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Restoring *Acipenser sturio* L., 1758 in Europe: Lessons from the *Acipenser oxyrinchus* Mitchill, 1815 experience in North America

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ABSTRACT

Acipenser sturio L., 1758 was once wide-ranging and common in Europe, but it now persists precariously in the wild only in relict populations. Its sister species, the morphologically and ecologically similar *Acipenser oxyrinchus* Mitchill, 1815, exists in the western North Atlantic. Although both forms have suffered from the same three liabilities –overharvest, habitat modification, and pollution– their net effects have been far greater for *A. sturio*. Historically, there were at least 35 populations of *A. oxyrinchus* in North America; their present statuses range from moderately abundant to possibly extirpated. However, interest in conservation of *A. oxyrinchus* has increased greatly over the past two decades and great strides have been made toward their restoration. Techniques used have included surveys of anecdotal information, directed fisheries surveys, comprehensive genetic analysis, hatchery culture improvements, experimental stockings of hatchery-produced young, and fundamental life history research. Moreover, the seriousness of sharp declines in the face of suddenly enlarged fisheries mustered the political will to protect *A. oxyrinchus* from directed fisheries in U.S. waters for a period of up to 40 years (although by-catch remains a concern). Because their intrinsic rate of increase is very protracted, it will be decades before particular populations are once again abundant. Nonetheless, the future for *A. oxyrinchus* appears promising. *A. sturio* is so scarce that each specimen is precious; thus, it is risky to experiment with them. But given the similarities between the two species, those seeking to restore *A. sturio* should be able to adapt much of the information learned from managers of *A. oxyrinchus*.

Key words: Sturgeons, genetic analysis, hatchery culture, relict population, restoration.

RESUMEN

Recuperación de* Acipenser sturio *L., 1758 en Europa: lecciones de la experiencia con* Acipenser oxyrinchus *Mitchill, 1815 en América del Norte

Acipenser sturio *L., 1758 estuvo ampliamente distribuido y fue común en Europa, pero ahora persiste precariamente en estado silvestre sólo en poblaciones relictas. Su especie hermana, el morfológica y ecológicamente similar* Acipenser oxyrinchus *Mitchill, 1815, existe en el Atlántico norte occidental. Aunque ambas formas han padecido los mismos tres riesgos —sobrepesca, modificación del hábitat y contaminación— sus efectos netos han sido mucho mayores en* A. sturio. *Históricamente hubo, al menos, 35 poblaciones de* A. oxyrinchus *en América del Norte; su estado actual varía entre moderadamente abundante a posiblemente extirpado. Sin embargo, el interés por la conservación de* A. oxyrinchus *ha crecido importantemente durante las dos últimas décadas y se han dado grandes pasos hacia su recuperación. Las técnicas utilizadas han incluido inspecciones de información anecdótica, revisiones directas de las pescas, análisis genético detallado, mejora del cultivo en criadero, sueltas experimentales de juveniles producidos en criadero e investigación básica de la historia natural. Además, la gravedad de los bruscos declives frente a los repentinos aumentos de las pescas reunió la voluntad política para proteger a* A. oxyrinchus *de la pesca directa en las aguas esta-*

dounidenses por un periodo de hasta 40 años (aunque la captura ocasional continúa siendo un problema). Debido a que su tasa intrínseca de crecimiento es muy lenta, tendrán que pasar décadas antes de que poblaciones particulares sean de nuevo abundantes. No obstante, el futuro para A. oxyrinchus *parece prometedor.* A. sturio *es tan escaso que cada ejemplar es precioso; así, es arriesgado experimentar con ellos. Pero dadas las similitudes entre las dos especies, los que pretenden recuperar* A. sturio *serían capaces de adaptar mucha de la información aprendida de los gestores de* A. oxyrinchus.

Palabras clave: *Esturiones, análisis genético, cultivo en criadero, población relicta, recuperación.*

INTRODUCTION

Although western Europe has been hypothesised to be the centre of origin for Acipenseriformes (Bemis and Kynard, 1997), this region, and particularly its Atlantic coast, is depauperate in sturgeons. Unfortunately, its single native anadromous form, the Atlantic sturgeon *Acipenser sturio* L., 1758, only exists as relicts in the wild. Once found from northern Europe to the Black Sea, the single indisputably extant population exists in the Gironde River, France (Williot *et al.*, 1997). The precariousness of *A. sturio* is recognised officially (Birstein, Bemis and Waldman, 1997); they are classified as endangered by the IUCN (as of 1994) and critically endangered by CITES (as of 1996).

A. sturio is now the focus of restoration efforts across much of its former range. However, such efforts are complicated by the long absence of the species from many of its native waters, so that there is little localised species-specific scientific knowledge or experience available. Moreover, given the scarcity of *A. sturio*, there are few specimens with which to conduct experiments useful toward its restoration.

One potential source of information that could be helpful in developing effective programmes to restore *A. sturio* is the American experience with *Acipenser oxyrinchus* Mitchill, 1815. *A. oxyrinchus* is the sister species to *A. sturio* (Wirgin, Stabile and Waldman, 1997; Birstein and DeSalle, 1998); one which is so similar morphologically and ecologically that they were treated as a single species prior to the study by Magnin (1964), or as subspecies (Scott and Scott, 1988; Birstein, 1993). *A. oxyrinchus* is found in large rivers from the St. Lawrence, Canada, to the Mississippi, USA. Two subspecies are recognised, *A. oxyrinchus oxyrinchus*, which occurs along the Atlantic coast of North America and *A. oxyrinchus desotoi* Vladykov, 1955, which is restricted to the Gulf of Mexico region (Ong *et al.*, 1996).

The broad distribution of *A. oxyrinchus* is comparable to the native range of *A. sturio* in Europe. Today, however, the conservation status of *A. oxyrinchus*, although strongly compromised, is far better than that of *A. sturio*. The chief difference is that despite severe reductions in overall abundance, *A. oxyrinchus* has lost only a few populations of the approximately three dozen that were known to exist (Waldman and Wirgin, 1998). But concern about *A. oxyrinchus* increased in the 1980s and 1990s, as indications accumulated that many of its stocks were declining. In response, there has been a flurry of research, monitoring, and regulatory actions designed to restore *A. oxyrinchus* populations. In the present paper, I briefly review the life history of *A. oxyrinchus* and its decline and management response, and suggest ways in which this experience can aid European efforts to restore *A. sturio*.

LIFE HISTORY

A. oxyrinchus spawns in deep reaches of large rivers. Spawning times range from February in southern rivers to July in Canadian waters (Smith and Clugston, 1997). Spawning sites typically include flowing water over hard substrate. After several years in fresh or brackish water, most *A. o. oxyrinchus* leave their natal rivers and they may spend a decade or more in the sea before their first spawnings, whereas *A. o. desotoi* (because of temperature constraints) only uses marine waters during winter. Thus, the marine movements of *A. o. oxyrinchus* may be extensive, although there appears to be a tendency to remain within coastal zoogeographic regions (Waldman, Hart and Wirgin, 1996). Despite these extensive movements, estimated gene flow rates and strong stock structuring suggest that the species homes with high fidelity (Stabile *et al.*, 1996; Wirgin *et al.*, 2000).

A. oxyrinchus can reach approximately 300 kg and live as long as 60 years. They mature late (10-25 years), with a positive relationship between reproductive age and latitude (Smith and Clugston, 1997). Females do not spawn every year; in the Hudson River the average spawning interval was estimated at four years (Secor, Stevenson and Houde, 1997). Fecundity ranges between 0.4 and 2.0 million eggs (Van Eenennaam *et al.*, 1996). Males also may not spawn annually (Bain, 1997).

There is little detailed information on the food habits of *A. oxyrinchus.* Riverine juveniles feed on plants, aquatic insects, and small crustaceans and mollusks (Scott and Scott, 1988). Johnson *et al.* (1997) examined stomach contents of 275 specimens caught along the coast of New Jersey and found that they consumed mainly polycheates and isopods.

Secor and Waldman (1999) believe that *A. oxyrinchus* shows a mixture of life history traits selected for both stable environments (large fraction of population biomass composed of adults, extremely delayed maturity, infrequent spawning, large adult size, rapid juvenile growth rates, precocial young) and periodically salubrious environments (high individual fecundity, long reproductive life span, complex age structure). Because of these characteristics, population growth rates are slow (Boreman, 1997).

THE DECLINE OF *A. oxyrinchus*

Declines of sturgeons are commonly attributed to overharvest, habitat modifications (particularly damming), and pollution (Waldman, 1995), but for *A. oxyrinchus*, it is clear that overharvest has been the primary agent. Exploitation by Native Americans occurred as long ago as 2190 B.C. These sturgeon were caught by European colonists with a large variety of gear, including pound nets, weirs, stake row nets, trammel nets, trawls, harpoons, and snares. However, floating and anchored gill nets eventually became the primary means of capture. Total US landings of *A. oxyrinchus* (including low but unknown proportions of *Acipenser brevirostrum* LeSueur, 1818) were first estimated in 1880, and they peaked in 1890 at about 3 350 t (Smith and Clugston, 1997) due to pressure from the international caviar craze of that period (Secor and Waldman, 1999). Delaware Bay supported the largest fishery, constituting 75 % of harvests between 1890 and 1899 (Secor and Waldman, 1999). But after the mid-1890s catches declined rapidly and by 1901 the Delaware Bay fishery had crashed.

Catches in other rivers declined also, but not always as dramatically. For much of the twentieth century, both the abundance of *A. oxyrinchus* and their fisheries remained at relatively stable but low levels. The stated goal of the Atlantic States Marine Fisheries Commission (ASMFC) was to restore *A. oxyrinchus* to fishable abundance throughout its US range, with fishable abundance defined as ~317 t (10 % of 1890 landings). But localised increases in catches in the late 1980s raised concern about the species. For example, the Hudson River stock persisted throughout the 20th century at a moderate abundance while being fished at low levels, primarily for meat. But landings in the state of New Jersey from near the mouth of the river (mostly subadults for meat) rose from 5 900 kg in 1988 to a high of 100 000 kg in 1990 (Waldman, Hart and Wirgin, 1996). Over the same period, a caviar-based fishery developed in the Hudson River which focused on spawning female sturgeon. Most ominously, recruitment in the Hudson continued to decline (Anon., 1998b).

Largely in response to these fisheries, but also due to concerns about *A. oxyrinchus* across its US range, ASMFC pressured states to close their sturgeon fisheries. During 1986, total landings were 42 t, or only 1 % of those reported about 100 years earlier. Closure of the directed fisheries affected about 65 fishermen (Anon., 1998a).

In 1998, a petition to place *A. oxyrinchus* on the federal endangered species list was denied by the U.S. Fish and Wildlife Service and the U.S. National Marine Fisheries Service. Nonetheless, Anon., (1998b) did amend its 1990 Interstate Management Plan for Atlantic Sturgeon in response to deteriorating stocks, most notably the Hudson River stock. All US fisheries were closed by April 1998. Furthermore, an indefinite moratorium was enacted, with the potential to continue for up to 40 years. This potentially extraordinarily lengthy period was defined in order to establish 20 protected year-classes of females in each spawning stock. The amendment also seeks to reduce or eliminate by-catch mortality, protect spawning sites, and where feasible, reestablish access to historical spawning habitats.

MANAGEMENT AND RESEARCH EXPERIENCE WITH *A. oxyrinchus* POTENTIALLY RELATED TO RESTORATION OF *A. sturio*

Define clear and realistic goals

Between 1990 and 1998, the stated goal of the ASMFC (Taub, 1990) was to restore *A. oxyrinchus* populations sufficiently to support harvests that were 10 % of 1890 levels. But this objective was arbitrary, and not based on any biological rationale. Moreover, it did not examine the levels of restoration that could be achieved on a population-by-population basis. History proved this plan to be insufficient and unrealistic, as populations continued to decline.

Possible objectives for mode of restoration of *A. sturio* include development of (1) self-sustaining populations, (2) hatchery-reared-only populations, and (3) hatchery-supplemented populations. Ultimately, these populations could be (a) fished or (b) not fished as “hands-off” populations for “biodiversity” purposes. The initial choice in the pairing of mode and fate in relation to the opportunity presented in a given river system is critical in shaping subsequent efforts.

Determine present and historical status of populations

Anadromous sturgeons are large, long-lived fishes that usually occur in deep waters. Also, they mature late and females spawn only in intermittent years. These characteristics make these large fishes, ironically, rather cryptic. That is, low numbers of sturgeon may persist undetected by man. For example, *A. oxyrinchus* was thought to be extinct in Chesapeake Bay, but increased research and media attention to their possible restoration there stimulated commercial fishermen to notify authorities of incidental recaptures. And researchers discovered not inconsequential numbers of young specimens in Virginia tributaries to Chesapeake Bay. These findings shifted the focus from reintroduction of the species using fish from elsewhere to restoration of the native genetic stock.

The use of publicly-provided information to help steer restoration attempts worked particularly well for *A. o. desotoi.* A pamphlet and poster were developed soliciting anecdotal reports from citizens regarding sturgeon in Gulf of Mexico drainages (Waldman and Wirgin, 1998). This approach yielded a surprisingly large amount of knowledge which subsequently helped steer more rigorous investigations.

The possibility of additional, undetected populations of *A. sturio* should be taken seriously. The British Marine Life Society has catalogued a surprisingly large number of sightings and catches in UK waters (A. Horton, pers. comm.) in recent decades in a part of Europe where it is not even certain the species ever reproduced. And Williot *et al.* (1997) provided a figure of almost 100 captures of *A. sturio* by commercial fishermen in coastal waters from France to Denmark between 1980 and 1994, which must be an underestimate of total incidental catches. However, Rochard, Lepage and Meauzé (1997) interpreted the patterns of distribution of tagged and untagged *A. sturio* in marine waters as indicating a single source, from the Gironde River.

Because relict populations of sturgeons are cryptic, it may be useful to test the likelihood of their persistence before making the critical decision to introduce fish from other stocks. Statistical methods have been developed to accomplish this using incidental captures over time (e.g. Reed, 1996; Grogan and Boreman 1998).

Assess limiting factors

When a long-established sturgeon stock becomes extinct, some factor or combination of factors must have been responsible for its demise. For *A. oxyrinchus*, overfishing appears to be the major cause of population loss (together with habitat modification, to varying degrees). It seems more likely that in Europe, habitat modification has been the primary agent (e.g. Elvira, Almodóvar and Lobón-Cerviá, 1991; Nicola, Elvira and Almodóvar, 1996). But continued directed fishing on declining stocks and by-catch mortality also may have contributed to declines of *A. sturio* (Williot *et al.*, 1997). However, such generalities are insufficient in assessing the limiting factors particular to the loss of each population of *A. sturio*.

The circumstances that led to the loss of each *A. sturio* population deserve a detailed and forthright analysis. For example, it is obvious that if construction of a dam blocked the spawning run in a river and if that dam still stands, then restoration to a self-sustaining population is impossible. But if in another river intense overfishing collapsed the stock but newly stocked fish can now be protected, then that river may be a good candidate for restoration. Each restoration effort is a gamble involving scarce financial and specimen resources. Clear-headed initiatives in well-designed and likely-to-succeed situations will lead to successes that instigate additional programmes; misguided efforts with low probabilities of success will be counterproductive to the overall European effort.

Habitat restoration

Because sturgeons in fresh water occur mainly in large, deep rivers, opportunities for habitat restoration on their behalf are scarce. Beamesderfer and Farr (1997) summarised the few examples of habitat restoration for sturgeons in North America, including manipulations of water levels and addition of artificial substrate to assist spawning. None of these examples included *A. oxyrinchus*. But there was one recent project that should benefit the *A. oxyrinchus* population of the Kennebec River in Maine –the July 1999 breaching of the Edwards Dam– which may be instructive toward European efforts for *A. sturio*.

The Edwards Dam was constructed in 1837, blocking movement of spawning anadromous fishes past Augusta, Maine. Despite its continuing usage as a hydroelectric facility, in a precedent-setting decision, the Federal Energy Regulatory Commission determined that the value of its electric generation was outweighed by its environmental costs, particularly to anadromous fishes. *A. oxyrinchus* was one of several fish species that will benefit from the reopening of 11 km of additional river.

Breaching of the Edwards Dam is the greatest success to date in a new national movement in the US to remove unused or marginally beneficial dams to defragment rivers and restore spawning runs of fishes. Although such actions are politically very difficult, it is worth reviewing the possibilities for similar programmes in European rivers to assist *A. sturio* and other anadromous fishes, it is likely that no other action would have as positive an effect.

Improve culturing capabilities

A. oxyrinchus was first spawned artificially in 1875, but little culture was performed beyond 1912, until recently (Smith and Clugston, 1997). Most notably, a research hatchery of the US Fish and Wildlife Service at Lamar, Pennsylvania, has been improving culture techniques for *A. oxyrinchus*. Tens of thousands of young have been produced from only a few parents. For the most part, these fish have not been stocked in the wild because of concerns about effective population size, non-native stock transfer, and uncertainty about the extinction of certain stocks. Nonetheless, the protocols exist to reliably generate large numbers of young for stocking if required.

Thus, in the US, opportunities for stocking *A. oxyrinchus* are very limited despite the capabilities. The reverse is true in Europe, where almost every river system that hosted *A. sturio* is now apparently devoid of them, but where hatchery production, due to more limited experience with sturgeon, is not as highly reliable. Moreover, reproductively mature *A. sturio* are so scarce that (1) there is a more than trivial chance that individuals may die in captivity, and (2) the chances of successful hatchery production must be weighed against the probable loss of natural production. This raises the important question as to whether European hatcheries are already prepared to culture *A. sturio* in an environment where the loss of broodstock and their potential spawn is serious.

An alternative would be to first practice and refine culture techniques using *A. oxyrinchus* (available from US and Canadian research facilities). But this should only be tried where multiple safeguards exist against their escapement into the wild.

Genetic concerns

Introduction of limited numbers of hatchery-cultured *A. oxyrinchus* into the Hudson River and Chesapeake Bay and the prospects of larger stockings in those systems and elsewhere led to concerns about their potential genetic effects. Genetic issues were two-fold, but not mutually exclusive. One was that of maintaining effective population size to guard against inbreeding. General guidelines for fish culture suggest minimum effective population sizes of 100 to 200 should be maintained (Kincaid, 1995). But because spawning females were so scarce and because the hatchery culture that took place was for research purposes, only one or two females were used in each spawning of the offspring that were later stocked in the wild. The second issue was interstock transfer, i.e. concerns about introducing genes from a non-native stock to a river that might still support a relict stock.

These concerns led ASMFC to develop a protocol for breeding and stocking *A. oxyrinchus* (St. Pierre, 1996). Among its recommendations was to adopt a generation effective population size scheme with 100 as the minimum effective population size of brood fish (with an inbreeding rate of 0.5 %). Year-class effective population sizes should be at least six. Clearly, adherence to this protocol would involve a long-term commitment, e.g. 10 years at an average year-class effective population size of 10.

A second important recommendation was to use, whenever possible, broodfish from the same river in which stocking will occur. When this is not possible, the source of broodfish should be from the same regional genetic grouping as the river being stocked (e.g. Waldman, Hart and Wirgin, 1996; Wirgin *et al.*, 2000).

These protocols developed for *A. oxyrinchus* bear on any parallel attempts to restore *A. sturio*, but with a different emphasis, i.e. the single extant *A. sturio* population of the Gironde River could be degraded by inbreeding depression. This argues all the more for their protection from this stress by either allowing them to increase in abundance naturally or to develop a hatchery-based programme that assures generation effective population size.

However, because almost all European rivers that once hosted *A. sturio* appear to be devoid of them, and because the sources of hatchery-cultured fish to be stocked will be so limited, intrastock transfer is not a primary concern. But it would still be advantageous to the prospects for success of any stockings if the fish planted were outbred.

Protect stocked fish

The population viability of newly stocked *A. sturio* in a river system may be precarious because of limits on the numbers of fish available to be stocked and their subsequent survival. Even if directed fisheries are banned, sturgeon life history characteristics render them particularly susceptible to the forces of by-catch mortality, in that low levels of unnatural mortality forestall recovery (Boreman, 1997). Also, because of their broad dispersion in coastal waters, by-catch mortality may make up a considerable proportion of total fishing mortality; for *A. oxyrinchus* in 1987, nearly 77 % of total landings at a time when directed fisheries still operated (Smith and Clugston, 1997). To minimise all forms of non-natural mortality, sufficient regulations, enforcement, and penalties will need to be in place and be well publicised.

Appropriate monitoring of each restoration effort

Restoration of self-sustaining populations of *A. sturio* will involve documentation of reproduction.

In the US, aspects of the biology of *A. oxyrinchus* stocked in the Hudson River and Chesapeake Bay have been studied and information about their behaviour in comparison with wild juveniles has been learned (e.g. Secor, 1996). But although such monitoring has value, the true measure of success will be whether the stocked fish reproduce. This means holding the major thrust of monitoring in abeyance for more than a decade as the fish mature.

Develop long-term commitments

With a lengthy maturation schedule and a low intrinsic rate of increase, the emergence of results of restoration programmes for *A. sturio* will be extremely protracted in comparison with most other fishes. It is unusual for government agencies to make funding commitments in fisheries on the time-scale necessary for these programmes, that of decades. Management of *A. oxyrinchus* is now being steered by compacts among states, with committee representation by scientists, fishermen, regulators, and academicians. It may be most advantageous if restoration efforts for *A. sturio* coalesce around consortia that involve public, private, and university participation, in addition to government involvement.

CONCLUSIONS

Because of their origins, reaching back one-quarter billion years, their unique morphologies, sometimes great size, and their provision of one of the world's great delicacies, few fish generate as much public interest as sturgeons (Bemis and Findeis, 1994). However, although interest is presently very high, it is not apparent that conditions in many waters of western Europe will be readily conducive to the restocking of sturgeon. Thus, restoration of *A. sturio* to its native European waters is a noble but difficult endeavour.

I have argued for using some information from the North American experiences with management of *A. oxyrinchus*, together with honest assessments of the potential of conditions of individual European rivers to help steer restoration efforts of *A. sturio*. Nonetheless, given the vagaries of present knowledge of the biology of *A. sturio*, the plasticity of its environmental requirements, and imprecise knowledge of the actual environments, it may not always be clear that the present conditions in a river system are suitable for the survival and reproduction of *A. sturio*. In such cases, if sufficient specimens exist, it may be best to conduct an empirical experiment, i.e. stock some sturgeon and let them "test" the waters, and then, patiently, to await the outcome.

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