common carp pituitary (CCP); sturgeon pituitary glycerol preparation (PGP); and GnRHa – a superactive synthetic analogue of mammalian gonadotropin-releasing hormone (des Gly10[D-Ala6] GnRH ethylamide) (Rottmann et al. 1991). Traditionally, males of all species should be subjected to a single injection scheme before initiating female injection. The dosage of hormonal preparation for males is half that used for females. Therefore, it is recommended to inject males 2-4 h before female administration (Chebanov and Galich 2011).

After 1990s, the private investors focused on developing caviar production from paddlefish and not for scientific research. Consequently, Russian researcher research efforts have diminished in laboratory examinations of physiological functions, genetics, and pathological studies in the Ministry of Agriculture

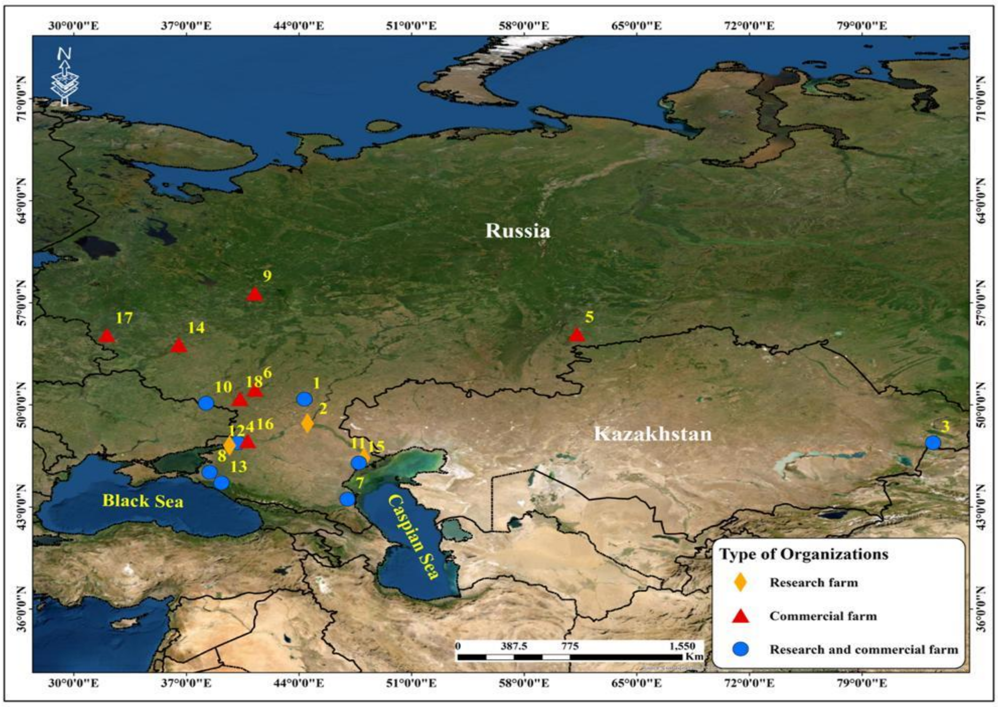

Fig. 1 The current distribution of American paddlefish farms in Russia

and Universities (Kudrenko and Lysenko 2007; Nikolskaya et al. 2006; Shapovalova 2005; Timoshkina et al. 2011). During the Soviet Union era, Russian historical paddlefish production was about 70 tonnes/year from three hatcheries (Melchenkov et al. 2009).

In 2015, the number of aquaculture facilities in Russia was 15, located in Dagestan, Krasnodar, Rostov, Astrakhan, Belgorod and Saratov provinces (Jarić et al. 2019). Seven of them were described as the central enterprises engaged in the cultivation of broodfish. They were distinguished by the distribution of offspring to the Oblasts surrounding them: LLC Fish farming enterprise "Angelinsky" (Krasnodar Krai, Krasnoarmeysky District, a village of Staronizhesteblievskaya); FSUE "Medveditsky" Experimental hatchery (Volgograd region, Danilovsky district, Danilovka settlement); LLC "Rybkolkhoz im. I.V. Abramova" (Rostov region, city of Semikarakorsk); FSUE "CaspNIRKh" (Astrakhan); CJSC "Smolenskrybkhoz" (town of Smolensk); CJSC "Pavlovskrybkhoz" (Voronezh region, Pavlovsky district, villages of Malaya Kazinka and Gavrilsk); LLC fish farm "Berezovsky" (Voronezh region, Bobrovsky district, Dry Birch village) (Dvoryaninova et al. 2016).

At the end of 2019, the Rosrybolovstvo registry includes 18 facilities for paddlefish aquaculture (Aquaculture 2018, 2020b; Rosrybolovstvo 2020). Table 2 reported all registered paddlefish farms and their activities, each one according to the type of organization, affiliation and geographical distribution (Fig. 1). Other producers are not listed in the state records because their total production is expressed without paddlefish. Therefore, the Rosrybolovstvo registry and records of the Ministry of Agriculture do not fully represent the current status and number of paddlefish aquaculture facilities. According to Rosrybolovstvo records, a significant number of small farms did not provide the necessary data. The statistics cover only half of the farms currently in Russia (Aquaculture report 2018, 2019, 2020a).

Most of these farms operate by private companies and do not release information on paddlefish production invoking data confidentiality (Jarić et al. 2019). Moreover, based on Rosrybolovstvo registry and the official site of aquaculture in Russia (Aquaculture report 2020a) for 2019, paddlefish farms are mainly (about 50%) located in the southern regions of Belgorod, Saratov, Volgograd, Rostov on Don, Astrakhan, Krasnodar and the Republic of Dagestan (Table 2). It is explained by the favorable natural and climatic conditions for paddlefish aquaculture in the Southern Federal Districts (SFD) (Karnai 2018).

Except in the southern areas, Russia had an insufficiency of paddlefish aquaculture farms (Golovin et al. 2019). There are so-called "logistics distribution centers or complex companies" responsible for supplying small farms with larvae based on the federal scope for each Oblast. The Volga-Caspian region,

Table 2 The Russian paddlefish aquaculture facilities

No.	Name of Organizations	Type of Organizations & Affiliation	Region	Cultured species	Paddlefish production tons/year	Total production tons/year
1	Federal State Budgetary Institution FSBI "Medveditsky experimental fish hatchery". https://ribzavod34.ru/	Research and commercial farm & Federal Agency on Fisheries (FAF)	Volgograd	Carp species, paddlefish, bester, and Siberian sturgeon.	340	1300-1350
2	The Lower Volga branch of the FSBI. https://nvrv34.ru/	Research farm & FAF	Volgograd	Carp species, paddlefish, channel catfish, Rolek	over 1 ton	3 million fry
3	FSBI "TINRO-Center" (Luchegorsky Research Station). http://www.tinro-center.ru/o-tinro-centre	Research and commercial farm & FAF	Vladivostok	Mackerel, sardine and Paddlefish.	over 1 ton	6000
4	Novocherkassk Fish Factory. http://fish.gov.ru/press-tsentr/obzor-smi/1530-novocherkasskij-rybokombinat-narashchivaet-proizvodstvo.	Research and commercial farm & Federal Agency on Agriculture (FAA)	Rostov	Sturgeon (Russian, stellate, Lensky) sterlet, beluga, spike, paddlefish.	80-100	5000-6000
5	Limited Liability Company LLC. http://mcx.ru/press-service/regions/boris-dubrovskiy-chelyabinskaya-oblast-mozhet-utroit-obemy-proizvodstva-ryby/	Commercial farm & Private foundation	Chelyabinsk	Trout, silver carp, common carp, smallmouth buffalo, sturgeon, sterlet, paddlefish.	200	500
6	LLC "Dawn-2". https://khopyor.moy.su/forum/20-1740-1	Commercial farm & Private foundation	Voronezh, Novokhopersky district.	Sturgeon (Russian, stellate), paddlefish, and channel catfish.	5-6 million larvae	100
7	LLC "Shirokolsky fish factory". https://shirokolskij-rybokombinat.tiu.ru/	Research and commercial farm & FAA	Republic of Dagestan, Makhachkala, Tarumovsky District.	Sturgeon species and their hybrids, carp species, paddlefish and other herbivores fish.	60	1200
8	Russian Socialist Party RSP Angelinskoye LLC. https://www.bibliofond.ru/view.aspx?id=653363	Research and commercial farm & FAA	Krasnodar, Krasnoarmeysky District.	Grass carp, Crucian carp, Silver carp, Sturgeon, and Paddlefish.	400-500	600-800
9	An Open Joint-Stock Company OJSC. http://vrh.ru	Commercial farm & Private foundation	Kostroma, Volgorechensk.	Paddlefish, Sterlet, Siberian sturgeon, bester, etc.	28	300-400
10	Joint-Stock Company JSC Rybkhoz "Uraevsky". http://fish.gov.ru/press-tsentr/obzor-smi/16169-yubilejnyj-god-belgorodskikh-rybovodov	Research and commercial farm & FAF	Belgorod, Valuysky district.	zander (Sander lucioperca), Paddlefish, Sturgeon, Carps	300	6855
11	"CaspNIRKh", FSBI "Caspian aquaculture Research Institute, Astrakhan branch". http://www.kaspnirh.ru/en/	Research farm & FAF	Astrakhan Oblast.	Paddlefish, Sterlet, Siberian sturgeon, bester, etc.	3.2	5300
12	Don sturgeon factory FSBI Azdonrybvod. https://rostov.dk.ru/wiki/donskoy-osetrovyy-zavod.	Research farm & FAF	Rostov-on-Don.	Sturgeon (Russian, stellate, Lensky), beluga, Don sterlet, spike and paddlefish.	120	8 million fry

Table 2 Continued

13	Goryachi Klyouch	Research and commercial farm & FAF	Krasnodar.	Russian sturgeon, stellate sturgeon, beluga, sterlet,and paddlefish.	600	30000-35000
14	Cage and pool facilities of Cherepetskiy Rybkhoz JSC. https://vypiska-nalog.com/reestr/7133000531-ao-cherepetskiy-rybkhoz.	Commercial farm & FAA	Tula Oblast, Suvorov district.	Russian sturgeon, beluga, and paddlefish.	Not available	100
15	LLC Ikryaninsky zonal hatchery Delta. https://vypiska-nalog.com/reestr/3021000568-ooo-ikryaninskiy-rybopitomnik-delta.	Research and commercial farm & FAF	Astrakhan Oblast.	Pike, grass carp, white and spotted silver carp, and paddlefish	4	40 million larvae
16	LLC "Rybkolkhoz im. I.V. Abramova ". https://ribaopt.pulscen.ru/	Commercial farm & FAF	Rostov Oblast, Semikarakorsk city.	Russian sturgeon, stellate sturgeon, beluga, sterlet, and paddlefish.	300-400	6000
17	A Closed Joint-Stock Company CJSC. https://vypiska-nalog.com/reestr/6729014891-ao-smolenskrybkhoz	Commercial farm & FAA	Smolensk Oblast, Smolensk city.	Silver carp, common carp, channel catfish, stellate sturgeon, sterlet, and paddlefish.	150	200
18	CJSC "Pavlovskrybhoz". https://vypiska-nalog.com/reestr/3620008171-zao-pavlovskrybkhoz	Commercial farm & FAA	Voronezh Oblast, Pavlovsky district.	Carp species, pikeperch, pike, and paddlefish.	The data has not been released yet.	200

Sources: Organizations location and websites: Official Russian Aquaculture Site (http://aquacultura.org/), Federal Agency for Fisheries (http://mail.fish.gov.ru/podvedomstvennye-organizatsii/rybvody), and Russian Fish on the Net (https://www.fishnet.ru/).

which contains 25% of the sturgeon farms, comprises Astrakhan Oblast (specifically, Medveditsky experimental fish hatchery and Caspian Fisheries Research Institute "CaspNIRKh", respectively), which is currently undergoing intensive sturgeon farming development (Anokhina and Zaitsev 2018). In the past, brooder and offspring mass production (approximately 90%) are issued to the Azov-Black Sea, Krasnodar Oblast, particularly from "Goryachi Klyouch" farm near the Black Sea. In fall 2019, Goryachi Klyouch complex company was liquidated and the production was transferred to a complex company "Angelynsky"(Aquaculture report 2020b). In this context, the larvae supply for farms are controlled through 11 logistical centers in various other regions (Table 2 and Fig. 1).

Restrictions and obstacles in cultivated paddlefish farming

Despite the extensive efforts of Soviet researchers to improve paddlefish stock restoration from 1970 to 1980, the distribution of government farms was so limited except in southern regions due to several geographical obstacles. As a result, it was necessary to develop new long-term strategies to address the challenges this industry may face and define the Russian Federation's role in supporting paddlefish culture systems until 2020 (Dvoretsky and Dvoretsky 2020).

The Russian government has a goal and vision for 2030 to achieve bio-safety, paddlefish broodstock reproduction, and increased commercial product volume (Rosrybolovstvo 2010-2017).

The main challenges related to Russian paddlefish aquaculture differ depending on the historical periods as follows:

a) During the Soviet Union era:

- The private sector investors do not intend to develop paddlefish aquaculture due to the almost complete absence of state support in the form of long-term, concessional loans; tax relief; subsidies for fish aquaculture facilities and feed.

– Inadequate availability of larvae produced from hatcheries at a suitable price.

– High cost of complete, balanced, specialized diets for juveniles.

– Limited performance of farming technologies, regulatory and methodological documentation.

b) After the USSR subversion:

– Insufficiency of highly qualified specialists in the field of paddlefish breeding. Numerous experts left the sector in the 1990s due to reduced governmental funding of (State) hatcheries production declined, and technologies introduced elsewhere were not adopted in the region (Chebanov et al. 2011).

– High cost of caviar: Counterfeiting some brands in the domestic market so as the resulting paddlefish to be sold at a higher price as "starry sturgeon caviar". Meanwhile, less than 1% of the Russian people have the purchasing power to afford to buy grayish-black caviar.

– The regulatory bodies position in issuing a periodic paddlefish development yearbook of paddlefish aquaculture facilities current status is absent.

– Russian scientists leading role declined in light of the decrease in the number of research centers responsible for conducting development research for paddlefish aquaculture from seven to three institutes located in Krasnodar, Rostov and Astrakhan.

– There is a scarcity of statistical evidence on paddlefish aquaculture output in both government and private farms.

– The spawning interval is one of the most considerable problems which takes 2-5 years, in contrast to the Soviet era, which occurred every 1-2 years. The paddlefish migration depends on the flow regime of the rivers. Damming and reducing flow rate due to agriculture irrigation in the Kuban River in the early 1980s resulted in total suppression of the adult fish anadromous autumn run and delayed the stages of gonad maturation in females migrating spring (Billard and Lecointre 2000).

– Disease outbreaks remain the common hindrance to paddlefish breeding in Russia, from 1974 until now.

The significant constraints faced in paddlefish cultivation are related to change of priorities as ensuing consequences of the economic, social, as well as political change (Beretar et al. 2007; Kudrenko et al. 2008; Sklyarov et al. 2013; Vasilyeva 2008). These changes impacted the methodology of caviar production, domestication (*i.e.*, adaptation of a non-indigenous species to artificial conditions), breeding, early sex determination, reduction of the spawning interval, growing viable juveniles, disease prevention, *etc*. Unfortunately, such research projects do not receive sufficient funds for their implementation (Vasilyeva et al. 2019), indicating that the political vision for developing aquaculture in the south of Russia is directed more towards cultured carp and herbivorous fish species. As in most EU countries, the state-owned paddlefish and sturgeon had inadequate farming facilities and requiring investment for development. Furthermore, the insufficient available data on real padddlefish output from governmental and private farms did not provide a good understanding of the current state of this fish species production. Also, the only official year book data provided by the Federal Fishery Agency 'Rosrybolovstvo' combined the productivity of both paddlefish and other sturgeons owing to the low yields offered by farms. (Mims and Shelton 2015). The major stressors in response to harmful environmental factors that have led to low survival rates and growth performance in paddlefish ponds are fluctuations in water temperature, the decline in zooplankton and existence pressure from predators of fish and birds, particularly during the larval stage (Hubenova et al. 2007; Vasilyeva and Elnakeeb 2019).

Paddlefish are grown based on the natural food web. It feeds on zooplankton (mainly on benthic crustaceans), phytoplankton and partially on detritus. That is why it is essential to achieve high and sustainable productivity in water bodies, for which mineral fertilizers are applied in fractional doses. They must be introduced in a well-dissolved form and cannot filter out undissolved fertilizer particles and swallow them, which can lead to high mortality (Alieva et al. 2016a,b).

Constraints in Krasnodar: After the subversion of the Soviet Union, work on obtaining paddlefish caviar in the southern parts of Russia, especially in Krasnodar, gradually stopped. Poaching in pond farms destroyed the paddlefish breeding stock, which was the most abundant resource in the Soviet era. Currently, the leading suppliers of caviar and paddlefish offspring are the Rostov and Astrakhan regions (Shagovskaya 2013).

Constraints in Voronezh: For the time being, "efforts are made to grow a small batch of this exciting and valuable fish" says Alexey Premyakov, general director of Zarya-2 LLC. Paddlefish is a pelagic fish, so the larvae that survive in large quantities in culture ponds are susceptible to waterfowl predation. Therefore, nets or alarms that discourage birds are necessary. Thus, the paddlefish hunt ponds visited by people were to limit the waterfowl attack (Club of Fishermen of paddlefish 2013).

Constraints in Rostov: The problem with the availability and replenishment of fish stocks in the Rostov region was pointed out at a meeting of the Maritime Council under the regional government by the head of the Azov-Black Sea branch of the All-Russian Scientific Research Institute of VNIRO (AzNIIRKh) Nikolai Gospodarov. In the Azov-Don region, the reproduction of aquatic biological resources is at the lowest level in history. The problem was rooted in 1952-1955 when the Volga-Don Canal was dug on the Don River. But then they understood that if you take water, then spawning will not succeed. Therefore, they built fish hatcheries that were supposed to reproduce fish as says by Gospodariev. In total, seven hatcheries were made in the Rostov Region during the USSR era. Now only one work - Semikarakorsky and the others went bankrupt or reduced their production. The two largest reproductive enterprises in the region were destroyed (Kuleshovskoe NVH and Susat-Don fish farm) (Shelkovnikova and Nefedov 2019).

Paddlefish aquaculture in Russia

Meat production

Russian Federation is the leading country in paddlefish farming and meat production. However, geographical distribution and temperature can alter the production type directions (Ji and Wang 2009; Vinogradov et al. 1986). In the north and northeast of the country, paddlefish and sturgeons are mainly grown for meat. The main species are Amur sturgeon (*Acipenser schrenckii* Brandt, 1869), Kaluga (*Huso dauricus* Georgi, 1775), Siberian sturgeon (*Acipenser baerii* Brandt, 1869) and hybrids of Amur and Siberian sturgeons-both interspecific and intergeneric cross-breeds (INAD 2016). In contrast, the southern regions provide a more suitable environment for stocking fish brooders within hatcheries for caviar production.

Paddlefish meat contains high-energy (protein content of 17.2-25.8% and total fat 5.7-8.4%) and good palatability, making it suitable for industrial food (Dvoryaninova et al. 2016). Mims and Shelton (2015) documented that the highest meat quality produced from paddlefish is that of Phase II juveniles (marketing size > 150 g). Also, the demand for paddlefish boneless white meat is increased in the small-sized harvested fish (0.5 kg).

The paddlefish body shapes unique structure affects the ratio of edible and inedible parts and the nutritional value of the produced meat (Kolpanosova et al. 2011). The yield of paddlefish meat ranges from 49% to 61% depending on feeding conditions. In general, the percentage of meat yield in paddlefish is higher than that of Starry sturgeon (*Acipenser stellatus* Pallas, 1771). The presence of a sufficient meat yield (up to 61%) permits two-year-old paddlefish (weighing more than 2 kg) to the canning industry. In addition, white meat is used as a raw material to produce hot and cold smoked fish products (Dulina et al. 2012; Ilyichev and Gurkina 2018; Melchenkov and Kanidieva 2015).

The Astrakhan Research Institute and the Lower Volga branch of Glavrybvod company price lists of commercial fish, reported that the retail list price of fresh or chilled paddlefish was similar to Sterlet sturgeon (*Acipenser ruthenus* Linnaeus, 1758) (400-450 rubles/kg equal to 5.6-6.3$ US/kg) (FAO 2012).

Caviar production, costs and returns

Paddlefish and other sturgeon species were defined by the State Register of breeding as domesticated sturgeon fish (Golovina et al. 2019). In 1993, the State Register approved paddlefish caviar marketing No. 9357533 (SRBAA 2019). After the USSR subversion, the experts could not have the ability to collect accurate information about paddlefish caviar production. Thus, the Rosrybolovstvo registry statistics deal with the fact that paddlefish is one of the sturgeon species producing black caviar called 'black pearls,' due to the similar to that produced by the Stellate sturgeon (Melchenkov 2001). Distinguished caviar in the global markets belongs to two major graded types: Beluga, paddlefish and Sevruga (from Stellate sturgeon) and Osetra (from Russian sturgeon *Acipenser gueldenstaedtii*).

Rosrybolovstvo (2018) recorded no official statistical data on paddlefish and sturgeon meat and caviar production and many values for total annual production, depending on the source of trade. The annual aquaculture production of black caviar was approximately 50 tonnes per year (Bronzi et al. 2011). Sturgeon caviar production is divided into three chronological periods. Before 2003, caviar resources were exclusively from fisheries. Until 1991, caviar production increased up to 2,000-2.800 tonnes. Black caviar was represented about 1,500 tonnes from total caviar production (VARPE 2017). The cost of 1 kg of black starry and American paddlefish caviar was $200-250 US (Kokoza 2002). During this period, a large amount of Stellate caviar (*i.e.* Sevruga) was harvested from the Volga-Caspia, representing 50.6% of all caviar production (VARPE 2017). From 1992 to 1995, sturgeon stocks dropped fourfold, from 200 to 50 million individuals. Therefore, the cost of black caviar went up 20 times.

In 2003, besides natural fish captures, aquaculture began to be another source of caviar. However, the black caviar price was higher than other fish products in the Russian markets. Therefore, a high variation was observed in the quality and costs of marketable caviar due to the high competition between the caviar gained from fisheries and aquaculture (Vasilyeva et al. 2019).

From 2004 up to 2019, the Russian caviar production of sturgeon was provided by aquaculture (Rosrybolovstvo 2018; Sytova 2017). Since August 2007, the Russian government restricted the black caviar trade for approximately ten years (Report 2014). The Russian caviar price boosted sharply from the early 1990s until the second millennium and then exhibited a decline in 2012.

The paddlefish stocking density allocated into reservoirs should be 20-30 adult fish per ha (40-60 kg/ha). Each mature female fish could produce two kg of caviar every one or two years. Mature females could be spawning at least five times throughout their life cycle (Melchenkov and Kanidieva 2015). The caviar price peak was approximately US $1,670-2,000 per kg, while in 2012 it reached 670 -1,170$ US per kg. In 2014-2017, statistics showed that the prices were stable, as caviar price ranged at 667-700$ US per kg (Karmanovsky 2017; VARPE 2017).

Conclusion

Up today, few reviews were carried out to investigate the paddlefish farming status and handling this species as marginal in sturgeon aquaculture in Russia. Furthermore, some studies have focused on tracking the paddlefish introduction history into the Soviet Union and Eastern Europe, regardless of the Russian scientists attempts in the following periods. Accordingly, a several studies indicated the gap of information relevant to the number, production and description of paddlefish facilities and the extent to which the Russian local market relied on these farms. Thus, the current study provides previously unknown information about the farming of this fish. Also, the presented translation information from the Russian language in this literature could resolve the confidentiality and scarcity of paddlefish data. Furthermore, the official statistics and reports about paddlefish flesh and caviar production could effectively present the current state of the sector and suggested new innovations for its development.

Currently, the paddlefish farming practices seem to reflect the failure to maintain the success path achieved in the past, particularly during the Soviet era. Nevertheless, future development prospects exist if government intervention aims to co-ordinate efforts to support the public and private sector, fund programs for the establishment and husbandry of broodstock throughout various Oblasts, careful planning, ensure production cost efficiency, market expansion and initiate marketing strategies. Furthermore, new alternative strategies must be proposed to resolve the major challenges obstructing the development of paddlefish cultivation in Russia, such as inadequacy of producing larvae, the absence of regulatory rules, the high cost of caviar production, long spawning intervals, and disease outbreaks.

Acknowledgments The authors acknowledge Evgeni Melchenkov, Doctor of Agricultural Sciences and Researcher at All-Russian Research Institute of Freshwater Fisheries, Rybnoe, Dmitrov Region, Moscow Province, for supporting by providing us with the information that enriched of the article.

Author's Contribution All authors contributed equally to this manuscript.

Conflicts of interest The authors declare there is no conflict of interest.

Ethical Approval Statement This literature does not contain any studies with animals performed by any of the authors.

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