Available online at www.sciencedirect.com

SCIENCE DIRECT®

Biological Conservation 121 (2005) 317–331

BIOLOGICAL CONSERVATION

www.elsevier.com/locate/biocon

Review

Threats, conservation strategies, and prognosis for suckers (Catostomidae) in North America: insights from regional case studies of a diverse family of non-game fishes

Steven J. Cooke [a,b,*,1], Christopher M. Bunt [c], Steven J. Hamilton [d], Cecil A. Jennings [e], Michael P. Pearson [f], Michael S. Cooperman [g], Douglas F. Markle [g]

[a] *Department of Forest Sciences, Centre for Applied Conservation Research, University of British Columbia, 2424 Main Mall, Vancouver, BC, Canada V6T 1Z4*

[b] *Centre for Aquatic Ecology, Illinois Natural History Survey, 607 E. Peabody Dr., Champaign, IL 61820, USA*

[c] *Biotactic Inc., 691 Hidden Valley Rd., Kitchener, Ont., Canada N2C 2S4*

[d] *Yankton Field Research Station, Columbia Environmental Research Center, United States Geological Survey, Yankton, SD 57078, USA*

[e] *United States Geological Survey, Georgia Cooperative Fish and Wildlife Research Unit, School of Forest Resources, University of Georgia, Athens, GA 30602, USA*

[f] *Fisheries Centre and Institute for Resources, Environment, and Sustainability, University of British Columbia, Vancouver, BC, Canada V6T 1Z4*

[g] *Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331, USA*

Received 10 December 2003; received in revised form 6 May 2004; accepted 18 May 2004

Abstract

Catostomid fishes are a diverse family of 76+ freshwater species that are distributed across North America in many different habitats. This group of fish is facing a variety of impacts and conservation issues that are somewhat unique relative to more economically valuable and heavily managed fish species. Here, we present a brief series of case studies to highlight the threats such as migration barriers, flow regulation, environmental contamination, habitat degradation, exploitation and impacts from introduced (non-native) species that are facing catostomids in different regions. Collectively, the case studies reveal that individual species usually are not threatened by a single, isolated factor. Instead, species in general face numerous stressors that threaten multiple stages of their life history. Several factors have retarded sucker conservation including widespread inabilities of field workers to distinguish some species, lack of basic natural history and ecological knowledge of life history, and the misconception that suckers are tolerant of degraded conditions and are of little social or ecological value. Without a specific constituent group lobbying for conservation of non-game fishes, all such species, including members of the catostomid family, will continue to face serious risks because of neglect, ignorance, and misunderstanding. We suggest that conservation strategies should incorporate research and education/outreach components. Other conservation strategies that would be effective for protecting suckers include freshwater protected areas for critical habitat, restoration of degraded habitat, and design of catostomid-friendly fish bypass facilities. We believe that the plight of the catostomids is representative of the threats facing many other non-game freshwater fishes with diverse life-history strategies globally.

Keywords: Suckers; Catostomidae; Freshwater fish; Threats; Conservation strategies; Case studies

* Corresponding author. Tel.: +1-604-228-1992.
E-mail address: scooke@interchange.ubc.ca (S.J. Cooke).
[1] All contributions were equal with order of authorship reflecting the sequence in which authors joined the writing team.

0006-3207/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biocon.2004.05.015

Contents

1. Introduction

Freshwater fishes in North America, and indeed the world, represent one of the most imperiled groups of animals and exhibit some of the highest rates of extinction (Moyle and Leidy, 1992; Bruton, 1995; Leidy and Moyle, 1997; Richter et al., 1997b; Cambray and Bianco, 1998; Ricciardi and Rasmussen, 1999). Historically, fisheries assessment and management efforts have been concerned only with species that are commercially or recreationally important and the subject of widespread fishing exploitation (Reynolds et al., 2002). In North America, fish species that do not provide any large-scale, direct financial, recreational, or other obvious benefit to humans are collectively referred to as "non-game" fishes. Generally, non-game fishes lack comprehensive management strategies, and those species are often pushed to extinction without the declines being noticed (Ricciardi and Rasmussen, 1999). The development and strengthening of legislation that mandates the development of recovery plans for all imperiled species in Canada and the United States does not discriminate between species that are to be conserved based upon perceived value to humans. Interestingly, however, most non-game species must be imperiled before conservation efforts and resources are focused on them. Indeed, while conservation efforts protecting terrestrial habitats and processes are well developed, protection of aquatic resources tends to be species-centric and lags behind that of terrestrial environments (Maitland, 1995; Naiman and Turner, 2000).

Great efforts have been expended summarizing the threats and conservation issues facing economically important freshwater fishes such as salmonids (e.g., Lynch et al., 2002; Mills, 1991), centrarchids (Koppelman and Garrett, 2002), percids (Craig, 2000), esocids (Craig, 1996), ictalurids (Irwin and Hubert, 2000) and acipenserids (Rochard et al., 1990). These summaries frequently identify common threats, direct conservation strategies, and promote awareness of species- or family-specific conservation issues. There have been few attempts to summarize the conservation issues facing less economically important freshwater fishes on the family or regional scale (except see regional approaches in the Unites States southwest by Minckley and Deacon, 1991; Moyle, 1995). In North America, the catostomids are a major family of freshwater fishes distributed across the continent in diverse habitats that include large warmwater rivers, coldwater streams, wetlands, and lakes of all sizes. In recent years, concern for non-game fishes has fueled an increase of natural history studies, taxonomic refinements, and threat assessments for fishes such as suckers. This effort probably can be attributed to the increased number of species being recognized as imperiled and the need to construct recovery plans. Because suckers occupy a diverse set of habitats in numerous geographic regions, and exhibit a variety of life-history strategies along a short-lived to long-lived continuum, they can serve as a model family for a series of regional case studies documenting the threats facing non-game freshwater fishes throughout North America. In fact, the plight of the suckers influenced by the large degree of

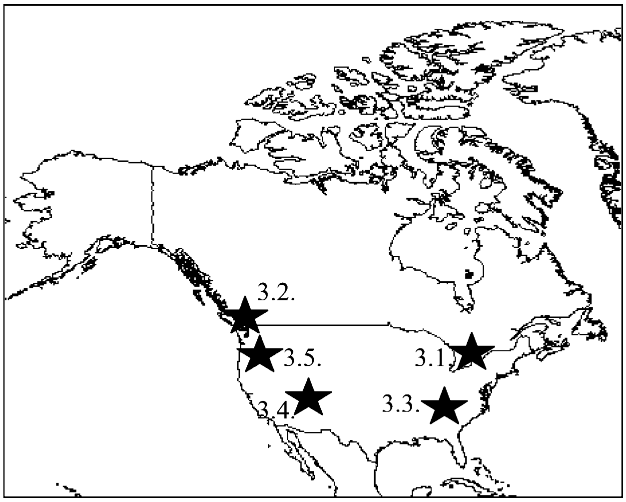

Fig. 1. Map of North America illustrating the location of regional case studies presented in this paper. Numbers on the map correspond to the section numbers for the different case studies.

life-history variation is likely similar to many other species of non-exploited freshwater fishes around the globe.

In this paper, we summarize the threats facing catostomid fishes in different geographic regions of North America (Fig. 1). In addition to expounding on regional issues, our choice of case studies illuminates a range of threats facing these fishes. We summarize the threats facing suckers and identify some of the factors that we believe are retarding sucker conservation. We also present an overview of some of the conservation strategies that have been utilized for suckers and those we believe would be most effective for promoting sucker conservation. Finally, we present a prognosis for this group of fishes and assess the value of using suckers as sentinels for monitoring the status of freshwater systems that may facilitate conservation of other aquatic organisms.

2. The suckers of North America

Here we present a brief overview of the family Catostomidae, and refer readers to recent detailed descriptions in Jenkins and Burkhead (1994) and Moyle (2002). The Catostomidae comprise at least 76 species, of which more than 10 are undescribed (Jenkins and Burkhead, 1994). Suckers are widely distributed among freshwaters in North America and Central America, one species is endemic to China, and one extends from North America to Siberia (Smith, 1992). The 75 species in North America comprise 7% of their freshwater ichthyofauna (Harris and Mayden, 2001). Suckers inhabit both lentic and lotic environments, with few species extending into low-salinity estuaries (Jenkins and Burkhead, 1994). Reproductive behavior is reviewed by Page and Johnston (1990) and is typified by spring migration to spawning grounds followed by trio quiver spawning (female flanked by two males), with no parental care. Suckers have fleshy, typically sub-terminal, protrusible lips, and most adult suckers feed on benthic plant and invertebrate material, although several species are midwater planktivores. Moyle (2002) categorized suckers into three broad ecotypes; (1) deep-bodied suckers, most with terminal mouths, inhabiting open water of large lakes and sluggish rivers; (2) small mountain suckers with horny plates on their lower lip for scraping invertebrates and algae from rocks in fast-moving streams; and (3) typical suckers with sub-terminal mouths that occupy a wide range of fluvial habitats. Extreme variation occurs in life-history strategies. For example, some species are small, short-lived, and functionally semelparous, whereas others are large, long-lived, and iteroparous. Distribution patterns of suckers in North America tend to reflect biogeographical processes and general habitat preferences, consistent with other North American freshwater fishes (Wiley and Mayden, 1985; Smith, 1992). These are general patterns; however, worthy of note is that the family has undergone substantial, and in some cases convergent, diversification (Harris and Mayden, 2001). Thus, there is widespread ecomorphological specialization within this group that has produced a fascinating and diverse group of fishes.

The population status of sucker species varies widely by jurisdiction. Some species are locally abundant but have a limited distribution. In other cases, rarity and conservation status is more of a reflection of political boundaries and range limitations. Our purpose here is not to provide a detailed listing of the status of each sucker species. Instead, we highlight the fact that many species are regionally threatened and an increasing number are being listed as federally threatened or endangered by Canadian (Committee on the Status of Wildlife in Canada, and the Species at Risk Act (SARA)) and US (Endangered Species Act (ESA)) authorities.

3. Case studies

3.1. River suckers of the Midwest

Spawning-related upstream migrations by salmonids and some species of warmwater fishes are well known. However, upstream migrations by catostomids (e.g., Tyus and Karp, 1990; Cooke and Bunt, 1999; Bunt and Cooke, 2001) are often more subtle and less well understood than migrations by other species (Lucas and Baras, 2001). Upstream migrations by adult fishes are thought of as a form of parental investment to reach suitable spawning habitat (Lucas and Baras, 2001). Offspring develop upstream from areas where parents embarked and by the time juveniles can negotiate river flows, they will not have been swept too far downstream where suitable habitat or food may be unavailable. Alternatively, fish migration may be associated with tendencies for natal homing that have not yet been identified among catostomids, but have been identified in non-salmonid species such as northern pike (*Esox lucius*; Miller et al., 2001). Many fluvial systems utilized by suckers have been affected by natural (e.g., beaver, *Castor canadensis*, dams, log jams) and man-made barriers (e.g., low head barrier dams). Barriers have the potential to impart a variety of negative effects including the alteration of natural bedload processes, hydrological disruptions, and physical obstruction of fish migration routes (Graf, 1999). One means of facilitating fish passage around barriers is through the use of fishways. Much effort has been devoted to developing fish passage technology for recreationally and commercially important fishes, but little effort has been devoted to assessing fish passage for suckers.

At present, the most comprehensive assessment of fishway passage of suckers emanates from the Mannheim Weir on the Grand River, southwestern Ontario (Bunt, 1999). The middle reaches of the Grand River are characterized as a moderate sized (mean width of ~60 m) warmwater system with a diverse community of fishes including six species of catostomids (white sucker, *Catostomus commersoni*; northern hog sucker, *Hypentelium nigricans*; greater redhorse, *Moxostoma valenciennesi*; shorthead redhorse, *Moxostoma macrolepidotum*; golden redhorse, *Moxostoma erythrurum*; black redhorse, *Moxostoma duquesnii*), of which only the black redhorse is afforded federal protection in Canada (Parker, 1989). A study by Bunt and Cooke (2001) determined that redhorses represented the largest constituent by biomass of the fish community in the middle reaches of the Grand River.

In the 1990s, two Denil fishways at the Mannheim Weir were used as migratory checkpoints to better understand fish movements related to water temperature, river discharge, water velocities within the fishways and seasonal dynamics (Bunt et al., 2001). Consistent annual patterns of migration were observed for all of the catostomid species excluding the black redhorse (Bunt et al., 2001). Each year, fishway use began about a week after fish were observed moving upstream toward the weirs where the fishways are located. In late April or early May (when water temperature was approximately 8 °C), male white sucker and northern hog sucker began negotiating the river obstruction, first using a lower velocity fishway, then using low and high velocity fishways as water temperatures approached 12 °C (Bunt et al., 2001). Not all species passed the weir in large numbers. For example, Cooke and Bunt (1999) report that large numbers of greater redhorse congregated below the weir, but only five fish passed during a 4-year period. Thus, although some individuals successfully ascend the fishways, others do not. Inter-specific differences in fishway use may be related to poor attraction efficiency (ability of fish to locate fishway entrance), poor passage efficiency, or issues associated with motivation to use fish passage facilities (Bunt, 1999).

Interesting size-specific patterns of fishway use were revealed in another study by Bunt et al. (1999). White suckers that used a high velocity Denil fishway were significantly smaller than those that used a low velocity Denil fishway. These results were related to hydraulic differences within the fishways and differences in hydrodynamic resistance of swimming fish. Differences in fish passage between large-bodied versus small-bodied fishes are related to differences in the cross-sectional area of the fish and the ability of the fish to use velocity refugia, boundary layer flows and spaces between Denil baffles. In many studies of fish passage, adult catostomids often comprise the majority of large fish passed (e.g., Schwalme et al., 1985, Bunt, 1999; Bunt et al., 2001) and almost always dominate in terms of biomass (Bunt et al., 2001). In fact, nearly every species of catostomid fish in rivers where fish passage studies have been conducted use fishways or fish ladders to varying degrees (Bunt, Personal Observation). In southern Ontario, the period of most intense fishway use by catostomids is very early spring, often during periods when fish passage facilities are non-functional because of debris accumulation and blockage caused by flooding and spring freshets. In cases where fish passage facilities are non-existent, or non-functional, anglers target catostomids that congregate at the dams, weirs or waterfalls that block fish movement. Also on the Grand River, Brown et al. (2001) noted that the formation of anchor ice and excessive frazil ice during winter could result in barriers to movement during the winter for white suckers.

Several other active fishways are on the lower Grand River, but only in recent years have there been attempts to determine sucker passage at a finer taxonomic resolution than "sucker". Data generated from fishway studies in the middle Grand River are being applied to the design of future fishways intended to pass non-salmonids throughout North America and to predict when species-specific patterns of fishway use will occur. At present, other specific restoration, management, or conservation actions for suckers in the Grand River are not underway. However, efforts continue to ameliorate habitat alterations associated with agricultural and urban development on entire fish communities including those that contain suckers. In particular, efforts that reduce silt loading may maintain suitable spawning habitat for greater redhorse (Cooke and Bunt, 1999), and modifications to fish passage facilities will allow passage of a broader array of fish species (Bunt, 1999).

3.2. Stream suckers of the Pacific Northwest

The Salish sucker is an evolutionarily significant unit that evolved from a population of longnose sucker (*C. catostomus*) isolated in a glacial refuge in Washington State (McPhail and Taylor, 1999). Its global distribution is confined to the Olympic Peninsula and Puget Sound Lowlands and to the Fraser Valley in British Columbia (McPhail, 1987). Here the Salish sucker is believed to be extirpated from one watershed and large portions of several others (McPhail, 1987; Pearson unpublished data). The primary pressures on this species are direct habitat destruction through dredging and channelization, water quality degradation related to reduced flows, and nutrient enrichment associated with urbanization and poor agricultural practices (McPhail, 1987; Pearson and Healey, 2003). The Salish sucker is listed as endangered in Canada (Campbell, 2001).

Salish suckers are small (<25 cm), short-lived (5 years), early maturing (2 years) and have a prolonged spawning period (10+ weeks; Pearson and Healey, 2003); these traits are suggestive of an opportunistic life-history strategy (Winemiller and Rose, 1992) that allow populations to recover rapidly from short-term disturbances of limited spatial scale, but leave them vulnerable to disturbances that disrupt recruitment over large areas for several consecutive years. From a management perspective, these traits suggest that populations will respond quickly to habitat restoration and may be re-introduced into suitable habitat in regions from which they have been extirpated.

Within watersheds, Salish sucker distribution is highly clumped within a few reaches in a small proportion of streams accounting for most of the British Columbia population (Pearson, unpublished data). Densities are much lower in areas around and between these clusters of high-density reaches (i.e., hotspots), a pattern indicative of source–sink population dynamics (Brown et al., 1996; Pulliam, 1988). Reaches in which Salish suckers are present are concentrated in headwater areas, especially those containing beavers. Such reaches have significantly more abundant and longer deep pools (depth >70 cm), more in-stream vegetation, fewer riffles and less urban land use within 200 m than those from which Salish suckers are absent (Pearson, unpublished data). Management strategies that prioritize hotspot protection and develop habitat restoration projects that emulate and are located near them are likely to be most successful (Pearson, 1998).

Some hotspots, particularly those in beaver ponds, endure near anoxic conditions during summer low-flow periods (Pearson, unpublished data). Based on dramatic changes in local abundance and a known aversion to crossing beaver dams (Pearson and Healey, 2003), this summertime habitat use pattern is believed to cause occasional reach-scale, mass mortality in some watersheds. The anthropogenic changes in stream habitat across the species' range (e.g., nutrient loading, reduced base-flow, loss of riparian cover) are likely to increase the frequency of such events and probably pose the major long-term challenge in management and recovery of Salish sucker populations. These problems can only be addressed by changing watershed scale land-use and development practices – actions that will directly and indirectly benefit a wide variety of endemic species. Current recovery efforts are focused on protecting existing hotspots, restoring reaches adjacent to them, and on landowner education aimed at reducing land use impacts.

3.3. River suckers of the Southeast

The fish assemblage in the southeastern United States is among the most diverse in North America (Burr and Mayden, 1992; Warren et al., 1997). The catostomid component of this fauna is just as rich comprising 44 recognized species in 10 genera (Warren et al., 2000). The genus *Moxostoma* (including the redhorses), is the most speciose (17 species in the southeast) of the family (Warren et al., 2000), and includes the endangered robust redhorse (*M. robustum*) that was rediscovered in 1980, 110 years after its description (Jenkins and Burkhead, 1994; R. Jenkins, Roanoke College, personal communication). Redhorses are found primarily in medium to large rivers with moderate gradients (Jenkins and Burkhead, 1994). Many such rivers in the region are dammed (Dynesius and Nilsson, 1994; Graf, 1999), and the resulting changes to riverine habitat (e.g., physical barriers to upstream reaches, physical alteration of the habitat, and changes in flow regimes) have adversely affected fish communities (e.g., Kinsolving and Bain, 1993).

The adverse consequences of regulated flows (i.e., timing and duration) for selected components of southeastern riverine fish communities have been well documented (Bain et al., 1988; Kinsolving and Bain, 1993; Travnichek and Maceina, 1994; Freeman et al., 2001). Generally, fluvial specialists such as redhorses are more abundant in unregulated reaches of rivers compared to regulated reaches of rivers with similar sizes and gradients (Travnichek and Maceina, 1994). The mechanism responsible for this pattern of abundance is unknown, but the phenomenon may be related to poor survival and growth of larval and juvenile redhorse exposed to highly variable, high-velocity water flows. For example, larval and juvenile redhorses exposed to high-velocity, pulsed flows do not survive as well or grow as fast those exposed to lower-velocity, shorter-duration flows (Weyers et al., 2003). The low survival and reduced growth of redhorses in highly regulated systems may be related to the increased bioenergetic costs necessary to maintain position in spatially dynamic rearing habitat (i.e., low velocity areas $\lesssim 7$ cm^{-s}) that occurs during hydropower generation (Ruetz and Jennings, 2000). The combination of these factors may be responsible for the reduced abundance of suckers and other fluvial specialists in highly regulated systems.

Preserving the rich diversity of suckers in the southeastern United States will depend on many factors including faunal surveys, basic and applied research, political negotiations, proactive, multi-stakeholder partnerships, and a genetically-sound, population enhancement and restoration program. Until recently, suckers did not receive as much scientific attention as economically valuable or endangered species. As a result, there is much to learn about their taxonomic relationships, abundance, and distribution patterns. Further, there are some sucker species (e.g., robust redhorse, and the undescribed Carolina redhorse and sicklefin redhorse) about which little is known, and conservation status is uncertain. In some cases where some information is known, operational conditions of hydropower facilities have been renegotiated to provide flows necessary during critical periods (e.g., spawning). For example, the license of a hydropower dam on the Oconee River in middle Georgia has been renegotiated to provide run-of-river flows during the spawning season of robust redhorse (Jennings, personal observation). The revised flows are intended to provide seasonal-stable flows, which would increase the reproductive success of the species and help to ensure its survival. The formation of a multi-agency, multi-stakeholder partnership (i.e., Robust Redhorse Conservation Committee) that includes state and federal natural resource agencies, private corporations, and nongovernmental organizations has been instrumental in garnering much-needed political and financial support for the effort to recover the species. Husbandry methods have been developed to produce otherwise unavailable larval and juvenile robust redhorse for basic research on their biology and ecology. Further, these husbandry methods have resulted in the production of genetically diverse (i.e., maximum parental crosses) stock for the enhancement of declining populations or the establishment of refugial populations in suitable reaches of rivers. Some combination of these approaches, applied in an adaptive management framework, will do much to safeguard catostomid diversity in the southeastern United States and beyond.

3.4. Suckers of the Colorado Basin

The razorback sucker was considered common in the upper and lower Colorado River basins in historical times, but since the 1940s has become rare except for populations in the Green River and lakes Mead and Mohave. It was listed as endangered in 1991 (USFWS, 1991). The remaining population of razorback sucker in the middle Green River basin in Utah was estimated at about 1,000 individuals in 1988 (Lanigan and Tyus, 1989) and at 300–600 in 1992 (Modde et al., 1996). Razorback sucker are rare in the upper Colorado River basin, where only 10 fish were found in the mainstem river between 1989 and 1996 (C. McAda, USFWS, personal communication). In addition to the razorback suckers, the upper Colorado River also provides critical habitats for the endangered (but non-catostomid) Colorado pikeminnow (*Ptychocheilus lucius*), humpback chub (*Gila cypha*), and bonytail (*Gila elegans*) (USFWS, 1995). A combined approach for recovery of the four endangered fish in the upper Colorado River basin has been undertaken by the Upper Colorado River Endangered Fish Recovery Program, which was initiated in 1987 (USFWS, 1987).

The reasons for the decline of these populations are related to a combination of factors including stream alteration (dams, irrigation withdrawals, dewatering, channelization), loss of habitat (spawning sites and backwater nursery areas), changes in flow regime, blockage of migration routes, water temperature changes, competition with and predation by introduced species, parasitism, and changes in food base (USFWS, 1987). Irrigation and pollution were suggested in 1976 as possible contributing factors to the decline of endangered fish (Seethaler et al., 1979).

Following the discovery of selenium-contaminated irrigation return waters in the San Joaquin Valley of central California in 1982, the Department of the Interior initiated the National Irrigation Water Quality Program (NIWQP) to identify other areas in the western U.S. that have water quality problems induced by irrigation drainage (Feltz et al., 1991). Analysis of water, bottom sediment, and biota collected since 1986 from the middle Green River basin and the Grand Valley, located in western Colorado, including portions of the Colorado, Gunnison, and Uncompahgre Rivers, have confirmed the presence of selenium and a few other elements at concentrations that could be potentially harmful to fish and wildlife (reviewed in Hamilton, 1998).

The long-term selenium contamination of the lower Colorado River basin (Anderson et al., 1961) from irrigation sources in the upper basin (Radtke et al., 1988; Radtke and Kepner, 1990) may have been one of the factors contributing to the disappearance of fish in the early 1930s. Hamilton (1998) concluded that selenium concentrations were sufficiently elevated to be causing reproductive problems in endangered fish such as the razorback sucker. In a follow-up paper, he reviewed historical data on selenium concentrations in the upper and lower basins, along with historical records and reviews of the occurrence of native, larger endangered fish, and hypothesized that selenium contamination from irrigated agriculture in the 1890–1910 period caused the decline of native fish in the upper basin in the 1910–1920 period and in the lower basin in 1925–1935 (Hamilton, 1999). More recently, two empirical reproductive studies with razorback sucker have shown that adults readily accumulate selenium and transfer it to their eggs when held in high selenium habitats (Hamilton et al., 2001a,b). Interestingly, fish held in high selenium concentrations for short periods (i.e., Hamilton et al., 2001a) had muscle selenium concentrations that were lower than 40% of wild razorback suckers sampled in the Green River by Waddell and May (1995) and Stephens and Waddell (1998). When the same adults were held an additional nine months in high selenium habitats (Hamilton et al., 2001b), wild razorback sucker adults in the Green River still had 27–33% higher selenium in somatic tissue. These results suggest that some wild adults choose to use high selenium habitats or are forced to use those habitats, because of a lack of uncontaminated habitats, and that adults can accumulate substantial selenium residues in their tissues with little depuration. Furthermore, when razorback suckers were fed dietary selenium concentrations of 4.6 μg/g of zooplankton in the lab, rapid mortality was observed in fish that fed upon them (Hamilton et al., 2001a; 2001b). This concentration is close to the proposed dietary selenium toxicity threshold (4 – 4.5 μg/g) proposed by selenium researchers (Maier and Knight, 1994; Lemly, 1996).

Coexisting in the Colorado River with the razorback sucker are two other native suckers: flannelmouth sucker (*Catostomus latipinnis*) and bluehead sucker (*Catostomus discobolus*). Both of these suckers are less well studied than razorback sucker (McAda, 1977). Flannelmouth suckers are one of the most abundant native fish in the upper Colorado River basin, but have declined in the lower basin. Bluehead suckers are more widely distributed than either flannelmouth sucker or razorback sucker. Larger population sizes, wider distribution, and other factors probably have made these two suckers less susceptible to the stress caused by selenium exposure, than razorback suckers.

Recovery efforts for the razorback sucker have focused primarily on stresses from exotic species, loss of habitat, and changes in hydrology, but not selenium concerns (Tyus, 1998). Thus, recovery efforts for the razorback sucker may be hampered until stresses from selenium contamination are addressed in conjunction with other recovery efforts. Conversely, the NIWQP has undertaken remediation activities in the Green River and the upper Colorado River to reduce selenium loading and selenium-related stresses to endangered fish.

3.5. Lake suckers of the West

This section is a summary of the present status, reasons for declines, recovery efforts, and controversies surrounding the three extant species of *Chasmistes* and the single species of the genus *Deltistes*, collectively referred to as 'lakesuckers' (Scoppettone and Vinyard, 1991). Lakesuckers are obligate lake dwellers, although the majority of spawning occurs in in-flowing tributaries. They have terminal to subterminal mouths – an assumed adaptation for water-column planktivoury, 30–40+ year life spans, attain sexual maturity between ages 4–10 years, and are highly fecund and iteroparous. Cui-ui suckers (*Chasmistes cujus*) are restricted to Pyramid Lake, Nevada, June suckers (*Chasmistes liorus*) are only present in Utah Lake, Utah, and shortnose suckers (*Chasmistes brevirostris*) and Lost River suckers are restricted to a few large shallow lakes in the upper Klamath River watershed (California–Oregon). Abundance of all lakesuckers is greatly reduced from pre-1900 levels and has been highly variable since. All have experienced one or more 15+ year periods of negligible recruitment. Cui-ui were protected as endangered under the US Federal Endangered Species Act in 1967 and the others were protected as endangered in the late 1980s. June suckers appear to be the most imperiled lakesucker, with an estimated population of about 300 individuals in the wild and no evidence of natural recruitment (USFWS, 1999). A fifth lakesucker, the Snake River sucker (*Chasmistes muriei*), is known from a single specimen and is presumed to have gone extinct in the mid 20th century. Scoppettone and Vinyard (1991) provide a more complete accounting of lakesucker natural history.

Historic over-harvest, extensive habitat loss and/or modification, recreational fishery development and, with exception of cui-ui, hybridization with other catostomids, have all contributed to lakesucker declines. All lakesucker populations were subjected to varying levels of commercial, recreational, and native people's harvest, and their long life spans make lakesuckers susceptible to over-exploitation (Markle and Cooperman, 2002). In the 1950s, reduced catch rates and size per fish in the recreational snag-fisheries for spawning suckers were among the first indicators of lakesucker declines (Scoppettone and Vinyard, 1991; Markle and Cooperman, 2002). Each lakesucker fishery was terminated around the time each species was listed.

Water development projects and other habitat alterations have had profound negative affects on lakesuckers. In the Pyramid Lake system between 1905 and the mid 1970s, the Newlands Project diverted approximately one-half of the Truckee River's annual flows producing an impassable delta at the river mouth that prevented cui-ui from entering the river to complete their reproductive cycle (Scoppettone et al., 1986). In the Provo River – Utah Lake system, channel morphology, hydrology, and ecology has been so extensively modified as a by-product of 100+ years of water resource and exotic species sport fishery development, the US Fish and Wildlife Service (1999) believes sufficient restoration of the system to allow natural recovery is unlikely. For much of its history, the federal Klamath Irrigation Project manipulated Upper Klamath Lake water levels above and below natural levels without concern for dewatering nursery habitats, accessibility of water quality refuges, or the potential to promote winterkill events (USFWS, 2001). Access to as much as 90% of shortnose and Lost River sucker historic spawning habitat is blocked by the Sprague River dam, which diverts water to a local irrigation district (USFWS, 2001). In both Utah Lake and Upper Klamath Lake, cultural eutrophication has led to annual summertime blue-green algae blooms that adversely affect water quality. For example, Upper Klamath Lake pH can exceed 10.0 and dissolved oxygen levels frequently fall below 2.0 $mg\,l^{-1}$ (Cooperman and Markle, 2003).

Lakesucker recovery efforts have been a mixture of technological fixes, habitat restoration, and adjustments to existing water management protocols. In the mid 1970s, Marble Bluff dam and Pyramid Lake fishway were constructed to by-pass the Truckee River delta, and water from Stampede reservoir was allocated to augment Truckee River flows during the cui-ui spawning period (Scoppettone and Vinyard, 1991). Initial post-project monitoring indicated several cui-ui year classes successfully formed once access to the river was restored. A formal cui-ui status review is underway and more detailed information is not available (G. Scoppettone, United States Geological Survey, Personal Communication). Because their environment remains too hostile for natural reproduction, June sucker recovery efforts have focused on developing a comprehensive artificial propagation program that protects the genetic integrity of the species while raising progeny to large enough size so they can survive release into Utah Lake (USFWS, 1999). Releases of artificially reared June suckers started in 1987 and there is limited evidence hatchery progeny have recruited to the naturally reproducing population. A captive management plan is currently under development with an anticipated goal of 3 million June suckers >100 mm total length released over the next 15 years (K. Conway, Director, Utah Division of Wildlife Resources, Personal Communication). In the Klamath system, management over the last decade focused on restoring wetlands and river-floodplain connectivity and restricting lake elevation fluctuations (USFWS, 2001). Although strong shortnose sucker and Lost River sucker year classes appear to have formed in 1991, 1993, and 1999, there were water quality related die-offs in 1995, 1996, and 1997 (Cooperman and Markle, 2003). Recent proposals for Klamath lakesucker recovery include continued wetland restoration efforts, removal of the Sprague River dam, reestablishment of extirpated populations in Upper Klamath Lake and elsewhere, and artificial oxygenation of portions of Upper Klamath Lake (NRC, 2003).

Despite their historic cultural, economic, and recreational importance, lakesucker recovery has generated significant controversy, particularly when initiatives affect water management and recreation opportunities (McCarthy, 2001; Service, 2003). Initiatives that reallocate water away from consumptive uses such as irrigated agriculture for the benefit of endangered suckers leads to the question, "how much water do lakesuckers need?" In most cases, scientific consensus does not exist (Cooperman and Markle, 2003; Lewis, 2003). Even if more water were allocated to lakesuckers, it is unclear whether habitats could be sufficiently restored or adverse affects of exotic species mitigated to ensure self-sustaining lakesucker populations. Although lakesuckers are not the only native fishes of the American West to be reduced to remnant populations, they present dramatic illustration of the magnitude of the issues. In several cases, populations that once numbered in the millions are now in the hundreds or thousands.

4. Summary of threats facing suckers

Whereas the case studies presented focused on issues in different regions, several commonalities exist (Table 1), despite the diversity of life-history templates exemplified by suckers. Thus, our synthesis focuses on broad-scale patterns that should be relevant to many catostomid species. Consistent with a global trend common to most threatened fishes (Cambray, 2000; Cowx, 2002; Skelton, 2002), suckers typically face multiple threats, not isolated factors. Agricultural and urban development, with associated habitat loss and degradation, including loss of connectivity between habitats and degraded water quality, combined with introduction of exotic species, were the most common threats (Table 1). Locally, threats such as the influence of saline water from water diversion projects, inter-specific hybridization, or exploitation can also be important. Exploitation is not a widespread threat affecting suckers, but exploitation can be locally significant. For example, the Lost River sucker is one of the few suckers that has been commercially exploited owing to their large size and accessibility during spawning. Commercially captured suckers are used for oil rendering and canned for food (Moyle, 2002). Suckers are also the focus of specialized sport fisheries (Markle and Cooperman, 2002), but are more frequently regarded as bycatch for anglers targeting other sportfish. In addition, in some jurisdictions, licensed anglers using spears or bow and arrow can also harvest migrating suckers. In Virginia, there is even one jurisdiction where using rifles to kill suckers is legal (Jenkins and Burkhead, 1994). Subsistence fisheries generally operated by native groups also target suckers as they are high in lipid and have cultural value. For example, razorback suckers once were one of the most abundant fishes in the lower Colorado and served as a major food source for native peoples (Moyle, 2002).

Table 1
Relative vulnerability of suckers in different regions to current threats[a],[b]

Threats	Midwestern rivers	Pacific Northwest streams	Southeast rivers	Colorado basin	Western lakes
Exotics	+	++	+	+++	+++
Environmental contaminants	+	+	+	++++	+
Habitat degradation – agriculture	+++	++++	+++	++++	+++
Habitat degradation – urbanization	+++	++++	++++	+++	++
Hydropower	+	NA	++++	+++	[c]
Migration barriers	++++	++	+++	++++	+++
Water diversion	NA	NA	NA	++	+++
Eutrophication	++	++	+	+++	+++
Exploitation – commercial	++	+	+	+	+
Exploitation – recreational	++	+	+	+	++
Exploitation – subsistence	+	+	+	+	+

This is a subjective evaluation, weighted towards the individual species covered in the case studies of this paper. More "+ "symbols indicate a greater relative threat. NA, not applicable.

[a] Additional threats may also exist, and other threats may exist but have not yet been identified or studied in all regions (e.g., environmental contaminants).

[b] Relative importance of threats may have differed historically (e.g., commercial exploitation now halted in Western Lakes).

[c] Hydropower development at this time may be a positive for some lake dwelling suckers as it serves as a "source–sink" situation providing temporary habitat for downstream populations.

Suckers are frequently a large component of regional baitfish industries, and use of suckers for bait may result in the homogenization of fish faunas (Rahel, 2002) and the continued belief that suckers are of little value. Suckers used as baitfish are raised in culture facilities or harvested from the wild, with most collection effort focused on white sucker, which is the third most popular baitfish species in North America (Litvak and Mandrak, 1993). Use of suckers for bait is banned in some jurisdictions such as North Dakota, but in general the practice is widely accepted by anglers and management agencies (Meronek et al., 1995). The localized capture and harvest may depress small reproductively isolated populations or affect other non-target sucker species, especially if fish collecting occurs in sensitive habitats or during seasonally sensitive periods. Collectively, the threats imparted from large-scale exploitation are generally low relative to other threats, making this group of fishes unique compared to those that are more heavily exploited and have higher commercial or recreational value. As food webs become fished down, targeting lower trophic levels (Pauly et al., 1998), organisms such as suckers may become more popular.

5. Issues retarding the conservation of suckers

One of the primary factors retarding sucker conservation is the lack of ability or interest in being able to identify different sucker species (Jenkins and Burkhead, 1994). Most sucker species are morphologically distinguishable by features such as scale and fin ray counts and lip/mouth geometry. These characteristics can be challenging to the trained eye, and even more challenging to individuals without specialized training. Many regional guidebooks used for identifying local fish fauna do not include all of the sucker species that reside in an area, and generally do not have keys that are completely effective at determining species identity. This situation extends to and is more complicated during early life-stages (Kay et al., 1994). Even basic monitoring by natural resource agencies often fails to consider suckers as individual species, instead lumping all catostomids into one composite group. Because some fisheries managers are uncertain of the ecological role of suckers, and because of limited recreational and commercial value, typical management strategies are rarely relevant or applicable for suckers. For example, there are few harvest studies, creel studies, or angler diary programs that have quantified harvest rates for suckers, and those that do exist have usually failed to utilize any taxonomic resolution beyond the family level even though game fish are identified to the species level (i.e., sucker; see Cooke and Bunt, 1999 for discussion).

Underlying the repeated "lumping" of sucker species is the absence of basic natural history information on most species. Information on seasonal habitat requirements, movement patterns, environmental tolerances, life-history characters, and ecological role would all aid in monitoring and conservation. Moyle (2002) proposed that for some sucker species, although there is very little known about their ecological roles, they might in fact contribute substantially to ecosystem function. For example, suckers could affect the composition of invertebrate communities either directly or indirectly through grazing. Suckers may also be responsible for nutrient cycling through ecosystems as they are quite fecund, with eggs potentially providing an important seasonal food source for other fishes (e.g., Merz and Vanicek, 1996). Given that many suckers make significant spawning migrations, they may serve as a vessel for nutrient relocation. Adult suckers can also provide an important seasonal food source for avian and mammalian predators (e.g., Jackman et al., 1999). Finally, many sucker species have also been identified as important hosts for the glochidia stage of endemic freshwater mussels (Watters, 1994).

Suckers also suffer from the perception that they are "trash" fish that are tolerant of poor water quality and degraded habitats. These misconceptions likely arose because some species may persist when other more visible or economically important species have been extirpated. However, suckers generally feed on lower trophic levels than game fish, and are subjected to less exploitation. In addition, the fishes of the family Catostomidae may have a wide range of tolerances to factors such as water temperature, but may be intolerant to silt. Suckers do share superficial morphological similarities (general size, mouth position, and coloration) with other species such as the introduced common carp (*Cyprinus carpio*) that do tolerate degraded environments. These superficial similarities may also help to perpetuate the notion that suckers are tolerant of habitat degradation.

The perception that suckers are detrimental to other species has been common for quite some time and is perpetuated by management actions focused on eradication of suckers to enhance other recreational fisheries. Indeed, for many years suckers were killed using chemicals or mechanical removal (Holey et al., 1979). The primary mechanisms by which suckers are thought to be harmful are by predation on offspring of other species or competition with other species for food and space (Marrin and Erman, 1982). An extensive literature review by Holey et al. (1979) summarized available research on the topic and concluded that although suckers do consume the offspring of other organisms, there was no evidence of any negative effects on prey populations. Further, although there can be substantial overlap in habitat use and food consumption between suckers and other fishes, there is little evidence that either is limiting, such that competition would be detrimental. Holey et al. (1979) determined that there was evidence that both supported and refuted the notion that sucker removal resulted in positive benefits to game fish. Few studies have considered the ecosystem effects of suckers, with most focusing only on changes in game fish growth and abundance. Fortunately, with today's increased focus on ecosystem management, enhancement of game fish populations should be balanced with conservation of native fish assemblages. In practice, however, ecosystem management still appears to be viewed as a theoretical construct (Slocombe, 1993).

Funding for research and monitoring has also proved to be a problematic issue in the quest to conserve non-game fishes. Unfortunately, dedicated funding for sucker research is generally only available after fish have been categorized as imperiled. For example, since being federally listed, there have been over 500 studies completed on Klamath basin endangered suckers (NRC, 2003). That level of research activity is an order of magnitude more than what was available prior to listing. Undoubtedly, such level of study is extremely helpful in developing recovery plans and understanding the mechanisms behind declines. However, knowledge of sucker life history prior to imperilment would be more productive and would be a more risk-averse strategy. In such cases where funding is only available after listing, the help may be too late. Government, private, and institutional funding sources must recognize the importance of research on all fish species, not just those with economic value, and support those research activities accordingly.

6. Approaches to conserving suckers

Unfortunately, comprehensive management and conservation of non-game fishes is rarely undertaken until it is deemed necessary to establish a recovery plan for an imperiled species. Although many strategies used for conservation of other freshwater fish are appropriate for suckers, individual conservation strategies differ in utility and applicability to different regional issues (Table 2), and we believe there are several strategies that may be particularly useful. Aside from species afforded special protection under either the Canadian SARA or the United States ESA, or general fisheries legislation (e.g., Fisheries Act in Canada) there are few specific regulations that are used to protect or manage suckers. Some regulations exist for specialized fisheries, such as bow or spear, but those tend to limit seasons or harvest quantities. In the future, regulations may be required to restrict harvest of fisheries targeting imperiled suckers.

Instead of regulations targeting harvest, efforts to conserve suckers would be best served by strategies such as the development of freshwater protected areas (FPA; Crivelli, 2002) that protect or restore habitats and processes such as natural flow regimes (Poff et al., 1997; Cowx and Welcomme, 1998). Several conceptual papers on the use of FPAs as a conservation measure have emphasized catchment scale focus with linkages between terrestrial and aquatic realms, from headwaters down (Crivelli, 2002; Saunders et al., 2002). We are unaware of any published studies that explicitly used FPAs for sucker conservation. Similarly, any legislation or policy that directly reduces alterations to critical habitats or water quality degradation would also directly benefit suckers.

Elimination of migration barriers, whether by physical removal or installation of fish passage devices would benefit many species of suckers throughout North America. Barrier removal to increase river connectivity

Table 2
Relative utility and applicability of conservation strategies for suckers in different regions[a] based on a subjective evaluation

Conservation strategy	Midwestern rivers	Pacific Northwest streams	Southeast rivers	Colorado basin	Western lakes
Legislation (exploitation)	++	+	++	+	++
Legislation (habitat)	++++	++++	++++	++++	++++
Protected areas	++	++++	++	++	++
Dam removal	++++	++	++++	++++	+++
Fish passage installation	++++	++	++++	++++	++++
Natural flow regimes[b]	++	+	++++	+++	+++
Habitat restoration	+	+++	++	++	++
Habitat remediation[c]	+	+	+	++++	+
Eradication of exotics	+	+	+	+++	+++
Captive breeding[d]	+	+	++	+++	++
Education and outreach	++++	++++	++++	++++	++++

More "+ "symbols indicate greater relative applicability.
[a] Additional conservation strategies also exist. The utility and applicability of individual strategies are focused on the specific species covered in each of the regional case studies.
[b] Natural flow regimes for lakes or reservoirs imply the importance of a natural hydrograph for the lentic environment.
[c] Habitat remediation is specific to the removal of environmental contaminants.
[d] Captive breeding is currently restricted to severely depleted stocks and should only be considered for such instances.

(Cowx and Welcomme, 1998) has become a popular strategy in North America in recent years (Stanley and Doyle, 2003). Despite strong evidence that suckers are migratory (Lucas and Baras, 2001), and that some have the capacity to use fishways (e.g., Bunt et al.,, 2001), little effort has been devoted to sucker passage. We encourage efforts that promote connectivity of habitats and that facilitate passage of suckers. We also recommend the incorporation of biological criteria into the design of fishways (Bunt et al., 1999).

Although hydropower dams have existed since the 19th century, maintenance of riverine flows to ensure functioning biotic communities has only received widespread attention since the mid-1970s (Jowett, 1997). Since then, approaches to ensure adequate amounts of water in rivers to support riverine biota and sufficient water behind the dam to meet electrical power demand have proliferated and have met with varying degrees of success (Jowett, 1997). Generally, water management that incorporates flow variability (i.e., mimics the natural hydrograph) offers better protection of aquatic biota than minimum flow- or habitat-based approaches (Jowett, 1997; Poff et al., 1997). For example, Richter et al. (1996) developed an index to determine the degree to which managed flows deviated from the natural hydrograph. This degree of alteration was then used to predict a level of "managed variability" that would satisfy the competing demands (i.e., hydropower generation and aquatic protection) for the water (Richter et al., 1997a). Sucker conservation in some regions, particularly in the Southeast and upper Colorado River, will depend upon reestablishment of more natural flow regimes in rivers impacted by hydropower and water development.

The role of habitat restoration and enhancement in management and recovery will vary among catostomid species according to life history traits and should be approached using an active adaptive management framework in which project effects are studied at a range of scales and coupled with controlled, replicated experimental designs (Walters and Holling, 1990). Habitat restoration and enhancement activities are most appropriate and effective when focused on relieving a specified shortcoming such as a recruitment bottleneck and matched in spatial scale to the ecology of the target species (Lewis et al., 1996). For example, the approach is likely to be far easier and cheaper for species such as Salish sucker that occupy home ranges on the scale of hundreds of meters (Pearson and Healey, 2003) than for greater redhorse or razorback suckers, which range over much larger distances (Bunt and Cooke, 2001; Tyus and Karp, 1990). A basic knowledge of life history is necessary for planning habitat restoration, but the projects themselves also offer many opportunities to test ideas about life history, habitat associations, and technique effectiveness.

Novel molecular genetic techniques have been recently applied to catostomids and show promise for the refinement of taxonomic relationships, stock delineation, and identification of undescribed species (e.g., Harris and Mayden, 2001). In addition, conservation geneticists have evaluated the genetic status of threatened populations or used genetic information for improving captive breeding programs for imperiled species such for robust redhorse in the Southeast. We encourage the continued application of these genetic techniques to both understanding catostomid natural history, the development of conservation strategies for these species, and improved understanding of catostomid evolution and diversity (Moritz et al., 2002).

Perhaps the best approach to conserving suckers may be through education and outreach. Cambray and Pister

(2002) emphasized that scientists have a key role of generating public awareness and support for the conservation of threatened fishes. The unfortunate and inappropriate view that catostomids are "trash" fish that serve no purpose could be changed by coordinated outreach efforts that highlight the ecological role of suckers. Emphasis on the need to conserve aquatic species diversity may promote a more accurate perception of and improved appreciation for catostomids. Outreach and education is particularly important for species such as the Salish sucker that occur almost exclusively on private lands where their habitat security depends upon landowner awareness. At present, there are very few constituent groups that lobby on behalf of non-game fishes (notable examples are the North American Native Fishes Association, and the Desert Fishes Council) relative to the many groups focused on game fish. More information on the effects of recreational fishing practices is required prior to encouraging catch-and-release angling as a component of a management and conservation strategy (Cooke and Suski, in press) to generate greater interest in suckers.

As outlined in Table 2, individual conservation strategies differ in the utility and applicability to different regional issues. Therefore, holistic approaches to sucker conservation, such as adaptive management in the southeast or for western lakesuckers, represent the best overall approach for conserving suckers and other species. Historically, recovery and management plans tended to focus on a single species such as those afforded protection under endangered species legislation. However, increasing efforts are being devoted to the development of more comprehensive multi-species approaches to recovery planning and management, particularly in the United States as part of the ESA (Clark and Harvey, 2002). Unfortunately, comprehensive management and conservation is rarely undertaken until the establishment of a recovery plan for an imperiled species is necessary.

7. Conclusion and prognosis

We hope this synthesis will help to generate interest in sucker conservation. Many of the threats faced by suckers are consistent with those faced by economically important and heavily managed species (see Cowx, 2002). However, some threats appear to be unique to suckers and other non-game fishes, mediated in large part by the many factors that have retarded sucker conservation. The wide distribution of suckers, the diversity of life-history strategies they employ, and variety of habitats they occupy present unique challenges to those devoted to their conservation. Other groups of non-game North American fish fauna such as darters and cyprinids have similar threats to those faced by suckers. All of these species also could benefit from greater understanding of their taxonomy, natural history, and ecological roles. Sharing this knowledge with stakeholders will hopefully increase the support for conservation of species with little apparent direct economic value (Cambray and Pister, 2002; Cowx and Collares-Pereira, 2002). Without a specific constituent group lobbying for conservation of non-game fishes, all these species, including the catostomids, will continue to face risk because of ignorance, misunderstanding, and neglect. Although we have presented case studies primarily focusing on preservation of individual species or regionally-specific groups of catostomids, we also advocate conservation of system function (Moss, 2000). Undoubtedly, catostomids are just one part of the larger community, and their interactions with others members of the community are mutually beneficial. The results of losses of non-game fish on ecosystem structure and function are impossible to gauge but will undoubtedly be devastating.

If greater emphasis is not placed on the conservation of fishes without direct economic value, much of the freshwater ichthyofaunal biodiversity in North America, and indeed the world, may be quietly lost over the next century (See Ricciardi and Rasmussen, 1999). Although the case studies presented here had a North American focus, our assertion is that freshwater fishes in developing regions such as Asia and Africa may be even more at risk than non-game species in North America (e.g., Skelton, 2002; Dudgeon, 2003). Human population growth coupled with cursory understanding of freshwater fish biodiversity and ecology provides little hope for freshwater fishes in developing regions (Wishart and Davies, 1998). This situation highlights the importance of outreach and education. Knowledge derived from conservation issues facing fishes of the family Catostomidae in North America will hopefully be useful in guiding the management and conservation of non-game fishes in other regions of the world.

Acknowledgements

The authors thank their respective institutions for supporting this endeavor. Additional financial support was provided by a number of organizations and agencies including the Natural Sciences and Engineering Research Council, the Izaak Walton Killam Trust, and the U.S. Bureau of Reclamation. We thank Robert Jenkins and an anonymous reviewer for comments on this manuscript.

References

Anderson, M.S., Lakin, H.W., Beeson, K.C., Smith, F.F., Thacker, E.J., 1961. Selenium in agriculture. US Department of Agriculture, Agriculture Handbook No. 200.

Bain, M.B., Finn, J.T., Brooke, H.E., 1988. Streamflow regulation and fish community structure. Ecology 69, 382–392.

Brown, J.H., Stevens, G.C., Kaufmann, D.M., 1996. The geographic range: size, shape, boundaries, and internal structure. Annual Review of Ecology and Systematics 27, 597–623.

Brown, R.S., Power, G., Beltaos, S., 2001. Winter movements and habitat use of riverine brown trout, white sucker, and common carp in relation to flooding and ice break-up. Journal of Fish Biology 59, 1126–1141.

Bruton, M.N., 1995. Have fishes had their chips. The dilemma of threatened fishes. Environmental Biology of Fishes 43, 1–27.

Bunt, C.M., 1999. Fishways for warmwater species: utilization patterns, attraction efficiency, passage efficiency and relative physical output. Ph.D. Dissertation, University of Waterloo, Waterloo, Ontario, Canada.

Bunt, C.M., Katopodis, C., McKinley, R.S., 1999. Attraction and passage efficiency of white suckers and smallmouth bass by two Denil fishways. North American Journal of Fisheries Management 19, 793–803.

Bunt, C.M., van Poorten, B.T., Wong, L., 2001. Denil fishway utilization patterns and passage of several warmwater species relative to seasonal, thermal and hydraulic dynamics. Ecology of Freshwater Fish 10, 212–219.

Bunt, C.M., Cooke, S.J., 2001. Post-spawn movements and habitat use of greater redhorse, *Moxostoma valenciennesi*. Ecology of Freshwater Fish 10, 57–60.

Burr, B.M., Mayden, R.L., 1992. Phylogenetics and North American freshwater fishes. In: Mayden, R.L. (Ed.), Systematics, historical ecology, and North American freshwater fishes. Stanford University Press, Stanford, CA, pp. 18–75.

Cambray, J.A., 2000. 'Threatened fishes of the world' series, an update. Environmental Biology of Fishes 59, 353–357.

Cambray, J.A., Bianco, P.G., 1998. Freshwater fish crisis: a blue planet perspective. Italian Journal of Zoology 65 (Suppl.), 345–356.

Cambray, J.A., Pister, E.P., 2002. The role of scientists in creating public awareness for the conservation of fish species: African and American case studies. In: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of Freshwater Fishes: Options for the Future. Fishing News Books, Blackwell Science, Oxford, pp. 414–423.

Campbell, R.R., 2001. Rare and endangered fishes and marine mammals of Canada: COSEWIC Fish and Marine Mammal Subcommittee status reports XIV. Canadian Field-Naturalist 115, 564–572.

Clark, J.A., Harvey, E., 2002. Assessing multi-species recovery plans under the Endangered Species Act. Ecological Applications 12, 655–662.

Cooke, S.J., Bunt, C.M., 1999. Spawning and reproductive biology of the greater redhorse, *Moxostoma valenciennesi*, in the Grand River, Ontario. Canadian Field-Naturalist 113, 497–502.

Cooke, S.J., Suski, C.D., in press. Do we need species-specific guidelines for catch-and-release recreational angling to conserve diverse fishery resources? Biodiversity and Conservation 00, 000-000.

Cooperman, M.S., Markle, D.F., 2003. The Endangered Species Act and the National Research Council's interim judgment in Klamath Basin. Fisheries 28 (3), 10–19.

Cowx, I.G., 2002. Analysis of threats to freshwater fish conservation: past and present challenges. In: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of Freshwater Fishes: Options for the Future. Fishing News Books, Blackwell Science, Oxford, pp. 201–220.

Cowx, I.G., Collares-Pereira, M.J., 2002. Freshwater fish conservation: options for the future. In: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of Freshwater Fishes: Options for the Future. Fishing News Books, Blackwell Science, Oxford, pp. 443–452.

Cowx, I.G., Welcomme, R.L. (Eds.), 1998. Rehabilitation of Rivers for Fish. Fishing News Books, Blackwell Science, Oxford.

Craig, J., 2000. Percid Fishes: Systematics, Ecology and Exploitation. Blackwell Science, Oxford.

Craig, J., 1996. Pike: Biology and Exploitation. Chapman and Hall Fish and Fisheries Number 19. Kluwer Academic Press, Netherlands.

Crivelli, A.J., 2002. The role of protected areas in freshwater fish conservation. In: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of Freshwater Fishes: Options for the Future. Fishing News Books, Blackwell Science, Oxford, pp. 373–388.

Dudgeon, D., 2003. The contribution of scientific information to the conservation and management of freshwater biodiversity in tropical Asia. Hydrobiologia 500, 295–314.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266, 753–762.

Feltz, H.R., Sylvester, M.A., Engberg, R.A., 1991.Reconnaissance investigations of the effects of irrigation drainage on water quality, bottom sediment, and biota in the western United States. In: Mallard, G.E., Aronson, D.A., (Eds.), US Geological Survey Water Resources Investigations Report 91-4034, Reston, VA, pp. 319–323.

Freeman, M.C., Bowen, Z.H., Bovee, K.D., Irwin, E.R., 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecological Applications 11, 179–190.

Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35, 1305–1311.

Hamilton, S.J., 1998. Selenium effects on endangered fish in the Colorado River basin. In: Frankenberger Jr., W.T., Engberg, R.A. (Eds.), Environmental Chemistry of Selenium. Marcel Dekker, New York, pp. 297–313.

Hamilton, S.J., 1999. Hypothesis of historical effects from selenium on endangered fish in the Colorado River basin. Human and Ecological Risk Assessment 5, 1153–1180.

Hamilton, S.J., Holley, K.M., Buhl, K.J., Bullard, F.A., Weston, L.K., McDonald, S.F., 2001a. The evaluation of contaminant impacts on razorback sucker held in flooded bottomland sites near Grand Junction, Colorado – 1996. Final report, US Geological Survey, Yankton, SD.

Hamilton, S.J., Holley, K.M., Buhl, K.J., Bullard, F.A., Weston, L.K., McDonald, S.F., 2001b. The evaluation of contaminant impacts on razorback sucker held in flooded bottomland sites near Grand Junction, Colorado – 1997. Final report, US Geological Survey, Yankton, SD.

Harris, P.M., Mayden, R.L., 2001. Phylogenetic relationships of major clades of catostomidae (Teleostei: Cypriniformes) as inferred from mitochondrial SSU and LSU rDNA sequences. Molecular Phylogenetics and Evolution 20, 225–237.

Holey, M., Hollender, B., Imhof, M., Jesien, R., Konopacky, R., Toneys, M., Coble, D., 1979. Never give a sucker an even break. Fisheries 4 (1), 2–6.

Irwin, E.R., Hubert, W.A., 2000. Biology and management of ictalurids: a summary of the proceedings of the international catfish symposium. In: Irwin, E.R., Hubert, W.A., Rabeni, C.F., Schramm Jr., H.L., Coon, T. (Eds.), Catfish 2000: Proceedings of the International Ictalurid Symposium. American Fisheries Society, Bethesda, MD, pp. 495–502.

Jackman, R.E., Hunt, W.G., Jenkins, J.M., Deitrich, P.J., 1999. Prey of nesting bald eagles in northern California. Journal of Raptor Research 33, 87–96.

Jenkins, R.E., Burkhead, N.M., 1994. Freshwater Fishes of Virginia. American Fisheries Society, Bethesda, MD.

Jowett, I.G., 1997. Instream flow methods: a comparison of approaches. Regulated Rivers Research and Management 13, 115–127.

Kay, L.K., Wallus, R., Yeager, B.L., 1994. Reproductive biology and early life history of fishes of the Ohio River Drainage. Vol. II – Catostomidae. Tennessee Valley Authority, Chatanooga, TN.

Kinsolving, A.D., Bain, M.B., 1993. Fish assemblage recover along a riverine disturbance gradient. Ecological Applications 3, 531–544.

Koppelman, J.B., Garrett, G.P., 2002. Distribution, biology, and conservation of the rare black bass species. American Fisheries Society Symposium 31, 333–341.

Lanigan, S.H., Tyus, H.M., 1989. Population size and status of the razorback sucker in the Green River Basin, Utah and Colorado. North American Journal of Fisheries Management 9, 68–73.

Leidy, R.A., Moyle, P.B., 1997. Conservation status of the world's fish fauna: an overview. In: Fiedler, P.A., Karieva, P.M. (Eds.), Conservation Biology for the Coming Decade. Chapman & Hall, NY, pp. 187–227.

Lemly, A.D., 1996. Selenium in aquatic organisms. In: Beyer, W.N., Heinz, G.H., Redmon-Norwood, A.W. (Eds.), Environmental Contaminants in Wildlife – Interpreting Tissue Concentrations. CRC Lewis, Baco Raton, FL, pp. 427–445.

Lewis, C.A., Lester, N.P., Bradshaw, A.D., Fitzgibbon, J.E., Fuller, K., Hakanson, L., Richards, C., 1996. Considerations of scale in habitat conservation and restoration. Canadian Journal of Fisheries and Aquatic Science 53 (Suppl. 1), 440–445.

Lewis, W.M.J., 2003. Klamath Basin fishes: argument is no substitute for evidence. Fisheries 28 (3), 20–25.

Litvak, M.K., Mandrak, N.E., 1993. Ecology and freshwater bait use in Canada and the United States. Fisheries 18 (12), 6–12.

Lucas, M.C., Baras, E., 2001. Migration of Freshwater Fishes. Blackwell Scientific Press, Oxford.

Lynch, K.D., Jones, M.L., Taylor, W.W. (Eds.), 2002. Sustaining North American Salmon: Perspectives Across Regions and Disciplines. American Fisheries Society, Bethesda, MD.

Maier, K.J., Knight, A.W., 1994. Ecotoxicology of selenium in freshwater systems. Reviews of Environmental Contamination and Toxicology 134, 31–48.

Maitland, P.S., 1995. The conservation of freshwater fish: past and present experience. Biological Conservation 72, 259–270.

Markle, D.F., Cooperman, M.S., 2002. Relationship between Lost River and shortnose sucker biology and management of Upper Klamath Lake. In: Braunworth, B., Welch, T. (Eds.), The 2001 Water Allocation Decisions in the Klamath Basin. OSU Extension Publication, Corvallis, OR, pp. 93–118.

Marrin, D.L., Erman, D.C., 1982. Evidence against competition between trout and nongame fishes in Stampede Reservoir, California. North American Journal of Fisheries Management 2, 262–269.

McAda, C.W., 1977. Aspects of the life history of three catostomids native to the upper Colorado River basin. Masters Thesis, Utah State University, Logan, UT.

McCarthy, T., 2001. High noon in the west. Time 16 July 2001.

McPhail, J.D., 1987. Status of the Salish sucker, *Catostomus sp.*, in Canada. Canadian Field-Naturalist 101, 231–236.

McPhail, J.D., Taylor, E.B., 1999. Morphological and genetic variation in northwestern longnose suckers, *Catostomus catostomus*: the Salish sucker problem. Copeia 1999, 884–893.

Meronek, T.J., Copes, F.A., Coble, D.W., 1995. A summary of bait regulations in the North Central United States. Fisheries 20 (11), 16–23.

Merz, J.E., Vanicek, C.D., 1996. Comparative feeding habits of juvenile chinook salmon, steelhead, and Sacramento squawfish in the lower American River, California. California Fish and Game 82, 149–159.

Miller, L.M., Kallemeyn, L., Senanan, W., 2001. Spawning site and natal site fidelity by northern pike in a large lake: mark-recapture and genetic evidence. Transactions of the American Fisheries Society 125, 307–316.

Mills, D., 1991. Ecology and Management of Atlantic Salmon. Kluwer Academic Press, Netherlands.

Minckley, W.L., Deacon, J.E. (Eds.), 1991. Battle against Extinction: Native Fish Management in the American West. University of Arizona Press, Tucson, AZ.

Modde, T., Burnham, K.P., Wick, E.J., 1996. Population status of the razorback sucker in the middle Green River (USA). Conservation Biology 10, 110–119.

Moritz, C., McGuigan, K., Bernatchez, L., 2002. Conservation of freshwater fishes: integrating evolution and genetics with ecology. In: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of Freshwater Fishes: Options for the Future. Fishing News Books, Blackwell Science, Oxford, pp. 293–310.

Moss, B., 2000. Biodiversity in freshwaters – an issue of species preservation or system functioning? Environmental Conservation 27, 1–4.

Moyle, P.B., 1995. Conservation of native freshwater fishes in the Mediterranean type climate of California, USA: a review. Biological Conservation 72, 271–280.

Moyle, P.B., 2002. Inland fishes of California. University of California Press, Los Angeles.

Moyle, P.B., Leidy, R.A., 1992. Loss of biodiversity in aquatic ecosystems: evidence from fish faunas. In: Fiedler, P.L., Jain, S.K. (Eds.), Conservation Biology: The Theory and Practice of Nature Conservation, Preservation and Management. Chapman and Hall, NY, pp. 127–169.

Naiman, R.J., Turner, M.G., 2000. A future perspective on North America's freshwater ecosystems. Ecological Applications 10, 958–970.

NRC (National Research Council), 2003. Endangered and threatened fishes in the Klamath basin: causes of decline and strategies for recovery. National Academy Press, Washington, DC.

Page, L.M., Johnston, C.E., 1990. Spawning in the Creek Chubsucker, *Erimyzon oblongus*, with a review of spawning behaviors in suckers (Catostomidae). Environmental Biology of Fishes 27, 265–272.

Parker, B.J., 1989. Status of the black redhorse, *Moxostoma duquesnei*, in Canada. Canadian Field-Naturalist 103, 175–179.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres Jr., F., 1998. Fishing down marine food webs. Science 279, 860–863.

Pearson, M., 1998. Habitat inventory and enhancement needs for the endangered Salish sucker (*Catostomus* sp.) and nooksack dace (*Rhinichthys* sp.). Fisheries Project Report No. 76, Province of British Columbia, Ministry of Fisheries.

Pearson, M.P., Healey, M.C., 2003. Life history characteristics of the endangered Salish sucker (*Catostomus* sp.) and their implications for management. Copeia 2003, 759–768.

Poff, N.L., Allen, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47 (11), 769–784.

Pulliam, H.R., 1988. Sources, sinks, and population regulation. American Naturalist 132, 652–661.

Radtke, D.B., Kepner, W.G., 1990. Environmental contaminants in the lower Colorado River valley, Arizona, California, and Nevada. In: Proceedings of the Arizona Hydrological Society Second Annual Symposium. Water Quality and Quantity Issues into the 1990s – Adaptation to Current Realities. September 14–16, Casa Grande, AZ, pp. 1–21.

Radtke, D.B., Kepner, W.G., Effertz, R.J., 1988. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Lower Colorado River Valley, Arizona, California, and Nevada, 1986–1987. US Geological Survey, Water-Resources Investigation Report 88-4002, Tucson, AZ.

Rahel, F.J., 2002. Homogenization of freshwater faunas. Annual Review of Ecology and Systematics 33, 291–315.

Reynolds, J.D., Dulvy, N.K., Roberts, C.R., 2002. Exploitation and other threats to fish conservation. In: Hart, P.J.B., Reynolds, J.D. (Eds.), Handbook of Fish Biology and Fisheries:, vol. 2. Blackwell Publishing, Oxford, pp. 319–341.

Ricciardi, A., Rasmussen, J.B., 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13, 1220–1222.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 4, 1163–1174.

Richter, B.D., Baumgartner, J.V., Wiginton, R., Braun, D.P., 1997a. How much water does a river need? Freshwater Biology 37, 231–249.

Richter, B.D., Braun, D.P., Mendelson, M.A., Master, L.L., 1997b. Threats to imperiled freshwater fish fauna. Conservation Biology 11, 1081–1093.

Rochard, E., Castelnaud, G., Lepage, M., 1990. Sturgeons (Pisces: Acipenseridae), threats and prospects. Journal of Fish Biology 37A, 123–132.

Ruetz III, C.R., Jennings, C.A., 2000. Swimming performance of larval robust redhorse *Moxostoma robustum* and low-velocity habitat modeling in the Oconee River, Georgia. Transactions of the American Fisheries Society 129, 398–407.

Saunders, D.L., Meeuwig, J.J., Vincent, A.C.J., 2002. Freshwater protected areas: strategies for conservation. Conservation Biology 16, 30–41.

Schwalme, K., Mackay, W.C., Lindner, D., 1985. Suitability of vertical slot and Denil fishways for passing north-temperate, nonsalmonid fish. Canadian Journal of Fisheries and Aquatic Sciences 42, 1815–1822.

Scoppettone, G.G., Coleman, M., Wedemeyer, G.A., 1986. Life history and status of the endangered cui-ui of Pyramid Lake, Nevada. US Fish and Wildlife Service, Fish and Wildlife Research 1. Washington, DC.

Scoppettone, G.G., Vinyard, G., 1991. Life history and management of four endangered lacustrine suckers. In: Minckley, W.L., Deacon, J.E. (Eds.), Battle against extinction: native fish management in the American West. The University of Arizona Press, Tuscon, AZ, pp. 359–377.

Seethaler, K.H., McAda, C.W., Wydoski, R.S., 1979. Endangered and threatened fish in the Yampa and Green Rivers of Dinosaur National Monument. National Park Service Transactions and Proceedings Series 5, 605–612.

Service, R.F., 2003. 'Combat biology' on the Klamath. Science 300, 36–39.

Skelton, P.H., 2002. An overview of the challenges of conserving freshwater fishes in South Africa. In: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of freshwater fishes: options for the future. Fishing News Books, Blackwell Science, Oxford, pp. 221–236.

Slocombe, D.S., 1993. Implementing ecosystem-based management: development of theory, practice, and research for planning and managing a region. BioScience 43, 612–620.

Smith, G.R., 1992. Phylogeny and biogeography of the Catostomidae, freshwater fishes of North America and Asia. In: Mayden, R.L. (Ed.), Systematics, Historical Ecology, and North American Freshwater Fishes. Stanford University Press, pp. 778–826.

Stanley, E.H., Doyle, M.W., 2003. Trading off: the ecological effects of dam removal. Frontiers in Ecology and the Environment 1, 15–22.

Stephens, D.W., Waddell, B., 1998. Selenium sources and effects on biota in the Green River basin of Wyoming, Colorado, and Utah. In: Frankenberger Jr., W.T., Engberg, R.A. (Eds.), Environmental chemistry of selenium. Marcel Dekker, NY, pp. 183–203.

Travnichek, V.H., Maceina, M.J., 1994. Comparison of flow regulation effects on fish assemblages in shallow and deep water habitats in the Tallapoosa River, Alabama. Journal of Freshwater Ecology 9, 207–216.

Tyus, H.M., 1998. Razorback sucker (*Xyrauchen texanus*) recovery plan 1998. Report to US Fish and Wildlife Service, Denver, CO.

Tyus, H.M., Karp, A.C., 1990. Spawning and movements of razorback sucker, *Xyrauchen texanus*, in the Green River basin of Colorado and Utah. Southwestern Naturalist 35, 427–433.

USFWS (US Fish and Wildlife Service), 1987. Recovery implementation program for endangered fish species in the upper Colorado River basin. US Department of the Interior, US Fish and Wildlife Service, Denver, CO.

USFWS (US Fish and Wildlife Service), 1991. Endangered and threatened wildlife and plants; the razorback sucker (*Xyrauchen texanus*) determined to be an endangered species. Federal Register 56, 54957-54967.

USFWS (US Fish and Wildlife Service), 1995. San Juan River Basin Recovery Implementation Program. San Juan River Recovery Implementation Program, Albuquerque, NM.

USFWS (US Fish and Wildlife Service), 1999. June sucker (*Chasmistes liorus*) recovery plan. US Fish and Wildlife Service, Denver, CO.

USFWS (US Fish and Wildlife Service), 2001. Biological/conference opinion regarding the effects of operation of the Bureau of Reclamation's Klamath Project on the endangered Lost River sucker (*Deltistes luxatus*), endangered shortnose sucker (*Chasmistes brevirostris*), threatened bald eagle (*Haliaeetus leucocephalus*), and proposed critical habitat for the Lost River/shortnose suckers. Klamath Falls Office, Klamath Falls, OR.

Waddell, B., May, T.W., 1995. Selenium concentrations in the razorback sucker (*Xyrauchen texanus*): Substitution of non-lethal muscle plugs for muscle tissue in contaminant assessment. Archives of Environmental Contamination and Toxicology 28, 321–326.

Walters, C.J., Holling, C.S., 1990. Large-scale management experiments and learning by doing. Ecology 71, 2060–2068.

Warren, M.L., Burr, B.M., Walsh, S.J., Bart, H.L., Cashner, R.C., Etnier, D.A., Freeman, B.J., Kuhajda, B.R., Mayden, R.L., Robison, H.W., Ross, S.T., Starnes, W.C., 2000. Diversity, distribution, and conservation status of the native freshwater fishes of the southern United States. Fisheries 25 (10), 7–31.

Warren, M.L., Angermeier, P.L., Burr, B.M., Haag, W.R., 1997. Decline of a diverse fish fauna: patterns of imperilment and protection in the southeastern United States. In: Benz, G.W., Collins, D.E., (Eds.), Aquatic Fauna in Peril: The Southeastern Perspectives. Special Publication 1, Southeast Aquatic Research Institute. Lentz Design and Communication, Decatur, GA, pp. 105–164.

Watters, G.T., 1994. An annotated bibliography of the reproduction and propagation of the unionoidea (primarily of North America). Ohio Biological Survey Miscellaneous Contributions, Number 1.

Weyers, R.S., Jennings, C.A., Freeman, M.C., 2003. Effects of pulsed, high-velocity water on larval robust redhorse and v lip redhorse. Transactions of the American Fisheries Society 132, 84–91.

Wiley, E.O., Mayden, R.L., 1985. Species and speciation in phylogenetic systematics, with examples from the North American fish fauna. Annals of the Missouri Botanical Gardens 72, 596–635.

Winemiller, K.O., Rose, K.A., 1992. Patterns of life-history diversification in North American fishes: Implications for population regulation. Canadian Journal of Fisheries and Aquatic Science 49, 2196–2218.

Wishart, M.J., Davies, B.R., 1998. The increasing divide between First and Third Worlds: science, collaboration and conservation of Third World aquatic ecosystems. Freshwater Biology 39, 557–567.