Final Draft

Modern Technologies for an Ancient Fish: tools to inform management of migratory sturgeon stocks

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INTRODUCTION TO MARINE-ORIENTED STURGEONS

There are 27 species of sturgeons and paddlefishes (Order Acipenseriformes) that inhabit rivers, lakes, estuaries, near-shore oceanic environments, and inland seas across the northern hemisphere (Table 1). The two species of paddlefishes (Family Polyodontidae) are strictly freshwater in life history while the 25 sturgeons (Family Acipenseridae) include 16 species that enter into estuaries, oceans or seas during some part of their life cycle, even if just for feeding. All sturgeons, however, spawn in freshwater habitats. The 16 marine-oriented species (species that spend a significant portion of their life history in marine environments) occur on all of the continents to which sturgeons are endemic, including North America, Europe and Asia.

The Acipenseriformes represents an ancient lineage that has an important place in the evolutionary history of fishes. Their history dates to the Lower Jurassic (200 Myr BP), earning them the status of 'living fossils.' Present evidence of their primitive origins remains in characters such as a heterocercal caudal fin, cartilaginous skeletons, notochord, and ganoid scales. These fishes originated in the Tethys Sea, and later diverged into a number of different taxa in Europe and Asia, and eventually North America (Bemis and Kynard 1997; Birstein et al. 1997b). Sturgeons have five rows of bony scutes and snouts with sensory barbels (Figure 1).

Sturgeons are generally long-lived fishes that exhibit late onset of maturity, slow growth and infrequent reproduction (reviewed in Pikitch et al. 2005). Some species of sturgeon have historic life spans of well over 100 years, and many females do not reach sexual maturity until 20-25 years of age or more (Billard and Lecointre 2001). These characteristics as well as their value as the source of black caviar (the unfertilized roe of female sturgeon) make them particularly vulnerable to overexploitation. The reliance of sturgeons on freshwater environments makes them particularly susceptible to the effects of habitat alteration. Damming of rivers has been particularly detrimental to many sturgeon stocks and species in that it can reduce and sometimes eliminate spawning and egg/larvae incubation habitats and change important environmental cues relating to flow regimes and hydrographic characteristics. Pollution, introduced species, reduced food supply, dredging, and water diversion are also problematic for these fishes.

As such, the sturgeons are now considered one of the most endangered groups of animals in the world. In 2010, the International Union for Conservation of Nature (IUCN) reviewed the status of the 25 species (and two subspecies) of sturgeon (*Acipenseridae*) in their "Red List" (list of threatened species);four species are listed as "threatened," five species as "endangered," and 18 species are "critically endangered" (likely to become extinct in a generation). The IUCN classifications take all stocks into consideration (and pool both week and strong stocks of the same species) and thus tend to be conservative. For example, the IUCN classifies white sturgeon (all stocks) as "least concern", whereas all stocks of white sturgeon in Canada are classified "endangered" under the national ranking system (COSEWIC 2003), and in the US, the Kootenai River white sturgeon is federally listed as an endangered distinct population segment.

While sturgeons deserve attention because of their unique characteristics and generally endangered status, they are also some of the least-well-known of the major taxa of concern in terms of their spatial distribution and abundance, particularly for marine-oriented species during the oceanic and nearshore phase of their life history. Almost all of the sturgeons that enter into saltwater have been understudied with respect to where they go and why (Table 1). Several marine-oriented species may inhabit natal estuaries during their first year of life, but once they outmigrate little is known regarding their migrations and habitat use. The spawning periodicity of female sturgeon varies between species (range 2-11 years; Billard and Lecointre 2001) and can be influenced by physical and environmental conditions. Understanding these information gaps is extremely important for conservation in terms of protecting habitats and distinct populations.

In this report we further explore this issue while providing case studies and tools for researchers to use in studying the movement and distribution of these ancient fishes.

Table 1. Sturgeons (Family *Acipenseridae*) of the world and their marine distributions. Sources: Birstein et al. 1997; Bemis et al. 1997; Ruban 2005; Artyukhin et al. 2007; Shmigirilov et al. 2007.

Species	Distribution	IUCN* Category
Siberian sturgeon, *Acipenser baerii*	FW, E/Bays	Endangered
Shortnose sturgeon, *Acipenser brevirostrum*	FW, E, Ocassionally Coastal	Vulnerable
Yangtze sturgeon, *Acipenser dabryanus*	FW	Critically Endangered (pe)
Lake sturgeon, *Acipenser fulvescens*	FW	Least Concern
Russian sturgeon, *Acipenser gueldenstaedtii*	E , Sea (Black, Caspian, Azov)	Critically Endangered
Green sturgeon, *Acipenser medirostris*	E, Coastal (Baja, California to the Bering Sea)	Near Threatened
Sakhalin sturgeon, *Acipenser mikadoi*	E, Coastal (Bering Sea, Sea of Okhotsk, Sea of Japan, south Sakhalin Island; range very restricted at present); $$	Critically Endangered
Adriatic sturgeon, *Acipenser naccarii*	E, Coastal; Adriatic Sea; range very restricted at present; $$	Critically Endangered (pe)
Ship sturgeon, *Acipenser nudiventris*	E, Sea (Black, Caspian, Azov)	Critically Endangered
Atlantic sturgeon, *Acipenser oxyrinchus* *Acipenser oxyrinchus desotoi* *Acipenser oxyrinchus oxyrinchus*	E, Coastal (Gulf of Mexico to Quebec)	Near Threatened
Persian sturgeon, *Acipenser persicus*	E, Sea (Black, Caspian)	Critically Endangered
Sterlet, *Acipenser ruthenus*	FW	Vulnerable
Amur sturgeon, *Acipenser schrenckii*	E, Coastal (distribution uncertain); $$	Critically Endangered
Chinese sturgeon, *Acipenser sinensis*	E, Coastal (Yellow and East China seas; range very restricted at present)	Critically Endangered
Stellate sturgeon, *Acipenser stellatus*	E, Sea (Black, Caspian, Azov)	Critically Endangered
European (Baltic) sturgeon, *Acipenser sturio*	E, Coastal (Baltic Sea; once throughout Western Europe; range very restricted at present)	Critically Endangered (pe)
White sturgeon, *Acipenser transmontanus*	E, Coastal (Aleutian Islands to Monterey California)	Least Concern
Beluga sturgeon, *Huso huso*	E, Sea (Black, Caspian, Azov)	Critically Endangered
Kaluga sturgeon, *Huso dauricus*	E. Coastal (Sea of Okhotsk, Tatar Strait, Sea of Japan; $$	Critically Endangered
Pallid sturgeon, *Scaphirhynchus albus*	FW	Endangered
Shovelnose sturgeon, *Scaphirhynchus platorynchus*	FW	Vulnerable
Alabama sturgeon, *Scaphirhynchus suttkusi*	FW	Critically Endangered
Dwarf sturgeon, *Pseudoscaphirhynchus hermanni*	FW	Critically Endangered
Syr Darya sturgeon, *Pseudoscaphirhynchus fedtschenkoi*	FW	Critically Endangered (pe)
Amu Darya sturgeon, *Pseudoscaphirhynchus kaufmanni*	FW	Critically Endangered

* International Union for Conservation of Nature

NOTES: FW = primarily freshwater over most of life history
E = estuarine
Sea = inhabits seas but not oceans
$$ = additional research is required to determine the marine distribution of these species
pe = possibly extinct in the wild

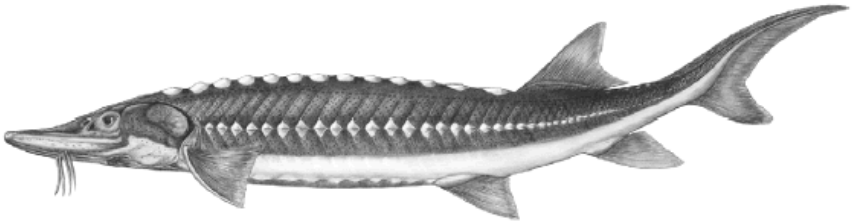

Figure 1. The white sturgeon, *Acipenser transmontanus*. (Drawing by Loucas Raptis of a specimen from the Nechako River, a tributary of the upper Fraser River, British Columbia, provided courtesy of BC Ministry of Environment.)

RATIONALE FOR RESEARCH

Where Do They Go – And Why?

In contrast to studying life on land, researching freshwater and marine life can add extra challenges due to the difficulties of observing and examining those organisms. Less opportunity may exist for easily counting the number of animals within a population or for determining when and where an individual animal or group of animals moves or migrates for feeding or reproduction. Similar techniques (e.g. external and electronic tags) can be used on land and in the water to address these questions but some specialized tools are required for research in aquatic environments.

But why is it so important to know the movement of an animal, specifically a sturgeon? As indicated above, we know very little about the movement and spatial distribution of many species of sturgeons, especially in marine environments. Without knowing where an animal goes to reproduce or feed, the route that an animal takes to get there, and the timing of both the travel to and the residency within a particular habitat, it is impossible to create a management scheme to protect a species from direct (e.g. illegal harvest, by-catch from fisheries that target other species) or indirect (e.g. habitat loss, pollution) impacts. However, once we have some understanding of the movement, migration, and distribution of a species, and the temporal and spatial residency of the species during important life-history events, we can then implement informed and effective stock management actions. We also can characterize the types of habitats that are used by the species of interest within a study area, and infer distribution of the species in other areas of its range. Environmental parameters can be studied to determine correlations between cues and behaviour. Such information can be particularly useful when evaluating the potential impact of habitat alteration (e.g. water flow alteration in a river bed). Lastly, knowing the route of migration, from spawning to feeding to overwintering habitats, for example, can be important in devising management options for reducing fishery or in-stream activity (i.e., dredging, gravel removal) interactions.

Sturgeons move from one location or habitat type to another for a variety of reasons, such as feeding, reproduction, or overwintering. Sturgeon movement within river systems can be complex and include multi-step migrations (Bemis and Kynard 1997). Within a species, populations can differ on the timing of migrations into river systems, time spent within the river (holding), and the location of spawning. Protecting the genetic heritage and diversity of a species requires an understanding of these complexities, including specific life-stage habitat requirements, and managing any harvest regimes accordingly. There may be sex-specific differences in the timing of movements (often males arrive at the spawning grounds before females) so harvest/interception regimes may need to be sensitive to this to maintain the male:female sex-ratio balance within the population.

This leads us to another fundamental question to be answered through movement studies: how many distinct populations exist within a species and where do these populations reproduce? Understanding this is critical to conservation efforts that seek to ensure that the ecological potential of a species and its ability to respond to environmental change is preserved. As sturgeons are thought to return to their natal river to reproduce, the individual rivers where sturgeons spawn often define the populations that need to be protected. Individual populations of sturgeon may differ in terms of abundance and reproductive capacity. This may be due, in some cases, to the ecological and habitat productivity of natal watersheds (or locations within watersheds). Thus, researchers and fishery managers may be particularly interested in minimizing the potential mortality of individuals from certain river systems while they are in marine environments. Movement studies can provide the information required by fishery managers to conserve and protect sturgeon at both stock and species levels. These studies further provide the basis for protective schemes under national and international legislation.

Knowledge about movement and the spatial distribution of stocks can also improve stock assessments and help in specifying suitable management or recovery plans. Despite the value of sturgeons globally and their imperilled status, stock assessments are still lacking for most species and are in some cases hindered by an insufficient understanding of spatial distribution. Sturgeon species or stocks with an anadromous life-history strategy may require assessment models that account for the seasonal movement patterns of different life-history stages exploited by fisheries (Michielsens 2003; Cunningham 2007). Tagging data can be incorporated into spatially explicit models to allow more accurate estimation of fishing mortality rates experienced by different age classes where fishing intensity varies by area (Sibert and Fournier 1994; Michielsens et al. 2006).

Insufficient data for parameterisation of models for migratory species with complex life histories can lead to large uncertainties in resource assessment and the likely effects of alternative management actions. The lack of data on key population dynamics parameters has been identified as a contributor to the depleted and endangered status of many sturgeon populations throughout their range (Rochard et al. 1990; Birstein 1993). Studies of Gulf and green sturgeon offer real examples of how movement studies have enhanced our knowledge base in support of species conservation (see **Case Studies**).

Case Studies

<u>Rationale-driven case studies: Gulf sturgeon and green sturgeon</u>

Gulf Sturgeon

The anadromous Gulf sturgeon *Acipenser oxyrinchus desotoi*, a subspecies of the Atlantic sturgeon *Acipenser oxyrinchus*, occurs in most Gulf of Mexico river systems from the mouth of the Mississippi River to the west coast of Florida (Figure 2; Photo Plate 1). Both mature and immature Gulf sturgeon participate in a freshwater migration, typically entering coastal rivers in March or April and outmigrating to the ocean in September or October (USFWS and the Gulf States Marine Fisheries Commission 1995). The cool-water period of estuarine or marine residency is critical for growth and reproduction, as Gulf sturgeon do not feed during their freshwater residency.

Early information about Gulf sturgeon distribution and migration came primarily from commercial fishing (Huff 1975). Fishing operations in individual rivers were mostly short-lived, as is typical for sturgeon species, but the catches provided some insights into the timing and extent of migration. More detailed information came from surveys in the 1980s conducted in response to declining catches and the species' listing by the state of Florida as a threatened species (Wooley and Crateau 1982, 1985). Marking with conventional tags mostly showed the extent of migration (e.g. recaptures of tagged fish by anglers below a dam or by commercial shrimp

trawlers in Gulf of Mexico waters), whereas the first use of radio tags (and manual/mobile tracking) provided insights about holding, staging and spawning areas (Wooley and Crateau 1985). These authors were able to characterize occupied riverine habitats in the Apalachicola River and to relate the timing of upstream and downstream migrations to environmental cues.

Radio transmitters worked well for manual tracking of Gulf sturgeon over long distances in rivers, but these transmitters cannot be detected in brackish or salt water. That led Odenkirk (1989) to tag some Gulf sturgeon with both radio and sonic tags. His study was also the first to use stationary receivers to detect and log passage events (in this case, to detect sonic tags as fish moved through barrier island passes).

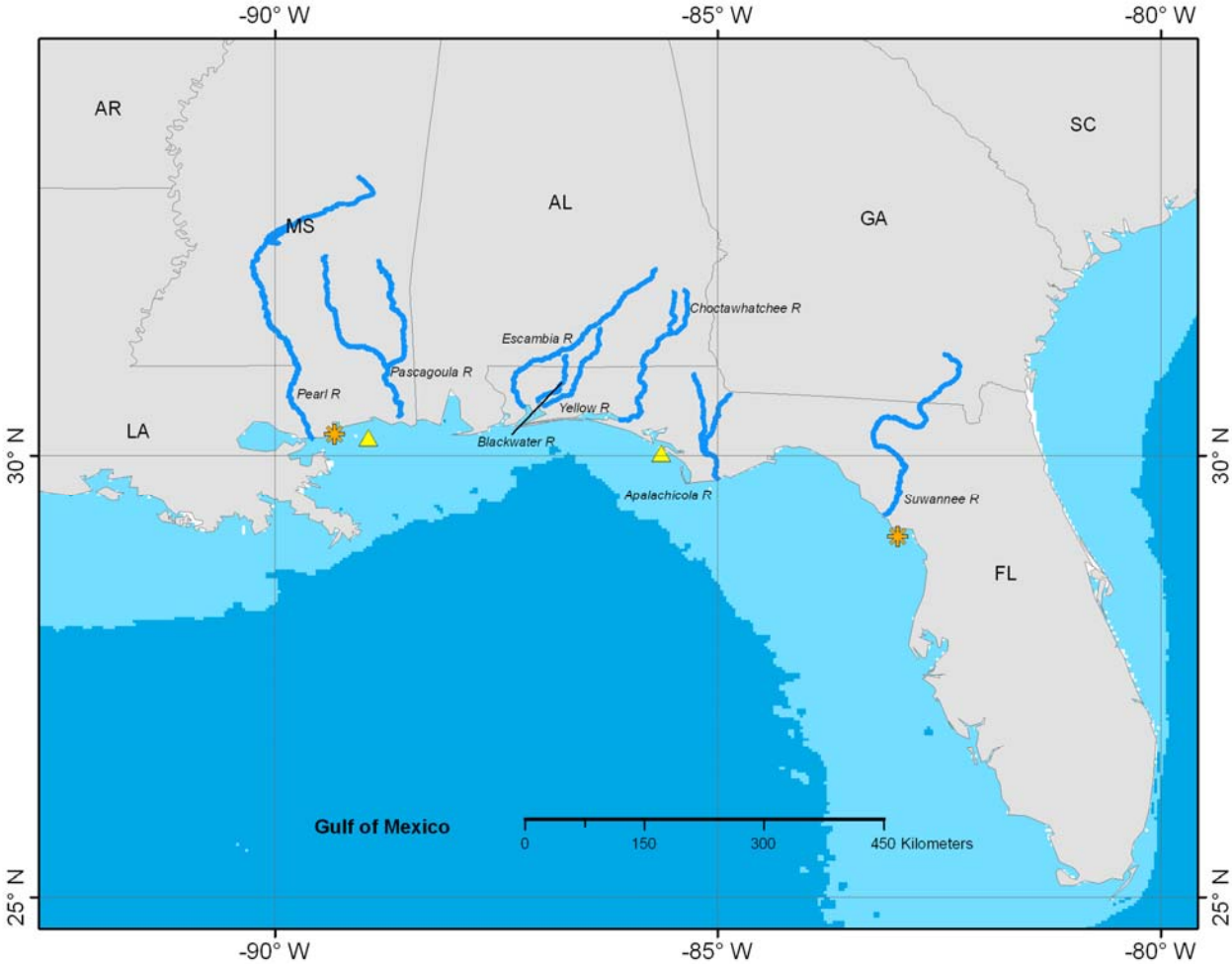

Figure 2. Documented distribution of Gulf sturgeon in North America, determined from acoustic and archival telemetry projects. The orange asterisks mark the easternmost and westernmost locations of confirmed detections of acoustic-tagged Gulf sturgeon. Gulf sturgeon spawn in coastal rivers including the eight shown on this map. Spawners and non-spawners typically remain in coastal rivers until fall and occupy estuarine and nearshore marine waters during winter. Yellow triangles indicate winter concentration areas for Gulf sturgeon from two or more river systems. The 100 m isobath is shown as the light blue areas near the coast.

Photo Plate 1. Gulf sturgeon (*Acipenser oxyrinchus desotoi). Photo: Joe Hightower.*

The listing of Gulf sturgeon in 1991 as a threatened species under the U. S. Endangered Species Act provided a further boost to research activity. For example, radio tracking studies in the Choctawhatchee River were done to identify potential spawning sites, with confirmation through the use of artificial substrates to collect the adhesive Gulf sturgeon eggs (Fox et al. 2000). Deployment of artificial substrates in a grid design provided fine-scale information about spawning habitat in the Suwannee River (Sulak and Clugston 1998). Marine habitat studies using sonic telemetry (and more recently, archival temperature-logging and pop-up archival tags) showed that Gulf sturgeon sometimes moved long distances along the shoreline and primarily used shallow nearshore areas (Edwards et al. 2003; Edwards et al. 2007; Parkyn et al. 2007; Ross et al. 2009). The fish occupying these marine habitats were often from multiple river systems; for example, Edwards et al. (2007) reported that Gulf sturgeon from the Yellow, Choctawhatchee, and Apalachicola rivers were located within a 25-km stretch of coastline (eastern winter concentration area shown on Figure 2). Ross et al. (2009) documented the co-occurrence of Gulf sturgeon from the Pearl and Pascagoula rivers in the concentration area off Mississippi (western area shown on Figure 2). Thus, marine and estuarine threats and management efforts may affect more than one population.

Genetic studies have also aided in understanding Gulf sturgeon migration patterns. For example, Dugo et al. (2004) showed that genetic structure occurred at least at the drainage level and possibly at the level of tributary rivers within a basin. The genetic analyses were helpful in interpreting telemetry results since some fish were tagged outside their natal drainage and others were captured or detected in multiple drainages.

These research results formed the basis for the Gulf sturgeon recovery plan and designation of critical habitats. These important habitats included upper basin spawning sites with limestone bluffs and outcroppings, estuarine and marine sites with preferred substrates and benthic fauna, and summer resting areas. Genetic results showed strong natal river fidelity, so critical habitat was defined in each of the seven river systems containing currently reproducing populations (Pearl, Pascagoula, Escambia, Yellow/Blackwater, Choctawhatchee, Apalachicola, and

Suwannee). This resulted in designation of nearly 2,800 river km as critical habitat for conservation of the species.

Green Sturgeon

In contrast to the relatively well-studied Gulf sturgeon, the North American green sturgeon (Photo Plate 2) was little studied until 2002, when the US National Marine Fisheries Service received a petition to list it under the US Endangered Species Act. A severe lack of demographic and basic life-history information hampered the subsequent status review (Adams et al. 2002). A particularly troubling unknown was the origin of green sturgeon that form dense aggregations in certain estuaries during summer months. Green sturgeon were known to use just three rivers for spawning (the Sacramento and Klamath rivers in California, and the Rogue River in Oregon), and to spend much of their lives in marine waters between Alaska and Baja California (Figure 3). The purpose of the summertime estuarine aggregations was unknown, as was the proportion of green sturgeon exhibiting this aggregation behaviour, but green sturgeon in these aggregations are vulnerable to capture in gillnet fisheries that target white sturgeon and salmon, as well as other environmental problems in the estuaries associated with shellfish aquaculture and nearshore industrial activities.

The recent development of new electronic tagging systems made it feasible to rapidly close some of these information gaps. Initial work focused on green sturgeon in the Rogue River, using radio and acoustic tags to learn that green sturgeon migrate into rivers in the early spring for spawning in up-river areas, and then hold in deep pools over the summer prior to emigration in the fall when flows rise with the onset of the rainy season (Erikson et al. 2002). Tagged sturgeon returned to the river to spawn every two to four years (Erickson and Webb 2007). Rogue River fish were also tagged with pop-off archival tags (PAT), which revealed that they remain in fairly shallow water (50-80 m) when in the coastal ocean, and showed that they migrate north to the west coast of Vancouver Island in the fall (Erickson and Hightower 2007).

A broader study using acoustic tags showed that green sturgeon make extensive seasonal migrations among spawning areas, over-summering in various estuaries and bays, and over-wintering areas in the coastal ocean, with many individuals using areas around northern Vancouver Island (Lindley et al. 2008; Lindley et al. (2010, in review). Further PAT work, using longer tag deployments, also showed this seasonal migration pattern, and fairly constrained depth and temperature distributions during the winter. Acoustic tags also revealed extensive use of and movement among non-natal estuaries. Green sturgeon from different populations all utilized and mixed together in large estuaries, but at different rates. Natal estuaries were used almost exclusively by fish from the associated natal river (Lindley et al. 2010, in review). Green sturgeon were also shown to have diverse patterns of migration within and among populations. Within the Sacramento River, acoustic tags revealed that a seasonal water diversion dam was a serious impediment to the spawning migration of green sturgeon (Heublein et al. 2009).

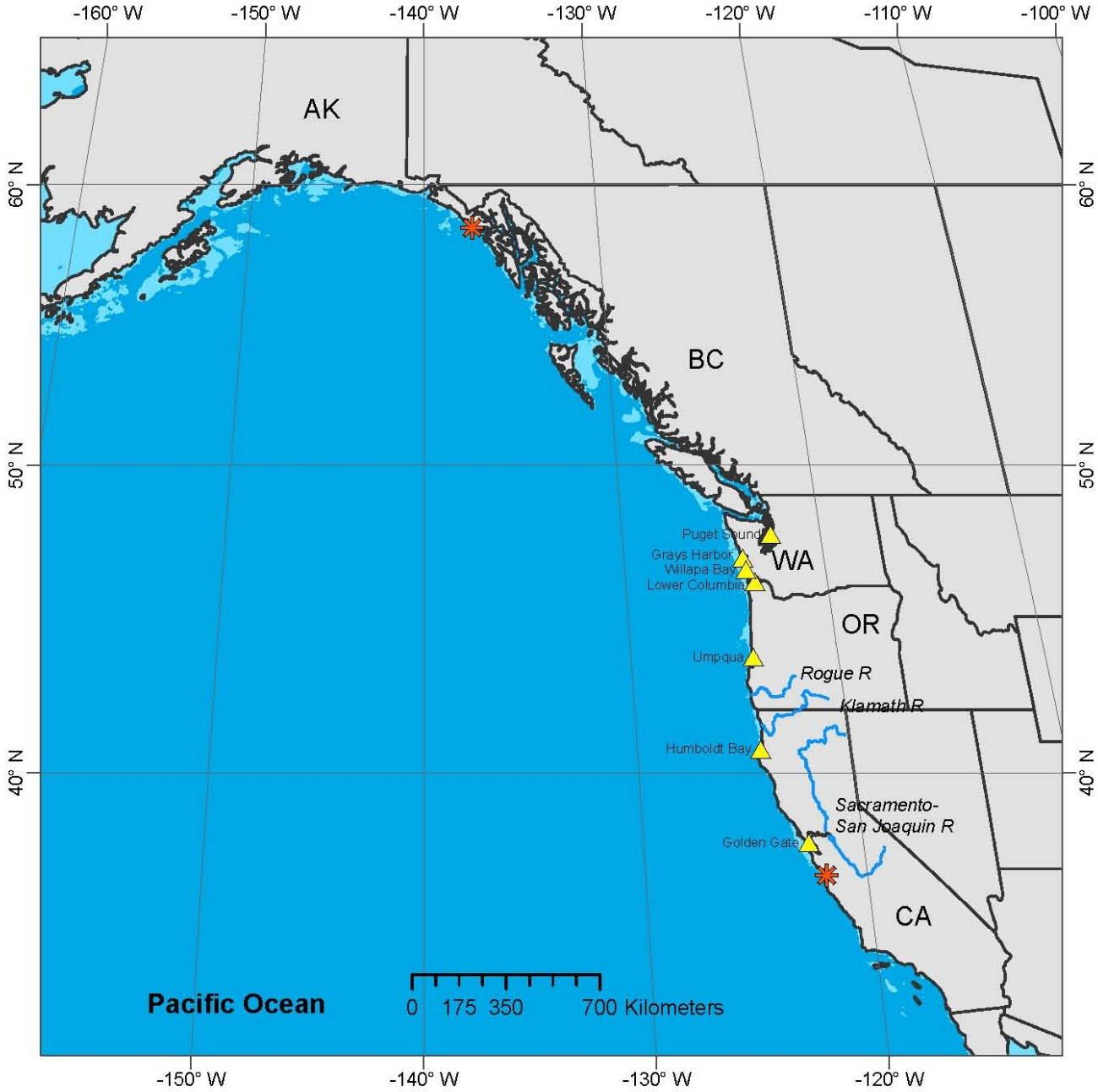

Figure 3. Documented distribution of green sturgeon in North America, determined from acoustic telemetry project with fixed receiver array. The orange asterisks mark the northernmost and southernmost locations of confirmed detections of acoustic-tagged green sturgeon. Green sturgeon spawn in California in the Sacramento and Klamath rivers, and in Oregon in the Rogue River (shown in blue). They spend summers in estuaries and bays in California, Oregon, and Washington, and utilize the coastal ocean between southern Alaska and Baja California, Mexico, generally remaining in water less than 100 m deep. Summer aggregation areas are shown as yellow triangles. The 100 m isobath is shown as the light blue areas near the coast.

In summary, electronic tagging revealed that green sturgeon make extensive seasonal migrations while remaining close to shore, move freely among diverse habitat areas, and spawn every two to four years in their natal river. While tagging revealed clear overall migration patterns, it also revealed a diversity of migratory behaviours that are likely important to consider in the conservation of this species. Complementary genetic studies have determined that two distinct population segments exist within green sturgeon, corresponding to northern and southern stocks, and that estuarine populations represent mixed stocks (Israel et al. 2009). Data acquired from electronic tagging has already been the basis of many of the conservation regulations put in place after the listing of the southern distinct population segment of green sturgeon by the US federal government. Critical habitat for green sturgeon was designated in 2009 along the continental shelf of the US from southeast Alaska to central California out to a depth of 110 m, as well as in a number of estuaries and bays in Washington, Oregon and California. Regulatory biologists are using the acoustic tagging data in their assessments of permit applications for activities such as dredging and dredge spoil disposal, large construction projects within and along the shores of estuaries, and the allowance of groundfish trawl fisheries in the coastal ocean.

Photo Plate 2. Green sturgeon (*Acipenser medirostris*). *Photo: Doug Killam (California Dept. of Fish and Game).*

Research from Europe and Asia

One area of the world where the movements of sturgeons is not well understood is the Caspian Sea. This water body is important because it was once, and still is on a smaller scale, the cradle of caviar production, with more wild caviar produced in this region than any other. Five of the species inhabiting this region (stellate, beluga, Persian, Russian and ship sturgeon; Table 1), including those that produce the highly prized beluga, sevruga and osetra caviar, are anadromous. Adult sturgeons move into river systems to reproduce in spring and sometimes winter and fall. Most adults migrating into the river in spring are thought to leave the river just after spawning, but those migrating in the fall and winter may overwinter in the river. The patterns of spawning migrations of Caspian Sea sturgeons differ amongst species, and the damming of rivers has likely altered migration patterns (Khodorevskaya et al. 2009).

After hatching, larvae and fingerlings remain within the rivers for several months depending on the species: for some species (e.g. stellate and Russian), fingerlings may over-winter in river deltas while for others (e.g. beluga), fingerlings will migrate into the Caspian Sea just after their downstream migration. Information regarding the behaviour and movement of juveniles as well as adults within rivers has been gathered through fisheries dependant surveys and fisheries-independent studies using nets. While a few tagging studies have been attempted (e.g. Doukakis et al. 2009), none have been conducted on the scale necessary to provide species-specific population and movement/migration information Such studies would be of further benefit in understanding the frequency of reproduction of the different species.

It also is unclear whether adult sturgeon in the Caspian Sea return to their natal rivers for reproduction, and how this behaviour has been affected by dams. Genetic studies using mitochondrial DNA have not shown differentiation amongst river populations (Doukakis et al. 2005), but preliminary data from microsatellites suggest that natal homing does occur. Hatchery supplementation and stocking in rivers may be affecting the natural population structure that once existed because hatcheries do not always use broodstock collected in the river system where the hatchery-produced juveniles are released. There is a great need to understand the population structure of Caspian Sea sturgeons so that management reflects and protects the natural stock structure.

Within the Caspian Sea, comprehensive information about the distribution of sturgeons is lacking (Khoderevskaya et al. 2009). Much of what is known has been collected through trawl surveys, which are limited in terms of depths covered and by the presence of sea ice, and the distribution of food resources. As stated earlier, genetic and tagging studies have been limited. The vertical distribution of sturgeons in the Sea has been examined through trawl and drift net surveys, but these studies have been limited in vertical and geographic scope. Understanding distribution and movement are critical for deriving accurate stock-abundance estimates given that abundance estimates and catch quotas are based on trawl surveys at sea. Studies are also needed to understand the response of different sturgeon species and different ages and size classes to trawl-survey gear to quantify catchability. There is thus a great need for a further research using the techniques discussed here and a comparative approach that also uses the data available from the trawl and net surveys (see Khodorevskaya et al. 2009 for compiled information). This will allow not only better fisheries management but also the establishment of protected areas around feeding and breeding areas.

In Western Europe, sturgeons have been heavily affected by historic fishing and habitat alteration and thus are only represented by very small, sometimes relict populations; examples include European (Baltic) sturgeon *(A. sturio)* and Adriatic sturgeon (*A. naccarii*; Table 1). Understanding the distribution of these species within their very restricted range and establishing corresponding plans for habitat conservation and take reduction is thus critical to conservation. Restoration projects for European and Atlantic sturgeon have released marked (mostly tagged) juveniles from captive breeding facilities to track subsequent movements and habitat use. Past studies have used acoustic telemetry to study young European sturgeon (*A. sturio*) in the Gironde River estuary and the influence of tidal cycles on their movement (Taverny et al. 2002). Animals were found to congregate in areas near the middle of the estuary and orient their movements to the direction of the tidal current; downstream during ebb and upstream during flood tides. Gessner et al. (2006) used acoustic telemetry to monitor reintroduction trials for American Atlantic sturgeon (*A. oxyrinchus oxrinchus*) to the Baltic Sea and European sturgeon to the Elbe River in Germany. Habitat utilization of up to 100 tagged fish per year, food selectivity, migration patterns and potential sources of mortality for reintroduced fish (2,000-5,000 tagged fish per year) were studied. The use of telemetry is considered key to the success of the reintroduction effort, owing to the limited knowledge of the biology and ecology of the reintroduced species and suitability of the modified river environments to sustain

viable populations. Understanding the movement and habitat use of these animals will be essential for guiding future restoration programs and protecting critical habitat. As time goes on, tagging studies will further reveal whether reintroduced animals survive to adulthood and return to their rivers of release to reproduce.

In the Black Sea, a study using acoustic tags examined spawning location and timing for stellate (*A. stellatus*) and Russian sturgeon (*A. gueldenstaedtii*) in the lower Danube River (Kynard et al. 2002). A high rate of interception of tagged fish as indicated by reported fishery returns of 38% in 1998 and 28% in 1999 limited the success of telemetry in this instance. An interesting result from this study was the high sensitivity of acoustic tagged Russian and stellate sturgeon to capture and handling, with over 50% of tagged fish aborting their upstream migration. This finding warrants further research into similar effects in other populations where a significant proportion of the population are being handled for tagging. Currently, tagging is again being attempted, as is use of a DIDSON acoustic camera (see **Observational Techniques**), to investigate movements. This study may be more successful now because of a 10-year moratorium on fishing currently in place in the Romanian portion of the Danube River.

The Russian Far East and China includes some interesting, but little-known (and under-studied) anadromous species (Shmigirilov et al. 2009; Erickson et al. 2007). The Amur sturgeon (*A. schrenckii*) and kaluga sturgeon (*Huso dauricus*) of the Amur River are still commercially exploited and provide valuable meat and caviar to national and international markets. These species are thought to undertake considerable migrations within the river, and the kaluga likely has a broad marine distribution. These species are also thought to have complex population structures. The Sakhalin sturgeon inhabits the Russian Far East and is believed to have a primarily marine life history. It is one of the least studied of the sturgeons and is also one of the most endangered, with spawning populations possibly reduced to a single river. As with the Caspian and European species reviewed above, these species would greatly benefit from studies of migration, movement and distribution so that appropriate management and recovery plans could be devised and implemented.

RESEARCH TECHNIQUES

Tagging and Marking

In fisheries science, the application of individually numbered or coded tags to fish prior to release is typically referred to as “tagging.” The term “marking,” while sometimes used in communications as a substitute for tagging, is typically used to reference batch or group “mark” applications. Subsequent recaptures of tagged fish will typically yield specific information regarding previous encounters with those same individual fish (specific release and recapture locations, dates, and individual fish measurements), whereas recaptures of marked fish will provide general information only regarding the entire mark group (date, location, etc.). If recapture rates are sufficiently high, capture-recapture data from tagging studies are very useful for fisheries stock assessment; these studies can provide information on population size, stock structure, movement rates, fishing/natural mortality and fish behaviour. Over the past several decades, sturgeon researchers have used a range of tag types and “marks” to identify movement and migration patterns, and to establish residency and range of species and stock groups.

<u>Considerations</u>
Sturgeon are long-lived animals; thus, tags or marks that can be positively identified many years following release should likely be considered for most research projects with objectives that include long-term data collection to determine movement, migration, and/or distribution.

Numbered or coded tags provide the opportunity to identify individual fish upon recapture, and thus compare any changes of capture locations over time. Multiple recaptures of individual fish (identified by unique tag number) over a period of several years can provide insights regarding movement, migration, and seasonal behaviour/residency when these data are pooled with other recapture data for a specific stock.

Although not always feasible, determination of the sex and maturity stage of individual sturgeon used in long-term tagging studies can provide greater insights regarding interpretation subsequent movement and migration patterns. All internal tag implants in the body cavity (typically electronic tags) should automatically include visual determination of sex and stage (Bruch et al. 2001); see Sex determination and stress in telemetry studies in the **Telemetry** section of this paper for additional gender-related considerations for tagging studies.

The use of uniquely identifiable tags can provide comparative growth and condition information for long-term studies with adequate sample sizes. Length data (i.e., fork length) collected during initial tag release events and again during subsequent recaptures can be used to calculate daily growth rates for individual fish (based on the number of days at large between the release and subsequent recapture events). Daily growth can be expanded to provide estimates of annual growth**,** which in turn can be pooled and averaged for size/age groups of fish; over time, these comparative data can provide insights regarding changes in overall stock growth rates and condition over time.

Marking

Sturgeon can be externally marked with traditional methods such as dye marking, tattoos, pigment implantation, or freeze branding. However, due to the nature of sturgeon skin, most of these marks cannot be clearly identified within several months or a year of application, and thus are not recommended for studies that present long-term recovery opportunities as they will become unidentifiable over time.

A common marking approach used by researchers, as either a primary or secondary mark (in conjunction with a numbered or coded tag), is scute removal. Scutes are a rather unique anatomical feature of sturgeon, and are one of the few body parts that can be removed (without significant impact to the fish) that will not grow back. Scute removal is typically accomplished with the use of a sharp, thin knife blade; the cut is made parallel to the wall of the body and directly alongside the bottom side of the scute. Most studies that use scute removals as an identifying mark will remove a combination of scutes from pre-determined locations on the sturgeon that translate into information such as location, year, and month. A scute removal schedule can be established and used to achieve this level of identification upon recapture. For example, the left lateral line of scutes can indicate year, and the right lateral line month; thus, the removal of the ninth scute on the left and the third scute on the right could indicate September 2003. The removal of a specific dorsal scute could indicate a specific location (bay, river, tributary). Scute removal may induce high levels of stress and some level of mortality and is not recommended for use on sturgeon populations that are critically endangered.

Other permanent marks that can be applied to sturgeon include barbel clipping and fin ray removal. Barbel removal is not a recommended marking technique due to the importance of barbels to sturgeon sensory physiology; for example, the removal of barbels for marking has been reported to reduce sturgeon fitness and increase mortality over time (Bordner et al. 1990). The total or partial removal of the lead pectoral fin ray has gained popularity and utility for sturgeon aging (fin ray cross sectioning) and can also be used for genetic analyses (fin tissue) and microchemistry analyses (fin ray composition analyses). The removal or clipping of a fin ray can also constitute a short-term (less than 5 years) mark, typically as a secondary mark to a tag

application. However, care should be taken to clip the fin ray beyond the articulated base (above the insertion point with the body wall) or mortality rates could increase (Kohlhorst 1979).

Tagging

Tag types for sturgeon fall into three major categories: telemetry, external, and internal (e.g. PIT) tags. The use of telemetry and the associated tag types (radio, acoustic, satellite) is presented in a dedicated section of this paper. External tags (attached to the outside of the sturgeon and visible upon recapture) are available in a range of materials and styles that vary based on how the tag is attached to the animal. PIT (passive integrated transponder) tags are small, individually coded tags that are injected into the body musculature or body cavity of sturgeon and are detected with a hand-held tag reader.

External tags

Tags that are attached to the outside of a sturgeon are typically attached to dorsal or lateral locations on the sturgeon with the intention to minimize the impact or influence of the tag (encourage natural behaviour) and maximize tag retention. Some external tags are applied with an application tool (such as “anchor” or “T” tags, that are applied with a “tagging gun”), while others may be attached by hand, sometimes with the use of an applicator or needle. Tag materials include plastic, PVC, nylon, and metal, and may be available in various colors to attract attention and/or assist with individual or batch identification. External tags are typically labelled with information that includes a single unique tag number, and may include contact information for tag reporting, such as an address or phone number. Retention rates for external tags can vary, but some can maintain retentions above 70% for up to 3 years (Rein et al. 1994). Some external tag applications do not provide the high levels of tag retention rates required for mark-recapture analyses.

Common external tags used for sturgeon include: the “monel” tag (metal tag that is usually clamped around the front or back of the dorsal fin, gill cover, or pectoral fin); the “disc” tag (a flat round plastic tag with a small hole in the center, typically attached to the base of the dorsal fin with stainless wire); the “anchor” or “T” tag (Plate 3), which is a length of small-diameter PVC tube with a “T” shaped plastic anchor at one end. The “cinch” tag (also known as a “loop” tag; see Photo Plate 4) is similar to a long anchor tag except that it is attached to the fish at both ends forming a loop.

Photo Plate 3. Illustration of a numbered “anchor” or “T-tag” attached to a white sturgeon at the base of the dorsal fin. *Photo: Fraser River Sturgeon Conservation Society.*

For sturgeon, popular attachment points for external tags are typically near the dorsal fin (either anterior or posterior of the fin, alongside the fin, or through the base of the fin). Other attachment points include the edge of the gill cover or pectoral fin (popular with monel or similar metal “clamp” tags). Some researchers have used dorsal scutes as an attachment point for externally attached electronic transmitters (radio or acoustic tags); a small hole is drilled through the scute with a hand-held drill, and a stainless steel wire is passed through this hole which is then secured to the external tag (RL&L 2000). Although the external attachment of transmitters has received negative reviews (due to a high rate of tag loss), the external attachment of conventional tags can serve some studies quite well, especially studies that do not require long-term recapture information.

Photo Plate 4. A recreational angler holds up a tagged juvenile white sturgeon, recaptured on the Fraser River near Chilliwack, BC, on 13 May 2004. This external "loop" tag (attached to the dorsal fin) identifies this fish as "Tag Number H104299," tagged and released on the Columbia River near Astoria, Oregon, on May 25, 1999. This fish travelled over 500 kms, mostly in the open Pacific Ocean, between the release and recapture locations. *Photo: Anthony Sprangers.*

Internal (PIT) tags

A popular and effective tag for sturgeon is the PIT tag, a small uniquely coded electronic tag that is applied internally via a hand-held syringe (Photo Plate 5). Long-term retention rates for PIT tags are typically above 95% (Rien et al. 1994; Ward 2000). Sturgeon researchers have typically used one of the following PIT tag insertion points: 1) body cavity; 2) base of pectoral fin; 3) base of dorsal fin (or between base of dorsal fin and lateral line); and 4) behind head plate (left or right of dorsal line). The position behind the head plate (Photo Plate 6) has gained popularity in recent years due to reports of tag loss from tags inserted in other positions, and also based on concerns regarding potential human consumption of tagged sturgeon (tags applied in the "head" area are less likely to be consumed, especially compared with tags applied in the dorsal/lateral location; Nelson et al. 2008). PIT tags used for sturgeon are typically 2 mm in diameter and 10-14 mm in length. Following application, there is no visible external indication that the fish has been tagged; the fish must be "scanned" with a hand-held PIT tag reader (scanner) to determine if the fish is tagged (Photo Plate 7).

The readers are typically battery powered, and display the tag number on a small screen. Tags can be detected with most hand-held tag readers from a distance up to about 20 cm, and the signal can be detected through water, flesh, etc. An audible "beep" is emitted by most readers when a tag is detected. PIT tag readers are also used to scan PIT tags prior to tag application (so that the tag number can be recorded), and, once the tag is inserted into a sturgeon, to confirm the active status of the tag and the number prior to release of the sturgeon. In the field, both released and recaptured tag numbers can be hand recorded on data sheets; they can also be stored in the memory of the reader and downloaded to a computer at a later time.

PIT tags can also be detected with PIT tag antennas that are built into passive underwater apparatus such as mats or a tube. When a PIT tagged sturgeon passes close to the mat or through the tube, the tag code is logged with time and date in the memory of a receiving unit

(connected by cable to the antenna apparatus or array) that is later downloaded. This application may be effective to gather recapture data for constricted locations where tagged sturgeon were forced to pass through a confined area. For some applications, remote PIT tag detection may provide information to calculate overall survival (Hewitt et al. 2010); however, without a secondary detection strategy to document the passage of non-tagged sturgeon (such as a video camera), the tag data alone will not allow sufficient data to conduct population estimates based on mark rates.

Considerations for PIT tags – PIT tags are typically more expensive (in the order of 5-10 times more expensive) per tag than most external tag types. However, PIT tags have high retention rates and PIT tag technology and equipment is supported by both the biological research industry and the animal/pet industry (PIT tags are used to identify domestic animals such as dogs and horses.) PIT tag information is transmitted from the tag by way of a specific radio frequency; both the tag and tag reader must be compatible and using the same frequency. Thus, when committing to a long-term research project that uses PIT tags, it is important to determine the long-term availability of both the tags and the compatible tag readers. Also, researchers should find out if any other sturgeon researchers that have worked on target stock or species have applied PIT tags to sturgeon in the past. If so, new studies that include PIT tag applications may want to consider using the same tag frequency so that previously tagged sturgeon can be identified.

Modelling

Beyond providing information on movement, the data gathered by tagging studies can provide information on other life-history aspects that are necessary to model population dynamics (such as growth, rate of natural mortality, and spawning periodicity). Using life-history traits to understand how populations may respond to perturbations such as harvest has been advocated as a useful approach to predicting extinction vulnerability and formulating management strategies (Musick 1999a; Dulvy et al. 2003). The high susceptibility of sturgeons to harvest-induced population decline and extinction is related to their life-history traits, such as slow growth, late reproductive maturation, infrequent spawning and moderate rates of natural mortality (Boreman 1997; Birstein et al. 1997).

A variety of modelling approaches have been used to gain an improved understanding of the population dynamics and status of sturgeon stocks. The majority of population dynamics models for sturgeon species can be classified as simulation models to evaluate the sensitivity of population productivity and growth rates to changes in the survival rates of different life stages, or to estimate maximum sustainable yield harvest rates (Beamesderfer et al. 1995; DeVore et al. 1995, 1999; Pine et al. 2001). Population dynamics models can be used to reconstruct unfished population abundance using known historical catches (Secor and Waldman 1999; Walters et al. 2006). Mark-recapture models have been used for parameterisation of population dynamics models in a number of cases, particularly for estimation of population abundance and survival rates (DeVore et al. 1995; Beamesderfer et al. 1995; Thuemler 1997; DeVore et al. 1999; Pine et al. 2001), but also for estimation of movement rates in spatially disaggregated models (Nelson et al. 2004; Walters et al. 2005, Whitlock and McAllister 2009). Information from marking and tagging experiments can also aid the design of subsequent surveys and the interpretation of the data collected. This is particularly relevant to Caspian Sea sturgeons as total allowable catch estimates are based upon stock assessments derived from trawl survey data.

In order to design a cost-effective and useful tagging study, practitioners should consider several aspects of experimental design. Foremost among these is possibly the sample size of tags needed to draw inferences from mark-recapture data and answer research questions of interest. For example, in the context of making inferences about temporal movement patterns

using archival tagging data, use of representative data sets (covering appropriate spatial and temporal scales) with a large number of reconstructed migrations (ideally 100+) has been recommended (Hunter el al 2005). Non-telemetry tagging studies (and other marking methods) should also aim to minimise tag loss and tagging related mortality and be done so that the tag reporting rate is known or estimable (Pollock et al. 1991; Martell and Walters 2002; Bacheler et al 2009). Where telemetry tags are not used, consideration should be given to the potential number of tags that are expected to be recovered (based on the number of tags deployed and the level of subsequent sampling effort to recover tags) and, if necessary, potential precision (for population estimates, etc.,) should be calculated. Where sampling effort to recover tags is not at the discretion of the experimenter, the expected reporting rate of recovered tags should also be taken into account when choosing an appropriate tag type and number of tags to deploy.

When a tagging study is conducted to test a specific experimental hypothesis, researchers should consider statistical power, and whether their sample size is adequate to detect the effect size of interest. The spatial and temporal distributions of sampling/tag deployment are further aspects of experimental design that warrant consideration. Depending on the context of the study, it might be desirable to try to stratify release and recapture effort by seasons and area across the known range of the population to minimise biases in estimated movement rates or migration routes that could result from uneven spatial or seasonal sampling. Further stratification by age or life-history stage may also be desirable (Pedersen et al. 2008). In the case of exploitation rate estimation, tagged fish should be representative of the exploited population, such that each exploitable fish is equally likely to be tagged (Walters and Martell 2004).

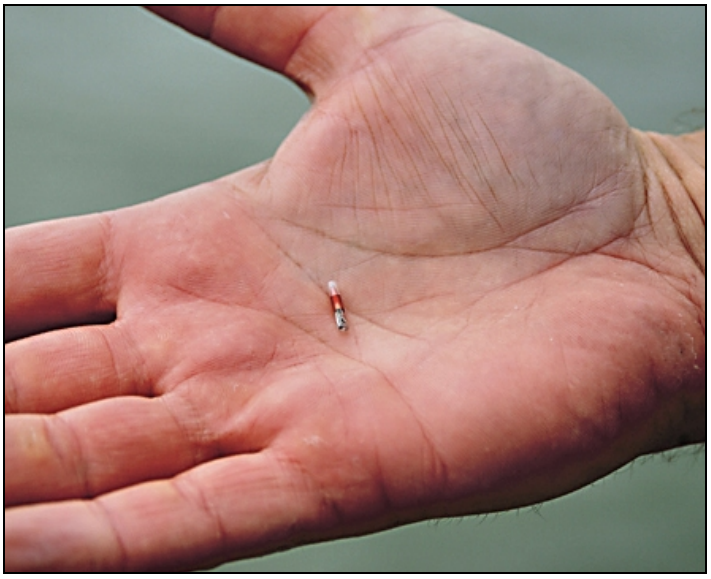

Photo Plate 5. A passive integrated transponder (PIT) tag consists of a coded microchip encapsulated in glass. PIT tag codes are typically 10-digit alpha numeric codes and are individually unique. This picture shows a typical PIT tag size used for sturgeon (2 mm in diameter and 12 mm long). *Photo: Fraser River Sturgeon Conservation Society.*

Photo Plate 6. Illustration of the preferred location of PIT tag application on a juvenile white sturgeon. The PIT tag is injected just beneath the skin, about 1 cm behind the head plate, on the left side of the dorsal scute line. *Photo: Fraser River Sturgeon Conservation Society.*

Photo Plate 7. Following capture, white sturgeon in the lower Fraser River, BC, are scanned by project volunteers with a hand-held PIT tag reader. This individual sturgeon may continue to provide credible and valuable recapture and growth information for decades. *Photo: Fraser River Sturgeon Conservation Society.*

Telemetry

The recent development and rapid advancement of electronic tagging technology has facilitated an explosion of research on sturgeon life history, generating powerful new insights into migratory behaviour, habitat use and demographic processes. Electronic tags also have the potential to overcome problems such as low recapture rates that plague typical conventional tagging experiments.

With conventional tags, recapture rates are typically low, and unknown reporting rates render estimation of mortality rates problematic (Hoenig et al.1998). Most tagged fish are never seen again, and there is therefore little prospect of the multiple resightings needed to establish migratory pathways. Electronic tags overcome this problem by either transmitting their identity to a passive receiver (which doesn't require recapture of the fish) or by archiving environmental data, including location, which may be recovered either when the data are transmitted at some pre-programmed point to a satellite or on return of the tag to the researcher. Although this latter mode requires recapture of the tagged fish, information between the time of release and recovery is archived by the tag such that a time series of locations can be constructed. In all cases, much more data are potentially generated per tag, giving researchers much sharper insight into their study questions: Electronic tags have been used to investigate many aspects of ecology and physiology including vertical and horizontal movement patterns, feeding and reproductive behaviour in relation to spatial movement, and habitat and metabolic rate (Nielsen et al. 2009). This is of course balanced by the high cost of electronic tags compared to conventional tags, but this initial expense is often more than offset by savings in the effort needed to apply and recover conventional tags.

Types of electronic tags

Electronic tags can be categorized by several characteristics. One distinction is whether tags transmit data in real-time to receivers (telemetry tags) or store data to internal memory for transmission at some later date (archival tag). Telemetry tags can be further differentiated by signal transmission mode: acoustic or radio. To date, telemetry tags have been most widely used in sturgeon research, although archival tags have been used with great success in studies of oceanic fish and marine birds.

Attachment of electronic tags

Telemetry tags are typically attached to sturgeon by way of surgical implant (internal application) or in conjunction with a harness or wire (external attachment). There has been a recent trend toward surgical implantation of radio and acoustic tags (see Photo Plates 8 and 9), although these tag types can also be attached externally (RL&L 2000). Additional information regarding tag attachment is presented in the following sections and associated references.

Photo Plate 8. In-field surgical procedure for the application of acoustic tags to white sturgeon in the lower Fraser River, B.C. Sturgeon held in custom sling while anaesthetic flushed into mouth and over gills. A small incision into the body cavity is made between the midline and the ventral row of scutes *Photo: LGL environmental research associates.*

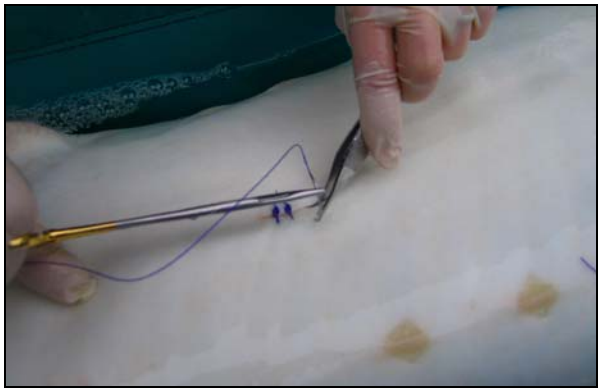

Photo Plate 9. Surgical application of an acoustic telemetry tag in a live white sturgeon in the lower Fraser River, BC. The acoustic tag is inserted through a small incision and into the body cavity (left photo). Sutures are applied across the incision prior to recovery and release of the sturgeon (right photo). *Photos: LGL environmental research associates.*

Acoustic tags
Acoustic tags transmit their identity, and possibly environmental data (e.g., temperature, depth, or even physiological measurements) via ultrasonic sound, which must be received by an appropriate hydrophone in the water within the range of the tag. Transmission is not affected by salinity per se, although density gradients due to salinity gradients, and sharp temperature gradients (thermoclines), can prevent detection of acoustic tags under certain conditions. Range of a given tag and hydrophone system is also influenced by ambient noise, the presence of sound-reflecting surfaces, entrained air bubbles, or suspended sediment.

Radio tags
Radio tags transmit their data by radio waves to a radio receiver. Radio and acoustic tags have similar capabilities and prices, but the signal transmission mode has important implications. Radio waves travel through both water and air, which means that the radio receiver doesn't need to be in the water, but could be in some safer location on shore, or in a moving vehicle such as an airplane. For mobile tracking, this can be very advantageous. Radio signals do not propagate far in salt water, however, limiting the utility of radio tags in studies of anadromous sturgeon where study questions involve the estuary or ocean.

Combined acoustic and radio tags (CART) combine both transmission modes, allowing radio receivers to be used in freshwater and acoustic receivers to be used in saltwater. Double tagging with both acoustic and radio tags is also feasible for sturgeon.

Archival tags
Archival tags record data to internal storage. Typical data include internal and ambient temperature, depth, light level, and, for some models, an estimate of location based on the time of sunrise and sunset. For tags that do not provide a location estimate, geolocation methods can be used to infer position from the tag's ambient light records and sea surface temperature (Sibert et al. 2003, Teo et al. 2004). Other sensors that can be included in archival tags include accelerometers and electromyograms for measuring swimming activity.

Pop-off archival tags (PAT; Photo Plate 9) transmit the archived data by radio to the ARGOS satellite system after releasing from the tagged animal at a pre-programmed time or when pre-programmed conditions are met (typically exceeding a critical depth or remaining at a constant depth for longer than a certain period, both indicating the death of the animal). There are two limitations of PAT tags. They must by applied externally to release, and attaching these relatively large tags to fish for long deployments is typically difficult, although as discussed below, sturgeon are good candidates for external tags due to their armouring (they do not appear to be subject to other fish attacking the tag, as is apparently common with pelagic species). The other limitation is that PAT tags must be in seawater to release from the fish, as the tag requires salt water to complete the circuit that burns through a wire, that when broken, allows the tag to release. Battery life limitations can prevent the tag from sending all of the archived data to the satellites, at least for some tags and longer deployments.

Regular (implantable) archival tags must be recovered from the tagged fish, but are not limited in their storage capacity by considerations of data transmission. Also, they can be implanted internally and, in principle, recovered surgically from live fish. In any case, the tagged sturgeon must be recaptured to recover the tag and its data. This normally daunting task can be made possible for sturgeon by double tagging with and acoustic or radio tag that can be used to locate the sturgeon when it returns to the spawning grounds.

<u>How have electronic tags been used?</u>
We searched the primary literature for sturgeon studies reporting the use of electronic tags, and found 49 relevant studies (summarized in Table 2). To date, the most frequent application of

electronic tagging has been to studies of habitat use and movement of wild sturgeon within rivers. A substantial fraction of these studies have identified the timing and location of spawning, a topic of obvious interest to those working on conservation of sturgeon. These studies have relied on both acoustic and radio tracking, often in combination, and typically have made use of mobile tracking to detect tagged sturgeon. A related type of study has been looking at the movement and habitat use of cultured sturgeon after release.

Photo Plate 10. Green sturgeon tagged with a pop-off archival (PAT) tag. *Photo: Dan Erickson (Oregon Department of Fish and Wildlife, Wildlife Conservation Society).*

Table 2. Summary of recent sturgeon studies that utilized telemetry technologies to acquire movement information, by species, electronic tag type, and tracking method.

Study Type	Species	Tag Type	Tracking Method	Citation
Habitat use and movements in rivers	*A. brevirostrum*	AC, RA	MT	Hall et al. 1991
	A. fulvescens	AC	MT	Caswell et al. 2003
	A. fulvescens	AC, RA	MT	Lallaman et al. 2008
	A. fulvescens	RA	MT	McKinley et al. 1998
	A. gueldenstaedtii	AC	FR, MT	Kynard et al. 2002
	A. medirostris	AC	FR	Heubline et al. 2009
	A. medirostris	AC, RA	FR, MT	Benson et al. 2007; Erickson and Webb, 2007
	A. medirostris	RA	FR, MT	Erickson et al. 2002
	A. oxyrinchus desotoi	AC, RA	MT	Fox et al. 2000
	A. oxyrinchus desotoi	RA	MT	Heise et al. 2004; Hightower et al. 2002; Foster and Clugston 1997
	A. stellatus	AC	FR, MT	Kynard et al. 2002
	A. transmontanus	AC	MT	Young et al. 2005
	A. transmontanus	AC	FR	Parsley et al. 2008
	A. transmontanus	AC, RA	FR, MT	Paramagian et al. 2001
	S. platorynchus	RA	MT	Curtis et al. 1997
Large-scale migration (includes marine)	*A. medirostris*	AC	FR	Lindley et al. 2008
	A. medirostris	PAT	AG	Erickson and Hightower 2007
	A. oxyrinchus desotoi	AC	FR	Sulak et al. 2009
	A. oxyrinchus desotoi	AC, RA, PAT	MT	Ross et al. 2009
	A. oxyrinchus desotoi	AC, PAT	MT	Edwards et al. 2007
	A. oxyrinchus desotoi	AC, RA, CART	MT	Rogillio et al. 2007
	A. oxyrinchus desotoi	AC, AR, CART	FR, MT	Edwards et al. 2003
	A. oxyrinchus desotoi	AC	FR, MT	Fox et al. 2002
	A. transmontanus	AC	FR	Welch et al. 2006
Movements and habitat use within estuaries	*A. medirostris*	AC	FR	Moser and Lindley 2007
	A. medirostris	AC	MT	Kelly et al. 2007
	A. oxyrinchus	AC	FR, MT	Hatin et al. 2002
	A. oxyrinchus desotoi	AC	MT	Harris et al. 2005
	A. sturio	AC	MT	Taverny et al. 2002
Behaviour of artificially-produced fish after release	*A. naccarii*	AC	MT	Bronzi et al. 2006
	A. oxyrinchus oxyrinchus	AC	FR, MT	Gessner et al. 2006
	A. sturio	AC	FR, MT	Gessner et al. 2006
	A. transmontanus	AC	FR	Neufeld and Rust 2009
	S. albus	AC	MT	Jordan et al. 2006
	S. albus	RA	MT	Snook et al. 2002
Passage through fish ladders	*A. brevirostrum*	RA	FR	Cooke et al. 2002
	A. transmontanus	CART	FR	Parsley et al. 2007
Habitat use and movements in lakes	*A. brevirostrum*	RA	MT	Collins et al. 2003
	A. fulvescens	RA	MT	Adams et al. 2006
Identifying spawning habitat	*A. brevirostrum*	AC	MT	Kieffer et al. 1996
	S. platorynchus	AC, AR	MT	Delonay et al. 2007
Dam operations (response)	*A. sinensis*	AC	FR, MT	Yang et al. 2006
	A. transmontanus	AC, EMG	MT	Geist et al. 2005
Survival (induced spawning)	*A. oxyrinchus desotoi*	AC	MT	Parkyn et al. 2006
Cultured fish survival	*A. fulvescens*	AC	FR, MT	Crossman et al. 2009
Demographic parameters	*A. oxyrinchus*	AC	FR, MT	Caron et al. 2002
Spawning success	*S. platorynchus*	AC, AR	MT	Holan et al. 2009
Habitat evaluation above barrier	*A. brevirostrum*	RA	MT	Finney et al. 2006
Basic life history	*A. brevirostrum*	CART	FR, MT	Kynard et al. 2009
Freshwater habitat, movement	*A. fulvescens*	RA	MT	Auer 1999

Tag Types: AC = Acoustic; RA = Radio; AR = Archival; PAT = Pop-off Archival; CART = Combined Acoustic and Radio; EMG = Electromyogram
Tracking Method: MT = Mobile Tracking; FR = Fixed Receivers; AG = Archival Geolocation

The second most frequent type of study has used electronic tags to investigate large-scale migrations, by which we mean movement of sturgeon among riverine, estuarine and marine waters. These studies have used all types of telemetry tags (except electromyogram tags) and tracking methods, and most have used acoustic tags, or a combination of acoustic and other tag types. The study of Lindley et al. (2008) is notable for its use of cross-shelf arrays of receivers to document annual migration of green sturgeon, which can cover more than 4000 kms per year. This was possible because the continental shelf off the west coast of North America is narrow, and a number of studies were underway using compatible tags and receivers, including the Census of Marine Life's Pacific Ocean Shelf Tracking (POST) program.

Movement and habitat-use studies in estuaries (n = 5) have relied on acoustic tags and mobile tracking, with the exception of the study of green sturgeon in Willapa Bay and the Columbia River estuary (Moser and Lindley 2007), which used arrays of fixed receivers, and a study of Atlantic sturgeon in the St. Lawrence River estuary that used mobile tracking and one fixed receiver (Hatin et al. 2002). Acoustic tags are needed to track movement in marine and estuarine waters. The combination of technologies is especially useful when mobile tracking is used to locate tagged sturgeon in freshwater, as surveys can be conducted at high speed in boats or aircraft.

The study by Holan et al. (2009) used a combination of archival tags, radio tags, and sophisticated data analysis to determine whether tagged individuals later spawned successfully. The radio tags were used mainly to relocate the shovelnose sturgeon (whose state of gonadal development had been determined) bearing the digital storage tags that recorded temperature and depth. The analysis involved fitting a switching model to the depth history of the sturgeon; spawning is indicated by a period of reduced depth variability. Tagging data, especially from archival tags, can be a rich source of information on behaviour that can be analyzed with appropriate models that connect behavioural modes to the tagging data (e.g., Jonsen et al. 2003, 2005, 2006).

Electronic tags have also been used to investigate behaviour of artificially-produced sturgeon after release (Bronzi et al. 2006; Neufeld and Rust 2009; Jordan et al. 2006; Snook et al. 2002), behaviour of sturgeon near potential fish passage impediments (Cooke et al. 2002; Parsley et al. 2007), experimental evaluation of habitat suitability (Finney et al. 2006), and to identify spawning habitat (Kieffer et al. 1996; Delonay et al. 2007). Geist et al. (2005) used both acoustic and electromyogram (EMG) tags to test the response of white sturgeon to changes in dam operations. EMG tags transmit radio pulses when muscles contract, allowing researchers to measure the physical activity of fish at finer scales than can be determined from tracking techniques that only provide coarse changes in position over time, or in flow fields where swimming speed in water may differ substantially from speed over ground.

Which technology to use?

The appropriate technology for a given study depends very much on the questions and situation of the study. Telemetry tags have similar capabilities and generate similar information, and the choice between them depends mainly on whether the sturgeon will be tracked in estuarine or marine environments. In this case, acoustic or combined acoustic-radio tags are required. In strictly freshwater settings, radio tags offer the most flexibility due to the efficient propagation of radio waves through water and air. This makes mobile tracking very efficient because receivers can be deployed in fast-moving boats or aircraft, allowing many stations or transects to be covered, compared to what could be done with an acoustic receiver.

Archival tags offer a fundamentally different sort of data. Rather than reporting the identity of the tags and perhaps some measurements from the tag's environment at that instant, archival tags record data intermittently throughout their deployment and acquisition of data is not reliant on

sampling by fisheries or the researcher. In this regard, archival tags can be a good option when little is known about a species, since information about spatial movements and habitat use will not be biased toward areas that are already known or well-sampled. PAT tags are optimal in this regard in that physical recovery of the tag is not necessary; however, one must know when the sturgeon will be in marine water to ensure that the tag can release successfully.

A key consideration in the design of tagging studies is the reporting rate of tags recovered by fishers to researchers. A relatively precise estimate of the tag reporting rate is important for estimation of mortality and exploitation rates (Latour et al. 2003; Pine et al. 2003). PAT or telemetry tags may actually be more cost effective in terms of the amount of data that is gained per dollar spent if conventional tag recovery and/or reporting rates are very low.

Developments are underway to merge the functions of telemetry and archival tags; an early example is the CHAT tag. This tag combines environmental sensor circuits and the ability to send and receive acoustic signals. The idea is to acoustically transmit the archived data to a receiver when the tag is within range of a receiver that transmits a signal to notify tags that it is nearby. In the “business card” model, each tag could receive and store data from other tags, creating an ad-hoc network of fish-born environmental sensors and fixed listening stations.

With respect to using tagging (simple internal or external) versus telemetry, there is a significant difference in terms of upfront costs of the different methods and there is a trade-off in terms of the data gathered. Simple internal and external tags may be less expensive, but they may require a high level of labour with respect to recapture. Electronic tags are more expensive and require some training in terms of data interpretation, but they can yield more information with less subsequent labour. The goals and objectives of a research project should help define which technology to use. For example, if the data gap being addressed for a marine-oriented species was the spawning periodicity of females, acoustic tags (with a long battery life) could be attached to a relatively small number of spawning females, and an array of receivers (positioned near the entrance of the natal freshwater river or stream, and near the presumed spawning area) could be established. The tagged sturgeon could be monitored over perhaps 1-2 spawning cycles, depending on the battery life of the tags and support for ongoing receiver deployment.

Data analysis

Electronic tags generate relatively new kinds of data, and methods for the analysis of these data are lagging behind the rapid development of the tags, and the increasing use of many tags. In the early studies, when tags were more expensive and their utility unproven, typical studies tagged a handful of animals. In this case, data arising from each tag could be presented separately and in full. Newer studies have tagged hundreds or even many thousands of fish (e.g., studies of riverine migration in Pacific salmonids), requiring statistical analyses to estimate demographic parameters or infer behaviours. Methods for analyzing the rich data streams from archival tags are relatively well-developed. Capture-recapture methods, such as the multi-strata robust design, would seem to be applicable to situations where sturgeon move among many different areas and experience different mortality rates according to their location or state (e.g., maturation status, sex), although several challenges must be solved. These include achieving large-enough sample sizes to reliably estimate the many parameters of such models, and dealing with the problem that detections of tagged sturgeon occur over the same time interval as the mortality process. Typical capture-recapture models assume that there is no mortality during the recapture process, which is essentially instantaneous.

Sex determination and stress in telemetry studies

Many biotelemetry studies have been conducted with juvenile and adult sturgeon without identification of sex and stage of maturity. In certain cases, such as identification of general

habitat use or spatial distributions of a population, it may not seem imperative to know the sex of individuals. However in many cases, such as when trying to understand why habitat is chosen or why migrations are initiated or ceased, identifying the sex and, in adult populations, the stage of maturity provides greater insight into the behaviour of the animal (Fox et al. 2000). It is often stated in the literature that sex and stage of maturity was not determined to reduce stress. It is critical to reduce stress, but trained personnel can determine sex and stage of maturity with very little increased handling time during transmitter application.

If transmitters are attached externally, ultrasonography or endoscopy may be used to determine sex and maturity (Vajhi et al. 2001; Kynard and Kieffer 2002; Moghim et al. 2002; Colombo et al. 2004; Chebanov and Chmyr 2005; Wildhaber et al. 2005; Divers et al. 2009). The primary limitation of these techniques is that it is often difficult to differentiate immature females from males and the stage of maturity in males cannot be determined as size of testicular lobe does not always confer stage of maturity. Ultrasound and endoscopy are useful tools in the identification of ripe females. When transmitters are implanted surgically, a sterilized otoscope or pen light may be used to visually determine sex and stage of maturity. A larger incision than the incision for insertion of the tag is not required under these circumstances. However, as in the case with ultrasound and endoscopy, the stage of maturity in males cannot be determined visually, though a small biopsy may be collected for histological analysis and stage of maturity determination. Measurement of circulating sex steroids may be used less invasively to determine sex and stage of maturity (Ceapa et al. 2002; Webb et al. 2002; Malekzadeh Viayeh et al. 2007; Craig et al. 2009; Webb and Doroshov, submitted). Under ideal circumstances, the misclassification rates of assigning sex and maturity in individuals to classes of maturity using plasma steroid concentrations would be determined for each species. However, when classification functions derived for white sturgeon to predict sex and stage of maturity (Webb et al., 2002) were applied to a small number of lake sturgeon comparable classification rates were found (Craig et al., 2009). Special consideration for the use of this tool should be made in populations that may be exposed to environmental contaminants (see Webb and Doroshov, submitted).

Less is known about the neuroendocrine control of the stress response and roles of allostasis and hormesis in chondrosteans compared to teleosts (see Schreck 2010). However, the cortisol response has been described in several sturgeon species in response to a stressor (e.g. Barton et al. 2000; Belanger et al. 2001; Bayunova et al. 2002; Lankford et al. 2003), and cortisol has been identified as the primary glucocorticoid in pallid sturgeon (Webb et al. 2007). Plasma cortisol concentrations (basal and stressed) in sturgeon vary by species (Barton et al. 2000; Webb et al. 2007), and variation in plasma cortisol concentrations may also be influenced by time of day, age, size, season, temperature, and capture and sampling techniques (e.g., Cataldi et al. 1998; Di Marco et al. 1999; Belanger et al. 2001; Lankford et al. 2003). It is essential to reduce stress (i.e., air exposure, handling time, etc.) during external attachment or surgical implantation of transmitters. Guidelines for the reduction of stress in capture and handling fish are provided in Kelsch and Shields (1996).

Genetics

Applying genetic techniques allows a researcher to understand the movements of sturgeons on a large scale and through evolutionary time. One of the most important questions that can be addressed using genetics is that of where an individual animal reproduces. As a first step in answering this question, the researcher must identify the reproductively isolated populations or stocks of a sturgeon species through genetic analysis. By knowing the number of distinct populations or stocks, a scheme can be created for protecting the species as a whole by ensuring that individual populations persist and the evolutionary and ecological potential of a species is preserved. Protecting multiple populations also can serve to buffer against extinction due to environmental change. Sturgeons are thought to return to their natal river to reproduce

and it is this behaviour that creates genetic structure and separate populations, although for some species there is admittedly little genetic data to evaluate natal philopatry. It is unlikely, on the timescale of interest to managers, that animals from one river system would replace those in another if an individual population were to go extinct so it is important to be able to minimize the chances of individual population extinction.

While information on the location of reproduction can be obtained through tagging studies, this approach does not answer the question of whether the animal effectively breeds in an area. Evidence of spawning can be gathered through biochemical means (e.g. measuring hormone levels or gonadal development) or specifically designed tagging studies (see the telemetry section) but only genetics is useful for identifying whether the individual actually contributes to the next generation. It also can be easier and less costly to use genetics to track breeding location. As described below, once the overall genetic structure of a species is characterized, it can be fairly straightforward to identify the population origin of any individual at any location.

Some of the fundamental questions that can be addressed using genetics include:

- How many populations exist within a species? Where do individuals from these populations breed and feed?
- How will an extractive activity such as fishing impact individual populations?
- Does a specific area in the ocean or in an estuary include individuals from a single population or multiple populations and if the latter, which ones?
- Do two or more populations exchange individuals?

Ideally, a good genetics study will begin with comprehensive sampling of all potential spawning populations. For some sturgeons (e.g. shovelnose, pallid, white, possibly Russian), multiple spawning populations may exist within a single river system. Population differentiation can be caused by differences in timing or geographic location of spawning and can occur in the absence of any physical barriers separating populations. The samples taken from each population should ideally have corresponding information about the relative age of the animals (larvae, juvenile, adult) and the spawning stage if an adult, although the latter is not essential. Information on life stage of the sample becomes especially important when sampling is conducted in lower reaches of the river and in estuaries because individuals can congregate in estuaries and coastal environments that are not in close proximity to their natal river of origin.

Sequencing of mitochondrial DNA (mtDNA) is one of the easiest genetic techniques to use for studying movement, distribution and stock/population structure. It has been applied in numerous studies (Grunwald et al. 2008; Wrigin et al. 2005; Doukakis et al. 2005). One or several rapidly evolving gene segments (e.g. control region, cytochrome b) are usually studied, but sequencing of the whole mitochondrial genome is now possible. The utility of the latter is debatable given that most of the variation exists within the control region segment. Methodologies for obtaining and working with the mtDNA from sturgeons are well established and can be conducted with ease. The mtDNA cytochrome b and control region also are useful in differentiating among species (Mugue et al. 2008; Birstein et al. 1998, 2005), so researchers working in areas where multiple sturgeon species coexist can conduct species identification using mtDNA. Methods such as sequencing or Restriction Fragment Length Polymorphism (RFLP) can be used to study population structure. The caveat in using mtDNA is that it tracks only the maternal lineage; this is an especially important consideration in cases where species hybridization and/or sex-specific dispersal may occur.

With respect to delineating stock structure, one of the best examples of the utility of mtDNA comes from the east coast of North America. The Atlantic sturgeon has been particularly well studied and this work has shown fine-scale population structure and spawning site fidelity (Grunwald et al. 2008). The data generated from this study have been used in developing

schemes of protection at the population level under the US Endangered Species Act. These data are further useful for attributing population origin to individuals captured in the ocean. Given that tagging studies are revealing large scale oceanic movements at significant distances from natal rivers, this is a particularly important application because fisheries operating at considerable distances from a natal river could be impacting that population. For example, Atlantic sturgeon sampled off of the New York Bight were found to consist of individuals breeding in southeastern US rivers (Waldman et al. 1996)

Microsatellites are increasingly being used to study population structure in sturgeons. Unlike mtDNA, microsatellites are biparentally inherited and genetic studies using these markers would not be biased by sex-specific differences in movements. In addition, microsatellites are highly polymorphic and may reveal population structure on a finer scale than even mtDNA control region data. However, there is less ease in terms of applying this technique across species (using techniques developed for one species on another species) and species-specific marker development is sometimes necessary. Complications can arise in using microsatellites for polyploid sturgeons (i.e., species with multiple genome copies), as some species may possess eight or twelve genome copies. If found to conform to Mendelian patterns of inheritance, however, microsatellites present in multiple copies may be treated as dominant markers (Rodzen and May 2002; Rodzen et al. 2004) and used to examine population structure. General concerns about microsatellites also have been raised by many authors (see Hauser and Seeb 2008). Despite the drawbacks, microsatellites are the current marker of choice for a researcher interested in population structure. Adriatic, Atlantic, green, lake, and white sturgeon have been the most well studied in terms of the application of this marker but Caspian Sea and Chinese species are becoming the subject of microsatellite investigations.

Microsatellites have been particularly useful in characterizing the marine distribution of green sturgeons and these studies, along with those on non-marine oriented sturgeons (white, shortnose; see Rodzen and May 2002; Rodzen et al. 2004) have pushed the boundaries of understanding the application of microsatellites to polyploid sturgeons. Within the green sturgeon range, two distinct populations have been identified using genetics, corresponding to northern and southern stock (Israel et al. 2009). The data generated in this study were then used as the basis for examining the origin (i.e., northern or southern distinct population segment) of individuals captured in estuaries. Individuals from the different population segments often mix in estuary areas and individuals do not always aggregate only in the estuary where they reproduce. Thus, estuarine populations represent mixed stocks. A further application of microsatellites in green sturgeon has been to estimate river-specific population abundance (Israel and May 2010). Microsatellites have been used to characterize the population structure of Atlantic sturgeon, to design a scheme of distinct population segments, and to characterize mixed stock fisheries (Atlantic Sturgeon Status Review Team 2007). Regarding the latter, microsatellite analysis revealed that Atlantic sturgeons captured in US waters off of Virginia and North Carolina originated from stock as far north as Canada and consisted to a large extent of animals originating in the Hudson and Delaware Rivers (Laney et al. 2007).

Many studies use both mtDNA and microsatellite markers to study population structure. One interesting application of this combined approach, which also used 4 single-nucleotide polymorphisms (SNPs), is the study of the historical distribution of European and Atlantic sturgeons. Application of these markers to archived and historic specimens revealed that Atlantic sturgeon (A. oxyrinchus) colonized an area in the Baltic Sea that was formerly thought to only be inhabited by European sturgeon (*A. sturio*; Tiedemann et al. 2006; Gessner et al. 2007). This work not only revised previous assumptions about species distribution, but also allowed restoration efforts to move forward in areas of Europe where sturgeons have been extirpated. Similar applications are ongoing to understand the former distribution of these sturgeons throughout Europe.

Emerging approaches that are being used for many other fishes include single-copy nuclear genes and SNPs (Hauser and Seeb 2008). The application of these approaches to sturgeon has been limited because of the possible complications associated with polyploidy and the relatively new development of these methodologies. However, current studies using these techniques are showing promise and may very well be useful in the near future. Experimentation is ongoing with development of SNPs in lake sturgeon, some species of Eurasian sturgeons and some southwestern US species. Once developed, SNPs will offer additional power in determining population structure and movement.

There are many different analytical tools in the field of population genetics that can be used to examine movements of sturgeon. Measures of genetic differentiation such as genetic distance, F-statistics, analysis of molecular variance (AMOVA), and exact tests can be employed to identify distinct sturgeon populations and measure gene flow between them. These methods are most useful when samples can be obtained from spawning adults or newly hatched larvae in a natal river, where a researcher can be assured that the individuals sampled belong to a particular spawning population. When sampling is conducted in a region of potential mixing between populations (lower river, lake, estuary, ocean, or sea), the origin of each individual examined is unknown and other methods are necessary to examine population structure. A powerful technique called population assignment testing can be used with microsatellite or SNP markers to identify the population of origin of individual sturgeon in an area of potential mixing. There are several types of population assignment tests but they all exploit differences in allele frequencies between populations to assign individuals to their natal population. The software program STRUCTURE (Pritchard et al. 2000) may be particularly applicable to sturgeon studies as it can accommodate polyploid microsatellite data. In addition to identifying the populations contributing to a mixed stock (as in Israel et al. 2009 cited above), population assignment tests can be used to evaluate individual dispersal behaviour. Drauch et al. (2008) used the assignment program GENECLASS2 (Paetkau et al. 2004) to identify two migrants originating from other river systems in the remnant lake sturgeon population in the White River, Indiana. Finally, population assignment tests might be used to study population structure at varying hierarchical scales. Welsh et al. (2008) used STRUCTURE to examine groups of related lake sturgeon populations in the Great Lakes basin.

Microchemistry

Differences in trace elemental profiles between habitats or bodies of water can be exploited to learn more about the migratory behaviour of fishes. Gradients in elements such as Sr, Ba, Ca, Mg, S, and B exist in regions of different salinities, temperatures, and bedrock influences (Coutant 1990). These elements are incorporated in minute quantities into the calcified structures of fishes, such as otoliths, fin rays or spines, bones, and scales (Coutant 1990). Differences in the presence or concentrations of trace elements among aquatic habitats create elemental “fingerprints” on calcified structures that can be used to determine where a particular individual originated (i.e., Mulligan et al. 1987; Warner et al. 2005; Clarke et al. 2007). This information may be used to detect stock structure, particularly in species where individuals from different populations mix during non-reproductive times, as has been done with some shell-forming invertebrates (e.g. Becker et al. 2007).

Otoliths are used most often in microchemical analyses of fishes since, unlike scales or skeletal bones, there is no potential for resorption or remodelling of this structure (Campana and Thorrold 2001). Although fin rays have the potential for remodelling, several researchers have shown the stability of elemental signatures in fin rays over time, suggesting they are stable structures appropriate for use in microchemical analyses (Veinott and Evans, 1999; Clarke et al. 2007).

One advantage of otoliths and fin rays is that changes in elemental composition between regions of incremental growth may be used to reconstruct patterns of movement in these fishes over time (e.g. Secor and Picolli 1996). Most work to date has focused on otoliths, although conducting microchemical analyses on fin rays holds much promise for long-lived species such as sturgeons. Microchemical analysis of non-lethally collected fin rays has the potential to reveal age or stage-specific movement behaviour or habitat preferences in threatened or endangered sturgeon species, where otolith collection is infeasible. In a study of Arctic grayling, Clarke et al. (2007) found that deposition of the elements Sr and Ba was highly correlated in both fin rays and otoliths, suggesting fin rays may have equal utility as otoliths in studies of fish movements.

Microchemical analysis has several advantages over other techniques traditionally used to examine movement behaviour in fishes. Tagging studies may only examine certain life stages, often are characterized by unknown levels of tag shedding, and may be time intensive and expensive to implement (Veinott and Evans 1999). Recapture rates often are low and the time to recapture may be very long, decreasing the informativeness of mark-recapture studies (Veinott et al. 1999; Elsdon and Gillanders 2003). The use of radio tracking or acoustic tags may provide more information than mark-recapture studies, but also are expensive to implement, whereas every fish may have a natural microchemical "tag." Battery life of a telemetry tag may allow only a small proportion of an individual's lifespan to be examined and often only a small number of individuals can be evaluated (Veinott et al. 1999). Low sample size may be a confounding factor in species with habitat preferences which may differ based on sex, age, or life stage. Whereas tracking studies only examine an individual's current habitat use, elemental signatures in bony structures have the potential to provide information on an individual's history of habitat use (Swearer et al. 1999; Veinott et al. 1999).

Application to sturgeon movement

Applications of microchemical techniques to understanding sturgeon movements have been limited to this point, focused primarily on examining changes in marine and freshwater habitat use over the lifetime of an individual. Veinott and Evans (1999) confirmed that fin rays were useful tools for examining sturgeon movements, as these authors did not detect changes in chemical composition due to bone remodelling or fin ray resorption over time in individual white sturgeon. They also showed a significant correlation in the deposition of many trace elements between fin rays within individuals over time (Veinott and Evans 1999), suggesting that deposition occurs in a predictable way. Since then, several researchers have exploited predictable differences in Sr:Ca ratios between freshwater and marine environments to examine migration of various life stages of sturgeon from freshwater to marine habitats. Veinott et al. (1999) found that ~10% of lower Fraser River white sturgeon subadults between ages 1-15 showed Sr:Ca ratios that were consistent with migration into the marine environment, although these movements did not appear to be seasonal or periodic. Intermediate concentrations of Sr:Ca ratios in fin rays of 58% of Fraser River adult white sturgeon examined were suggestive of estuary use at this life stage (Veinott et al. 1999). Sr:Ca ratios in both otoliths and fin rays were used to detect freshwater to saline migrations of subadult and adult Russian sturgeon (Arai and Miyazaki 2001; Arai et al. 2002). Some individuals were characterized by a single movement into the Caspian Sea (from freshwater), while other adults had patterns consistent with diadramous movements between freshwater and seawater (Arai and Miyazaki 2001; Arai et al. 2002). Allen et al. (2009) used Sr:Ca, Ba:Ca, and Sr:Ba ratios to evaluate the age of marine entry of subadult green sturgeon. They also conducted *ex situ* experiments to evaluate whether elemental deposition of Sr, Ba, and Ca in green sturgeon fin rays was proportional to environmental concentrations of these elements in freshwater and seawater environments. Allen et al. (2009) confirmed that ambient ratios of elements in freshwater and saltwater were nearly identical (Sr:Ca) or proportional (Ba:Ca; Sr:Ba) to the ratios found in fin rays of individuals held in freshwater or saltwater, respectively (but see Warner et al. 2005). In

examining wild fish, Allen et al. (2009) determined that green sturgeon subadults enter brackish estuary habitat between 0.5 and 1.5 years of age, and make their first migration into marine habitat between 2.5-3.5 years of age. They found that utilizing both Ba:Ca and Sr:Ca ratios aided in interpretation of more complex environmental histories involving transitions between freshwater, brackish estuary, and marine habitats (Allen et al. 2009). Although not the goal of these movement studies, some local differences in elemental concentrations (Veinott et al. 1999; Allen et al. 2009) suggested the potential for elemental “fingerprinting” in stock composition analysis for sturgeon.

Future research

Microchemistry techniques might be applied to resolve many uncertainties regarding sturgeon movements and habitat use. Otolith microchemistry may continue to have utility in sturgeon populations that still sustain harvest, as these structures might be removed from fish harvested by anglers or commercial fishers. However, the ability to non-lethally sample and analyze trace elemental deposition in fin rays make this technique particularly valuable for use in endangered or vulnerable sturgeon species. Although there are some uncertainties associated with deriving age estimates from sturgeon fin rays (Rien and Beamesderfer 1994; Jackson et al. 2007), the ability to examine habitat preferences and movement patterns of approximate age classes will be very useful in enhancing our understanding of sturgeon life history, particularly for those species with access to numerous and complex habitat types. Of particular interest would be the identification of important nursery or rearing habitats for early life stages of sturgeons, as this is unknown for many species. One possible use of elemental “fingerprinting” would be in examining spawning site fidelity in sturgeon. Although homing to natal spawning grounds has been assumed for many species, the long generation times of wild sturgeon have to date, precluded direct confirmation through tagging studies. Population genetic data for several species (Israel et al. 2004; Grunwald et al. 2008; Welsh et al. 2008) show genetic structure between spawning populations, which suggests that sturgeon do exhibit homing behaviour. However, elemental profiles in the core of fin rays of spawning adults might be compared to ambient elemental profiles in spawning habitats, which could confirm the hypothesis that the adults returning to spawn in a particular stream or river originated from there as well. Before these types of analyses are attempted, however, experimental work must establish that larval residency time in natal rivers is long enough for the incorporation of ambient elements in detectable concentrations. Also, it will be important to establish whether trace elements detected in otoliths and fin rays are consistently represented proportionally to ambient trace elements. In a study of marine larval fishes, Warner et al. (2005) found that only one of 12 elements examined showed a similar correlation between ambient concentration and otolith deposition in an open-sea environment. The findings of Allen et al. (2009) of a proportional relationship between fin ray trace element concentration in green sturgeon and ambient water concentration might have been due to the coarse scale (freshwater vs. saltwater) at which environmental differences were examined.

Elemental profiling might be paired with population genetic analysis to examine the composition of mixed sturgeon stocks, as levels of genetic differentiation as well as differences in elemental “fingerprints” might be used to assign individuals to their population of origin. Examination of differences in elemental profiles within and among river systems will indicate the resolution one might expect in making these population assignments with microchemical methods. Differences in population assignments made by genetic and microchemical methods would raise interesting questions regarding gene flow, homing behaviour, and environmental chemistry.

In that some toxic elements are deposited in calcified structures (Veinott and Evans 1999), microchemical methods might also be used to examine exposure to contaminants. Throughout their Holoarctic distribution, sturgeon inhabit degraded ecosystems often polluted with various toxicants (Foster et al. 2001; Anan et al. 2005; Cloern et al. 2006; Limburg and Waldman 2009).

Microchemical techniques can be used to identify toxic elements such as Pb or Cd to which an individual might have been exposed at a particular life-history stage. These data might be used to pinpoint sources of potentially harmful contamination that may be deleteriously affecting a particular population(s) (Coutant 1990; but see Secor et al. 2001).

Microchemical techniques have the potential to provide a great deal of information about sturgeon movement and life history. However, interpretation of elemental profiles in fish bony structures is dependent on an accurate understanding of the factors that influence element deposition. Additional work to ascertain the influence of water temperature, salinity, and the interaction between these parameters on element deposition in sturgeon otoliths and fin rays must be conducted to avoid misinterpretation of elemental profiles (Thresher 1999; Secor and Rooker 2000; Elsdon and Gillanders 2003). In addition, ontogenetic changes in element deposition in otoliths have been documented in other species (e.g. Fowler et al. 1995) and these could be quite confounding when reconstructing historical movements and habitat preferences of sturgeon and other long-lived fishes. Diet, too, may affect element deposition in otoliths and fin rays. We also must determine how residency time in a particular habitat affects element deposition (Elsdon and Gillanders 2003). Sturgeon are capable of fairly rapid movements between habitat types (Hatin et al. 2002; Welch et al. 2006; Hublein et al. 2009) and it is uncertain if these movements would be represented accurately in otolith or pectoral fin ray elemental “fingerprints.” Also, it will be important to characterize the rate at which elemental profiles within particular locations vary, as high rates of natural or anthropogenically induced environmental change may reduce our ability to accurately reconstruct the movement of individuals over longer timeframes using otoliths and fin rays (Campana et al. 2000). Before microchemical techniques are applied more widely to learning about sturgeon movements and habitat preferences, we need to first take the time to address these uncertainties so that we can be certain of obtaining the most accurate information possible.

Observational Technologies

Sturgeon can occupy marine environments or large, deep and typically turbid river systems where direct visual observation of behaviour, movement, or habitat use is difficult and often impossible. Consequently, until recently, what little was known about these attributes of sturgeon ecology were based on anecdotal observations or inferences drawn from capture and tagging studies. In the last two decades, substantial advances in remote sensing technologies have provided researchers with a greater variety of tools that allow direct observation of sturgeon behaviour and habitat use. These technologies can generally be grouped into two categories: those that use underwater cameras to provide light-based images and those that rely on sound waves to produce sonic-based images. Each of these observational categories and their applicability for use in studying sturgeon behaviour and habitat use is discussed below. Although most of the applications encountered in the reviewed literature were used for the study of sturgeon in freshwater systems, in many instances they also have applicability for the study of sturgeon and their habitats in marine and estuarine environments.

Underwater Photography

The use of underwater photography as a tool to examine sturgeon behaviour has only recently begun to be explored. Advantages of using underwater cameras are the ability to directly observe fish in their natural habitats and for some sturgeon species, the absence of any apparent avoidance behaviour of underwater cameras and lights. Disadvantages include limited use in aquatic environments with low water clarity and difficulties in long-term monitoring of fish that are engaged in active feeding or large-scale movements.

Obtaining underwater footage has been facilitated in recent years through the development of small submersible Remote Operated Vehicles (ROVs) and technological advances in low light digital and video cameras. Several ROVs are presently on the market with a variety of standard options or custom configurations. ROVs have been used in freshwater applications to examine the real-time effects of hydroelectric plant operations on sturgeon feeding behaviour (Golder 2009a). Underwater videography using ROVs has been employed for several years in the upper Columbia River in Canada to document behaviour and habitat use by wild white sturgeon adults and by hatchery-reared and released juveniles (Hildebrand et al., 1999) as well as to document unusually large (approximately 60,000 fish) aggregations of sturgeon in the stilling basin below the spillways at Bonneville Dam (http://videos.oregonlive.com/oregonian/2008/05/sturgeon_ball.html). An ROV also was used to identify critical overwintering habitats for the endangered white sturgeon in the Nechako River, a tributary to the Fraser River in British Columbia, Canada (RL&L 1997).

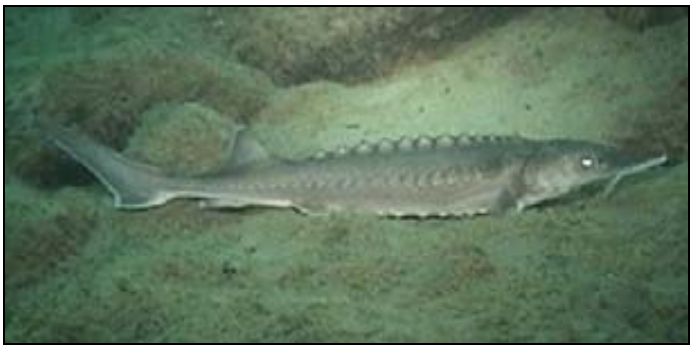

Photo Plate 11. Screen capture of hatchery-released juvenile white sturgeon in the Columbia River, British Columbia. *Photo: Golder Associates Ltd.*

Underwater video camera systems have been used to study overwintering habitats of shortnose sturgeon in the upper Kennebecasis River, New Brunswick, Canada (Xinhai et al, 2007), characterize lake sturgeon spawning and substrate preference in the Big Manistee River in Michigan (Chiotti et al., 2008), and identify white sturgeon spawning and early life-stage rearing substrates in the upper Columbia River in Canada (Golder 2009b). White sturgeon use of tailrace areas below existing hydroelectric dams in the Columbia River (Canada) was also examined using fixed video cameras and the information generated led to a plan to protect sturgeon during tailrace excavation (Golder 2003; Plate 3). White sturgeon mortality at the Brilliant Expansion power plant was reduced after video monitoring of the powerplant draft tubes and outlets illustrated behavioural responses to reduced flow (Golder 2009c). Cameras were used to provide real-time data on sturgeon presence during short duration forced outages of the powerplant; video footage recorded after the shut down were reviewed by the dam operators to assess if sturgeon have entered the draft tubes. Depending on the results, different start-up protocols were implemented to reduce risks to sturgeon.

Photo Plate 12. Screen capture of adult white sturgeon in the plungepool of Brilliant Dam (Kootenay River, British Columbia). *Photo: Golder Associates Ltd.*

Hydroacoustic Technologies

Fisheries acoustics has its origin in the marine environment. Over the last three decades, active hydroacoustic techniques have developed and proven to be a relatively easily applied method of unobtrusively evaluating fish populations in various freshwater and marine environments (Nealson and Tritt, 2003). The principles of hydroacoustic assessment of fish are provided by Burczynski (1979) and MacLennan and Simmonds (1992). Hydroacoustic techniques have a very high sampling power and do not affect fish health, behaviour, or the environment being monitored and have been successfully applied to a variety of fisheries evaluations, including both mobile and stationary assessments of aquatic systems.

Mobile survey hydroacoustic techniques are generally conducted by placing a hydroacoustic system in a boat, traversing predetermined transects in a body of water, and sampling fish and bottom characteristics (Nealson and Tritt, 2003). Sampled fish produce characteristic acoustic signals that can be processed using specialized software to produce estimates of fish density, abundance, behaviour, and size distribution. Sonars and sounders have been developed that can be used to characterize sea, lake and river bottoms and profiles of the upper layers of the ocean bottom. Advanced substrate classification analysis can be achieved using calibrated (scientific) echosounders and parametric or fuzzy-logic analysis of the acoustic data. Side-scan sonars can be used to derive detailed maps of the topography of an area by moving the sonar across and just above the bottom. Low frequency sonars have been used for continental shelf wide surveys while high frequency sonars are used for more detailed surveys of smaller areas. Various synthetic aperture sonars (SAS) are under active development (http://www.hydro-international.com/issues/articles/id920- Synthetic_Aperture_Sonar_Challenges.html). This technology has now become commercially viable and the technique is particularly well suited for towed or remotely operated underwater vehicles. SAS is expected to replace traditional side-scan sonars for many applications in the future.

Acoustic systems presently all have some sampling limitations with respect to their ability to resolve targets very close to boundaries, such as the bottom. Sturgeon are primarily benthic oriented and often in close proximity to the bottom. In addition, research describing sturgeon target strength, or the amount of acoustic energy reflected from the fish, is limited. To be

effectively detected, a fish must return target strength values greater than the surrounding background noise levels. The primary reflecting structure in most fish is the swim bladder, although bones, scutes and other body structures do provide some contribution (Jech and Horne 1998). The sturgeon swim bladder is the primary acoustic reflecting structure and is located just below the spine, some distance from the ventral surface of the fish. This may aid in detecting these fish on the bottom with a downlooking acoustic system, as there is some inherent separation between the upper surface of the bladder and the bottom itself due to fish morphology (Nealson and Tritt, 2003).

The following describes some specific applications of how hydroacoustics have been used as an observational technology in the study of sturgeons or their habitats.

Split Beam

The split-beam technique offers several advantages not available with other hydroacoustic techniques (Ehrenberg 1984). With split-beam target tracking, individual measured echoes may or may not be retained, depending on selection criteria that discriminates fish echoes from other echoes. Selected echoes are tracked to group all echoes from one individual fish. Mean target strength is calculated from the group of echoes from one fish, based on individual-echo target strength measurements made using the split-beam method. As with the other techniques, the signal can be echo integrated, to provide biomass estimates, if desired.

The advantages of split-beam techniques over other hydroacoustic techniques lay primarily in their improvements in location within the acoustic beam (and in resulting estimates of fish target strength), and in minimized susceptibility to noise. Given identical levels of bias in angular resolution, the split-beam system can locate fish within the beam with much greater resolution than single-beam, dual-beam, or sidescan systems (Traynor and Ehrenberg 1990; Ehrenberg and Torkelson 1996). The three-dimensional location of each fish is known for each ping (i.e., each ensonification). This improved spatial resolution results in improved target strength estimates. More accurate target strength estimates allow more accurate spatial expansions, resulting in more accurate estimates of fish abundance and/or biomass.

Split-beam hydroacoustics was used to detect shortnose sturgeon (*A. brevirostrum*) in the Delaware River (Nealson and Tritt, 2003). The study was conducted by measuring shortnose sturgeon target strength (using net captured fish) and the range from the bottom at which sturgeon could be acoustically-resolved. The authors concluded that shortnose sturgeon could be readily detected by a scientific split-beam hydroacoustic system using a combination of attributes (target strength, position relative to the bottom, and echo envelope shape). The demersal distribution of shortnose sturgeon is well-established and also appeared to be a useful metric for distinguishing these fish from other species.

Fixed-location, split-beam sonar technology was used successfully to identify adult lake sturgeon (*A. fulvescens*) as they moved upstream and downstream for spawning in the Sturgeon River, Michigan (Auer and Baker, 2007). Data collected included direction of movement, swimming speed, range from transducer, time and date of passage, and target strength. The lake sturgeon spawning population size was estimated and results showed that spilt-beam sonar can be applied to spawning assessments, without the stress of actually handling the large, pre-spawning fish.

Side Scan

Trawling and side scan sonar analysis was used to document an area of consistently high lake sturgeon density in Lake St. Clair near the St. Clair River delta (Thomas and Haas, 2002). Side scan sonar was used to estimate the abundance of lake sturgeon in a 255-ha section of the lake

and the data were used to enhance protection and habitat restoration efforts for lake sturgeon in this and other Great Lakes connecting waters.

On the Lower Missouri River, side-scan sonar data were collected in areas with the potential to contain shovelnose sturgeon (*Scaphirhynchus platorynchus*) and pallid sturgeon (*S. albus*) habitats (Reuter et al., 2008). Hydroacoustic data sets were collected at the reach scale (mean reach length, 2.4 kilometres) to include the immediate vicinity of a targeted sturgeon location as well as the full range of adjacent habitats. The images obtained were useful for visualizing channel substrate and detecting the presence of adult sturgeon.

The NOAA Chesapeake Bay Office (NCBO) used side-scan sonar to characterize the benthic habitats of Atlantic sturgeon (*A. oxyrinchus oxyrinchus*) in the James River, Virginia and identify habitat attributes that may be required to sustain viable sturgeon populations (http://www.thsoa.org/hy09/0512P_02.pdf). Areas of high frequency sturgeon occurrence (as determined through concurrent telemetry studies) were targeted using a side-scan sonar system. Numerous habitat features were identified and the data will be integrated with tracking data and habitat imagery to identify essential Atlantic sturgeon habitats.

Broadband

Experiments were conducted in the tidal Delaware River to determine if shortnose sturgeon could be detected by broadband sonar and, if so, to develop classifiers that could differentiate shortnose sturgeon from co-occurring fish species (Brundage and Jung, 2009). The false-positive rate of incorrect identification of a sturgeon was 16.5%. Notwithstanding this potential problem, the authors concluded that the results of this preliminary study were promising, and further investigations to improve classifier performance were warranted.

To assist in identifying potential lake sturgeon (*A. fulvescens*) habitat in the lower Bad River complex, a digital sonar system combined with a global positioning system was used to provide georeferenced data, and specialized sonar, bottom typing, GIS and statistical software to acoustically map bottom substrate types, locations and bathymetry (Cholwek et al., 2005). Ground truth data were developed from both petite Ponar bottom samples and associated acoustic data which were processed with bottom typing software. These data were used to produce substrate models and maps.

Fish finders

Many commercial and recreational sturgeon anglers use high quality hydroacoustic gear to locate sturgeon in estuarine and marine environments along the east and west coast of North America. A fish finder with multiple zoom settings, bottom lock, and split screens options are best (http://www.nwfish.com/Sturgeon/fish_finders_101.htm). Units that allow setting the window size for a specific number of feet while in bottom track, will provide higher signal resolution into that will show any irregularities on the bottom as well as fish holding right on the bottom. Sturgeon are very difficult to see when they are holding tight to a hard bottom such as bedrock or gravel, and are usually represented by a "spike" or "bump"

Figure 4. Examples of common representations of sturgeon on a fish finder. The image on the left depicts sturgeon when they are slightly suspended off of the bottom. The image on the right shows sturgeon when they are holding tight to the bottom.

DIDSON

In large rivers, a common approach for estimating population size of anadromous fish is to count upstream-migrating fish at a fixed site, using split-beam hydroacoustic equipment. A disadvantage of split-beam sonar in this application is that it generally does not provide sufficient information to allow species identification. A newer technology that can be used to count upstream migrants is the DIDSON™, a high-definition imaging sonar that provides near-video quality images. When used at a range of 5-10 m, video files clearly show body shape and swimming behaviour of individual fish. Split-beam gear provides more precise information about fish position, but DIDSON data are much easier to interpret, can be used to identify sturgeon to genus, and allow for on-screen measuring of fish lengths. Initial field trials showed potential for utilizing these technologies to determine habitat, identify sturgeon, and estimate densities (http://cars.desu.edu/aqua-sci/Abstracts/LB_et_al_acoustic.pdf). DIDSON™ has also been used to document white sturgeon presence and activity in the vicinity of power plant outlets (LGL and Golder, 2009).

Restoration and management of the Lower Missouri River (LMOR) to support recovery of the endangered pallid sturgeon required quantifying habitats to isolate specific habitats that may present bottlenecks to reproduction and survival (Jacobson et al., 2009). The approach taken involved intensive reach-scale hydroacoustic mapping using a suite of multi-beam bathymetry, Acoustic Doppler Current Profiler (ADCP), high-resolution side scan sonar, and DIDSON imagery combined with intensive telemetric tracking. This approach provided measures of habitat availability and selection variables at sub-meter to bedform scales, commensurate with the scale at which fish occupied these habitats. The DIDSON imagery indicated that during spawning, sturgeon occupy the lee slopes of dunes facing upstream (presumably to minimize energy expenditure) but episodically move out of dune fields and into deep, fast water over coarse substrate (presumably to release eggs and milt). This multi-scale, multi-instrument remote-sensing approach was essential for improving understanding of the linkages between life stages of a rare fish and its environment.

Future research

At present, observational techniques for sturgeon research have primarily been used to provide information on sturgeon behaviour and habitat use. These techniques enable researchers to directly observe sturgeon in their natural environment in a manner that does not influence their behaviour and have substantially increased our knowledge of how sturgeons interact with each other and their environment. Most importantly, these techniques have identified critical sturgeon habitats that in turn, have resulted in the protection of these habitats through direct management regulations. As these observational techniques are developed further, their potential uses will continue to expand. Direct observation of sturgeon behaviour at dams and existing fish passage facilities, either through video or sonic imagery can be used to provide information that may lead to the development of appropriate passage facilities for anadromous

sturgeon. As sonar techniques are refined and new algorithms to process and interpret digital signals are developed, these techniques have the potential to be used to identify individuals and provide large area assessments of sturgeon distribution and abundance.

DISCUSSION AND CONCLUSIONS

The marine life history and distribution of many sturgeons remains a mystery. However, new technologies developed over the past two decades have greatly increased our knowledge base regarding the life history of some sturgeons. Refined methods of analyzing DNA provide fine-scale information about genetic structure at the river basin or even sub-basin level. Improvements in telemetry equipment and observational techniques have allowed researchers to identify and characterize key habitats, from spawning sites at the upstream extent of migration to overwintering sites and migratory paths in coastal ocean waters. Telemetry and tagging studies have also shown that estuarine and marine sites used for foraging or overwintering may contain sturgeon from multiple populations. Tagging, genetic, and observational studies have revealed that sturgeon can travel considerable distances from their natal rivers, but that they generally inhabit coastal, shelf areas during their migrations. Also, individuals generally seem to return to natal rivers for reproduction. Taken as a whole, this information shows that sturgeons have complex life-history strategies that are reliant on specific habitats for different life stages. As such, to fully protecting a given species requires a comprehensive approach including research and conservation efforts in rivarian and marine environments.

Yet even with these technological advancements, there are few sturgeon species for which we have a fairly comprehensive understanding of respective life histories, particularly in the marine environment. For the 16 marine-oriented sturgeons, only two (green and Gulf sturgeon) have been well studied with respect to their marine distribution (see: Table 1; **Case Studies** section), and even these species would benefit from additional study of the habitat use by early life-history stages in marine environments. Current studies of Atlantic sturgeon in North America are now providing an understanding of the marine life history of this species. For the remaining species, many of which are Critically Endangered and some of which are still subject to commercial and recreational fishing, there is a pressing need to apply many of the tools discussed here. As illustrated in Table 2, only two species of sturgeon (Adriatic and European) outside of North America have benefited from telemetry studies and our review has indicated few other studies where other techniques have been applied to non-North American taxa. European and Asian species are clearly in need of studies that utilize the techniques described here. Thus, while we have numerous tools in our management toolbox, we are lagging in our application of these tools to study most sturgeon species.

The different tools reviewed here can be used individually or in combination to answer certain questions; we have highlighted several of these questions within the text of each section and in Table 3. As illustrated for many species, tagging, telemetry, genetics and sometimes observational techniques are often used in combination. Tagging and genetics are complementary tools for characterizing movement on an immediate and fine ecological scale (tagging) as well as an evolutionary scale (genetics). Tagging can also include multiple methods, with simple internal or external tags combined with electronic tags. Population and dynamics models, which are in some cases the vessel that is being driven by both conventional and telemetry-based tagging studies, may determine the core study design and elements such as number of tags deployed, level of recapture effort, etc. Microchemistry techniques may be used to complement movement studies and to add information on contaminants. Background research may be needed, however, to correctly apply and interpret microchemistry results, and additional work is required to validate some aspects of the approach. Observational techniques

are most useful in characterizing habitat uses within marine or freshwater environments, behaviour, and small scale movements, although recent advances has shown promise for use in assessing abundance and distribution as well.

Table 3. Schematic of the appropriate techniques for understanding different aspects of the biology of sturgeons. Applicable techniques are ranked 1-4 in order of utility with a rank of 1 being highest in terms of applicability.

	Genetics	External or PIT Tags	Electronic Tags	Microchemistry	Observational
Marine distribution	3	2	1	4	
Population structure	1	3	2	4	
Habitat characterization		4	2	2	1
In-river distribution		2	1	4	3
Population abundance/ modelling	2	1	3		3
Response to disturbance (e.g. dam or dredging operation)		3	2		1
Life-history characterization (e.g. spawning periodicity, age at maturity, growth)		2	1		

Tagging, telemetry studies, and photographic imagery can be useful ways to engage the public in research and raise awareness about the conservation status of sturgeons. Angler programs using tag and release can provide a means of engagement and collecting useful data on growth and movement. Telemetry studies, particularly those using satellite tags, can be accomplished through individual sponsorship of a tag and an individual fish. The movement data generated can be shared with the sponsoring individual and with the public through a dedicated website. Imagery of sturgeon behaviour in the wild is a powerful visual tool can be used to enhance public outreach programs and galvanize public support for protection and recovery. Such programs can also be useful for education purposes as they can be used by school groups studying fish movement and conservation.

Data collected by the methods described in this paper can provide useful insights into the life history of sturgeon stocks, and ultimately enable suitable management and conservation plans to be made and implemented. For example, information regarding temporal and spatial movements, migrations, and periodic residency, coupled with a general knowledge of life history events such as spawning and in-river overwintering, could provide a high level of confidence regarding the location and extent of proposed habitat protection for stock conservation. Genetic data on population structure is essential for identifying particularly vulnerable or endangered stocks and setting appropriate management actions to conserve them. Gaining an

understanding of life-stage-specific movement patterns and spatial distribution is also required to properly assess the impacts of anthropogenic activities such as fishing and gravel extraction and to specify management actions accordingly.

All of the techniques and applications discussed require a certain amount of specialized training. Given the widespread use of many techniques, however, especially for sturgeons, assistance can be readily obtained via contact with experienced researchers. Collaborative research is likely the best approach given that many techniques require up-front purchasing of expensive equipment and the learning curve can be steep. We hope that this review sparks interest and enthusiasm amongst researchers, especially those outside of North America, and provides some necessary tools and references for forming new studies. Sturgeon conservation would be greatly enhanced by increased knowledge of the marine distribution of these incredible imperilled creatures.

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