

Review

Foundation and Prospects of Wild Population Reconstruction of *Acipenser dabryanus*

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Abstract: *Acipenser dabryanus* is an endemic fish inhabiting the upper reaches of the Yangtze River in China. It is classified as a first-class nationally protected animal in China and is listed in the International Union for Conservation of Nature (IUCN) Red List of Critically Endangered Species (CR). Recently, there has been a decrease in natural reproduction of *A. dabryanus*, and the wild population is almost extinct. This paper summarizes the changes observed in the natural population of *A. dabryanus* and the factors leading to its endangerment. Based on the process of artificial propagation and achievement of relevant protection goals, this paper presents the concept and technical framework for reconstruction of the wild population of *A. dabryanus*. In addition, by comprehensively reviewing the research findings and existing problems in the resource protection and monitoring of *A. dabryanus* in recent years, we assessed the possibility of wild population reconstruction and resource restoration for *A. dabryanus*. Reconstruction and restoration measures for the wild population of *A. dabryanus* are proposed, with the aim of providing a scientific basis for the reconstruction of the natural population and the improvement and restoration of critical habitat of this species. Furthermore, it is hoped that this paper will serve as a reference for the protection and restoration of other endangered fishes.

Keywords: *Acipenser dabryanus*; endangered species; protection countermeasures; wild population reconstruction



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1. Introduction

1.1. Biological Characteristics of *Acipenser dabryanus*

Acipenser dabryanus, also known as Dabry's sturgeon and Yangtze sturgeon, belongs to the class Actinopterygii, family Acipenseridae [1]. Male individuals sexually mature at 4 years old, while female individuals reach sexual maturity at 6 years old. *A. dabryanus* reaches body lengths of up to 130 cm and may weigh > 16 kg [2]. In terms of food habits, *A. dabryanus* is considered omnivorous; however, the food types of juvenile and adult fish are different. In the juvenile stage, *A. dabryanus* feeds on animals, such as aquatic insects and benthic invertebrates, whereas adult fish mainly consume plants, such as stems, leaves, fragments of vascular plants, and algae [3]. In addition, benthic small fish are a preferred food source for *A. dabryanus* [4].

1.2. Historical Distribution

Prior to the construction of the Gezhouba Dam, *A. dabryanus* was widely distributed in the mainstream, tributaries, and river-connected lakes in the middle and upper reaches of the Yangtze River. Compared with *Acipenser sinensis* (Chinese sturgeon), which inhabits the same river, *A. dabryanus* shows considerable differences in its life history characteristics. Adult *A. sinensis* with mature gonads migrate upstream for spawning from the East China Sea to the middle and upper reaches of the Yangtze River, and their juveniles migrate downstream and leave the river after approximately one year [1,5]. In contrast, the whole

life history of *A. dabryanus* always occurs in fresh water and does not involve the estuary [6] (Figure 1). Due to the lack of conclusive evidence, to the best of our knowledge, no accurate description of the natural spawning ground of *A. dabryanus* has previously been reported. Only the approximate spawning river section was determined, which was in the lower reaches of the Jinsha River below Maoshui, and its feeding ground was in the upper reaches of the Yangtze River below the spawning ground [1,7]. Due to the barrier effect, the natural *A. dabryanus* population below the Gezhouba Dam gradually disappeared after the closure of the dam in 1981 [1].

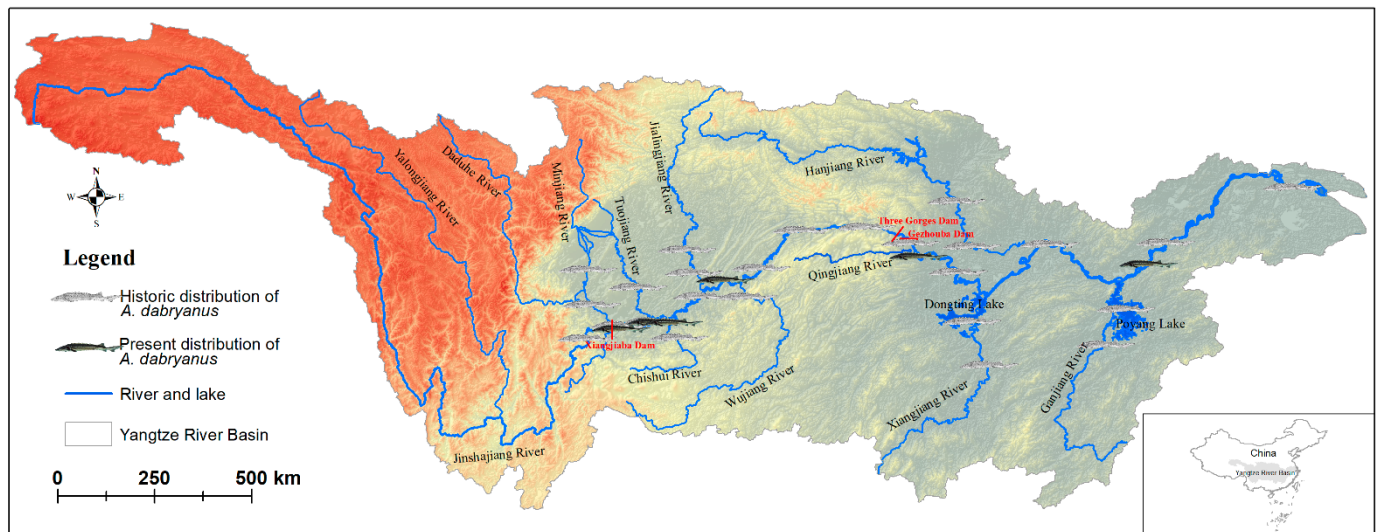


Figure 1. Historical and present distribution of *Acipenser dabryanus*.

1.3. Population Trends

High *A. dabryanus* abundance occurred historically. In the 1970s, the annual catch of mature *A. dabryanus* was 100–200 in the Hejiang section of the upper Yangtze River. During the spawning migration of *A. dabryanus* in spring, fishermen in Sichuan province of China could harvest approximately 5000 kg of *A. dabryanus* [1,7]. In 1981, the predominant migration route of *A. dabryanus* was divided into two parts by the Gezhouba Dam. Sturgeons downstream of the dam were unable to migrate upstream for foraging and spawning, resulting in the failure of normal spawning and reproduction of *A. dabryanus* under the dam. Furthermore, *A. dabryanus* migrating upstream for spawning and foraging were unable to return downstream. In addition, the turbine unit, noise pollution, and water temperature effect of the Gezhouba Dam, coupled with the impact of overfishing, exerted direct or indirect adverse impacts on migrating sturgeons, leading to a decline in abundance of *A. dabryanus*. In 1982, the fishing of *A. dabryanus* was prohibited. From 1984 to 1993, 124 *A. dabryanus* were accidentally caught in the Luzhou section of the upper reaches of the Yangtze River. From 1994 to 1996, 27 were unintentionally caught in the Yibin section of the upper reaches of the Yangtze River. A total of 39 *A. dabryanus* were detected in the upper reaches of the Yangtze River during 2006 to 2010 [8]. However, there have been few reports on the observation of wild individuals in the upper reaches of the Yangtze River after 2010. According to the data derived from the monitoring of this species, natural breeding of wild *A. dabryanus* has not occurred since 2000 [8,9]. In the past four years, monitoring of this species in the entire Yangtze River Basin (including mainstream and tributaries, and large river-connected lakes) detected no wild *A. dabryanus* [10]; rather, all the captured *A. dabryanus* were those that were artificially propagated and released. All the *A. dabryanus* currently inhabiting the natural waters of the Yangtze River were artificially propagated and released.

2. Implemented Protection Measures

2.1. Artificial Species Conservation

Although wild *A. dabryanus* have been difficult to locate, fortunately, original wild *A. dabryanus* were captured before the natural population disappeared. A total of 17 *A. dabryanus* from the wild population still remain in captivity in China. As early as the 1980s, artificial *A. dabryanus* breeding experiments were carried out in China. However, these experiments failed to obtain larvae on a large scale due to the immaturity of the technology at that time. It was not until 2003 that a breakthrough was made in the large-scale artificial breeding of wild, mature *A. dabryanus*. Success in the full artificial reproduction of the second and third generation of *A. dabryanus* was achieved, respectively, in 2007 and 2018. Currently, there are more than 1000 first-generation mature *A. dabryanus* in China. The number of mature fish of the second generation has reached 20,000 and the annual large-scale breeding capacity has reached more than one million. The successful artificial reproduction of the third generation of *A. dabryanus* represents another breakthrough in the ex situ protection of this species and indicates the success of the sustainable artificial propagation and species conservation.

2.2. Stock Enhancement

Artificial reproduction and release have played a vital role in the conservation of various species of fishes [11] and have become the primary means of the protection of fishery resources in China [12]. The artificial reproduction and release of *A. dabryanus* can be roughly divided into two stages. The first stage was from 2007 to 2017, during which cultured juvenile *A. dabryanus* were released. However, the effect was not ideal due to poor environmental adaptability and a low survival rate of the released individuals [13]. The second stage was from 2018 to 2021, during which the release of *A. dabryanus* was still dominated by the release of juvenile fish; however, the release of the mature fish started for the first time during this period. In the past four years, more than 200,000 *A. dabryanus* individuals have been released, including over 500 adult individuals (i.e., having reached the third phase of gonadal development). The released mature sturgeons were still mainly distributed in the lower reaches of Jinsha River below Xiangjiaba Dam and the main stem of the Yangtze River above Lizhuang town. Released juvenile sturgeons have also been detected in some main stem and tributaries of the upper reaches of the Yangtze River. Artificial reproduction and release have become the most important means of maintaining the *A. dabryanus* population in the wild.

2.3. Other Methods of Protections

In addition to the measures of artificial conservation (i.e., artificial reproduction and release), another critical protection measure for *A. dabryanus* is the establishment of a national nature reserve and the introduction of special rescue action plans. As early as the year 2000, a national nature reserve was established in the upper reaches of the Yangtze River to protect >100 species of rare and endemic fishes. This was followed by the establishment of a special fish propagation and release station with the development and operation of the cascade hydropower stations in the upper reaches of the Yangtze River, such as the Xiangjiaba Dam. The aim of the stations were the artificial breeding, reproduction, and release of endemic fishes (e.g., *A. dabryanus*, *Coreius guichenoti*, and *Procypris rabaudi*) in the upper reaches of the Yangtze River. In 2018, the Ministry of Agriculture and Rural Affairs of the People's Republic of China issued the Rescue Action Plan for *A. dabryanus* (2018–2035) to plan conservation, improvement, and restoration measures for the natural population and habitat of *A. dabryanus* from 2018 to 2035. In addition, the Chinese government commenced a 10-year fishing ban in the Yangtze River Basin on 1 January 2021 and a permanent fishing ban has been applied in 332 aquatic biological reserves. This is encouraging news for the future recovery of the natural populations of endangered and endemic fishes, such as *A. dabryanus*, in the Yangtze River Basin.

3. Foundation of the Natural *A. dabryanus* Population Reconstruction

Currently, the wild population of *A. dabryanus* is almost extinct. Successful artificial propagation brings the potential for the reconstruction of the wild *A. dabryanus* population. The core task of *A. dabryanus* species protection is to restore the wild population and facilitate its natural reproduction. It is critical to effectively recover the resources required by the wild population (including the breeding population and supplementary population resources) and to restore suitable habitat (spawning ground, feeding ground, and migration channel) for the reconstruction of the wild population of *A. dabryanus*. Based on the above two considerations, the specific tasks of wild population reconstruction should include two aspects: (1) large-scale artificial population release, which directly increases the population of the mature *A. dabryanus* in the wild. At the same time, large-scale release of juvenile fish obtained by artificial breeding can increase the supplementary population resources. (2) Habitat restoration, whereby, based on the suitability assessment of the key habitats of *A. dabryanus*, key habitats (such as spawning grounds) should be restored and improved. Habitat restoration should focus on replenishing the species that *A. dabryanus* feeds on to facilitate its effective sustenance, fattening, and overwintering in its natural habitat. Here, we propose the conceptual framework for the wild population restoration of *A. dabryanus* (Figure 2).

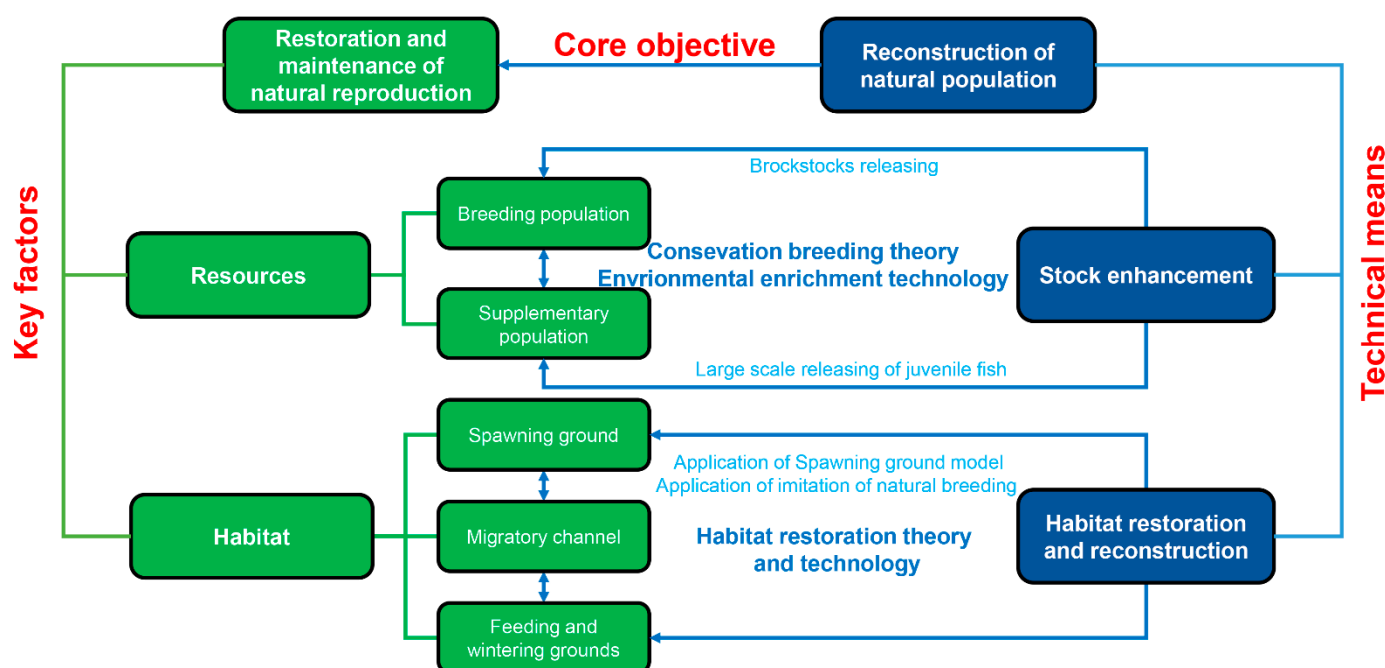


Figure 2. Conceptual framework for wild population reconstruction of *Acipenser dabryanus*.

3.1. Sufficient Artificial Breeding Population

As an endemic fish in the upper reaches of the Yangtze River, the natural habitat of *A. dabryanus* has been maintained at a very low level since the 1980s. After >20 years of artificial propagation and species conservation, breakthroughs have been made in the artificial propagation of wild *A. dabryanus*, including whole life cycle breeding of the first and the second generations. Ex situ conservation has saved this endangered species, and, further, the preservation of the breeding capacity of the mature population of the first and second generations has considerably improved. Based on the breeding ability of the captive *A. dabryanus*, the number of larvae of the second generation can reach 3–5 million/year that could be produced at the hatchery, providing a solid foundation for the restoration of the *A. dabryanus* population. The advancement of gonad development identification technology, mature fish breeding technology, male and female synchronous regulation

technology, as well as the accumulation of relevant knowledge and experience related to the basic biological characteristics and reproductive biological features of *A. dabryanus*, have provided technical support, vastly improving and guaranteeing the restoration of the *A. dabryanus* population.

3.2. Natural Reproductive Potential of Cultured Individuals

To maintain the biological instinct of *A. dabryanus* and evaluate the potential of spontaneous spawning, natural reproduction of *A. dabryanus* was achieved in the artificial simulated environment for the first time in 2016 by artificially regulating the environmental induction (i.e., providing artificial bottom material and water flow). From 2017 to 2018, repeated experiments were conducted in the artificial conservation bases of *A. dabryanus* in Yibin (Sichuan Province) and Jingzhou (Hubei Province). All these experiments were successful in the achievement of natural reproduction of *A. dabryanus* in the controlled environment. Furthermore, over 60,000 third-generation seedlings were obtained for the first time [14] and more than 18,000 healthy juvenile fish of >20 cm were harvested in 2018.

The success of natural reproduction of *A. dabryanus* in the controlled environment suggests that appropriate regulation of an artificial environment can induce natural spawning in this species. The success also indicates that adult *A. dabryanus* of the first and second generations maintain the biological instinct of natural reproduction, which is of great significance to the development of artificial populations and resource conservation of *A. dabryanus*. This result provides a reference basis for improving the protection and breeding methods of rare and endangered aquatic animals.

3.3. Key Habitat Functionality

The breeding time of *A. dabryanus* is generally from March to April (in spring). The weights of a sexually mature male ($\sigma > 4$ years) and female ($\varphi > 6$ years) fish are typically 4–12 kg and 9–16 kg, respectively [7]. Although the natural breeding activities of *A. dabryanus* have ceased, their spawning grounds, feeding grounds, and other critical habitats still exist. From 2012 to 2018, the distribution of *A. dabryanus* in the upper reaches of the Yangtze River has been extensively investigated, and the river section from below Xiangjiaba Dam to above Chongqing (where spawning grounds and main feeding places are located) remained in good condition. By tracking and monitoring mature sturgeons released into the wild, it was found that they rarely migrated a long distance downstream, unlike the migration of young sturgeons following release [13]. Furthermore, mature sturgeons were predominantly distributed in the Jinsha River below Xiangjiaba Dam and the mainstream of the upper reaches of the Yangtze River [15]. The distribution of released juvenile fish covered approximately 500 km from Yibin to Fuling, and the primary gathering area was from Yibin to Hejiang River (Figure 3). The main distribution area of released mature and juvenile *A. dabryanus* highly corresponded with its historical spawning and feeding grounds. The individual distribution of the mature sturgeon after release indicated that the functionality of the key habitat of *A. dabryanus* still partially exists, which can maintain behaviors, such as habitat choice.

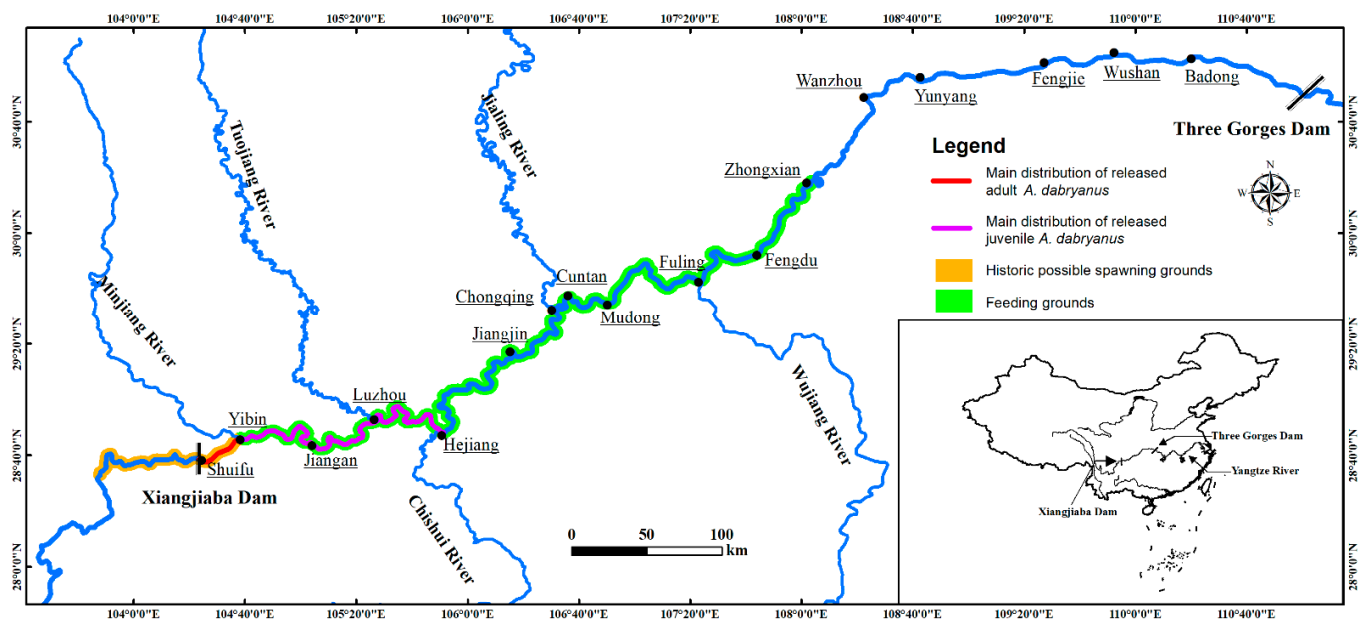


Figure 3. Diagram showing spawning and feeding grounds of *Acipenser dabryanus*.

Currently, the total length of the river section of the national nature reserve for rare and endemic fishes in the upper reaches of the Yangtze River is about 1162 km, covering the main-stem and tributaries of the upper reaches of the Yangtze River, including the lower reaches of Jinsha, Minjiang, and Chishui rivers. These river sections cover the main distribution areas and key habitats, such as spawning and feeding grounds, which have been effectively preserved. Thus, these habitats can facilitate the restoration of a natural *A. dabryanus* population.

3.4. Successful Cases of In Situ Conservation of Sturgeons

Research on the ecological needs of natural reproduction of sturgeons has always been an important topic in sturgeon protection studies. Considering *A. sinensis* (which inhabits the same river as *A. dabryanus*) as an example, numerous studies have emphasized the natural reproduction requirements of *A. sinensis* regarding water flow, current, and eddy flow from various aspects and evaluation models [16–19]. In addition, the impact of regulation of the Three Gorges Project on *A. sinensis* was evaluated. Moreover, numerous studies have reported on the riverbed material of sturgeon spawning grounds and revealed that the grain size, composition, and layout of riverbed material have an impact on natural reproduction. Clean riverbed material is conducive to natural spawning of most sturgeons [20–22] and the embeddedness of riverbed material determines the spawning position of sturgeons [23]. Hence, the riverbed material is a significant inducer of sturgeon spawning. In a previous study, the riverbed morphology model of the *A. sinensis* spawning ground was successfully developed [24]. Furthermore, follow-up research revealed that the riverbed morphology of the new *A. sinensis* spawning ground was formed under the dam due to the closure of Gezhouba Dam. This new riverbed provided the relevant velocity and clean riverbed material required for embryonic development. According to the characteristics of natural sturgeon reproduction demands, in addition to water temperature, water flow (velocity, flow, water level, and water depth) and riverbed material (riverbed shape and grain size) are the major factors affecting natural reproduction in this species. These findings provide theoretical support for the restoration of *A. dabryanus* spawning ground.

Currently, the research results based on the ecological needs of sturgeon natural reproduction have been successfully applied in the reconstruction and restoration of spawning grounds. For example, artificial reefs were placed in the river to restore the spawning grounds of *Acipenser fulvescens* [21]. During appropriate water flow, the riverbed material would also induce the natural reproduction of 17 other fish species. Adding riverbed

material is a common method applied to the artificial spawning ground, and the spawning substrate and the spawning velocity environment are created simultaneously [22,25]. Placing 20–30 cm pebbles in the water is beneficial for *A. fulvescens* spawning, and adding larger gravels is conducive to providing habitat and shelter for mature fish. Similar successful cases were reported on artificial spawning in *Acipenser gueldenstaedtii* and *Acipenser ruthenus* [26]. These findings provide theoretical and practical support for the restoration of *A. dabryanus* spawning grounds.

4. Analysis of Existing Problems and Countermeasures

4.1. Habitat Hydrological Rhythm Changes

During the past few decades, dam construction has been deemed as one of the primary reasons for the change in the river ecosystem. The risk of fish habitat function degradation and loss, the decline in the diversity of fishes in rivers, and even species extinction caused by dam construction have become global concerns [27,28]. The survival of *A. dabryanus* is threatened by a series of problems caused by dam construction. The mature sturgeons released into the Yangtze River had a high survival rate and fed and survived in the lower reaches of the Jinsha River below Xiangjiaba Dam. However, following the successive operation of cascade hydropower stations in the upper reaches of the Yangtze River, changes have been observed in the hydrological conditions below Xiangjiaba Dam. In particular, with the storage and operation of Baihetan Hydropower Station in the upper reaches of the Yangtze River in 2021, the increase in outflow temperature will delay the spawning time of endemic fishes in the upper reaches of the Yangtze River and further reduce the area of suitable habitat [29].

4.2. Improvements in Methods and Means of Stock Enhancement

The artificial breeding population of *A. dabryanus* is predominantly concentrated in Sichuan and Hubei, and artificial breeding has progressed to the third generation of offspring. From the current artificial breeding water temperature and conditions of several aquaculture areas, artificial breeding can be commenced when the water temperature reaches approximately 15 °C. It is difficult to achieve “soft release” for the propagation and release of aquatic organisms, especially fishes, compared with terrestrial animals. The artificially bred individuals could adapt to the natural environment ahead of time in semi-natural or natural water bodies prior to release. In contrast, “hard release” could lead to poor propagation and release or complete failure, because it is hard for the breeding individuals to adapt to the natural environment in a short time.

In the past 3 years, >500 mature *A. dabryanus* (average weight = 18.0 ± 5.3 kg) have been released in the upper reaches of the Yangtze River. The gonadal development of these mature sturgeons was in phase III or above [30,31]; however, no natural breeding activities were observed in these three years.

Regarding the two problems faced in the restoration of *A. dabryanus* population, this study proposes that semi-natural or natural water bodies must be returned to their wild state by induction experiment for releasing *A. dabryanus* into its critical habitat. The main purposes are: (1) to perform better adaptation in semi-natural waters before release, and to release the cultured *A. dabryanus* after domestication induction for a period; (2) to carry out the experiment of returning cultured mature sturgeon to the wild in semi-natural waters. In this way, habitat preference, gonad development, and feeding status of cultured mature sturgeon in semi-natural waters can be observed. The induction test can help understand the behaviors of cultured *A. dabryanus* in a semi-natural environment and can have a positive impact on improving the survival rate of cultured *A. dabryanus*, especially after the release of juvenile fish. Meanwhile, it has important guiding significance for the subsequent natural population restoration and habitat improvement of *A. dabryanus*.

5. Looking into the Future

In 2020, 16 species of freshwater fishes worldwide were declared extinct [32], including an endemic species that inhabited the Yangtze River Basin—*Acipenser transmontanus* [6]. The natural living conditions of two other kinds of sturgeons in the Yangtze River Basin are not optimistic. The natural breeding activities of *A. sinensi* have been interrupted for four years (i.e., only small-scale breeding activities were reported in the spawning ground below Gezhouba Dam in 2016), while natural breeding activities of *A. dabryanus* have not occurred for many years. Fortunately, breakthroughs have been made in the artificial breeding technology of these two sturgeons, and that of *A. dabryanus* has progressed to the third generation. With the promulgation and implementation of the Chinese government's action plan for the rescue of *A. dabryanus* and the 10-year fishing ban in the Yangtze River Basin, as well as the enforcement of the Yangtze River Protection Law in China, there are new opportunities and challenges for the restoration of the natural stocks of endangered fish, such as *A. dabryanus* and *A. sinensi*, in the Yangtze River.

The factors leading to *A. dabryanus* becoming endangered can be classified as direct and indirect [9]. On the one hand, the direct factors encompass water conservancy projects focusing on dam construction and river regulation. These projects have caused changes in the river's hydrological regime, thus affecting life processes (e.g., reproduction) of *A. dabryanus*. On the other hand, indirect factors include pressure from commercial fishing, whereby overfishing has led to the sharp reduction in the natural population of *A. dabryanus* in the past few decades. Fortunately, the adverse effects of fishing have been eliminated (i.e., the species will not be threatened by fishing, at least for the next 10 years). In the future, to protect and restore the population of *A. dabryanus*, it is necessary to focus on the specific impacts of dam construction and operation under water conservancy projects on *A. dabryanus* and its key habitat. With the help of studies on *A. sinensi* spawning grounds and relevant experience of *A. fulvescens* habitat reconstruction, natural reproduction of *A. dabryanus* could be restored through the restoration of spawning grounds and the ecological regulation of cascade dams. Significantly, considering the potential reduction in the genetic effective population size and inbreeding depression, genetic management plans should be taken seriously for an effective restocking and restoring program of *A. dabryanus* [33,34]. Although 2020 was not an optimistic year for freshwater fishes, we believe that the reconstruction and restoration of the ancient and endangered species can be anticipated in the future.

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Conflicts of Interest: All the authors declare that there is no conflict of a commercial or financial interest regarding the publication in this paper.

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