OPTIMAL HARVEST OF SHOVELNOSE STURGEON (*SCAPHIRHYNCHUS PLATORYNCHUS* RAFINESQUE) IN THE WABASH RIVER, ILLINOIS

by

AMY WHITEHEAD

(Under the Direction of James T. Peterson)

ABSTRACT

Shovelnose sturgeon (*Scaphirhynchus platorynchus* Rafinesque) are harvested in a modest caviar fishery from the Wabash River, Illinois. However, little is known about the status of the population or its ability to sustain a harvest. A Lefkovitch matrix model was constructed using available data to examine the population dynamics, while stochastic dynamic programming was utilized to determine the optimal harvest rate. Shovelnose sturgeon populations are susceptible to high juvenile and adult mortality, making them vulnerable to harvest. A maximum sustainable harvest rate of 2.7% of spawning adult females was predicted under two stock recruitment scenarios. This corresponded to low yields of roe, suggesting that a caviar harvest may not be economically viable at the optimum policy. Management policies should be conservative until more information is available on the population status of shovelnose sturgeon in the Wabash River.

INDEX WORDS: shovelnose sturgeon, optimal caviar harvest, Lefkovitch matrix model, stochastic dynamic programming, *Scaphirhynchus platorynchus*,

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INTRODUCTION

Shovelnose sturgeon (*Scaphirhynchus platorynchus* Rafinesque) are the smallest of the North American sturgeons and have been harvested sporadically since the end of the 19th century for both caviar and flesh. Population declines have been noted over most of their range due to a combination of habitat degradation and exploitation, and they are currently protected in some states. However, a small fishery still exists and this appears to be increasing in size due to the collapse of the sturgeon stocks in the Caspian Sea.

Shovelnose sturgeon in the Wabash River, Illinois, are currently being harvested as part of a commercial caviar fishery. The fishery targets large ripe-and-running females for the collection of roe, while males and unripe or immature females are returned to the river. However, there is little knowledge of their population dynamics. At present, there are no size restrictions on harvest, although the use of trammel nets is illegal (Illinois Administrative Code Section 830.40).

The Illinois Department of Natural Resources (DNR) began tagging shovelnose sturgeon in 2000 as part of their requirements under CITES legislation (Williamson, 2003; Rob Maher, Illinois DNR, *personal communication*). Three participants in the commercial fishery actively assist local DNR biologists with tagging and recapture efforts, while an additional 30 fishers assist by reporting the tag numbers of recaptured fish. Since 2000, greater than 3500 individuals have been tagged and released. However, the recapture rate to date has been poor (0.11%; Rob Maher, Illinois DNR, *personal communication*). As a result, the DNR are unable to

incorporate any information on population dynamics in the Wabash River into their management decisions.

In this thesis I attempt to address three major areas concerning the caviar harvest of shovelnose sturgeon in the Wabash River, Illinois. First, I look at the potential population dynamics of an unharvested population of shovelnose sturgeon using available data from the DNR mark-recapture program and the literature in a stage-based population projection matrix model. I examine the elasticity of the population growth rate predicted by this model to changes in the vital rates and use these to identify possible management strategies and areas of future research. Secondly, I address the idea of optimal harvest through stochastic dynamic programming. Finally, I examine techniques that could improve the efficiency of the current mark-recapture program, providing further information for management decisions.

LITERATURE REVIEW

Nomenclemature, Taxonomy & Distribution

Sturgeon belong in the Order Acipenseriformes, an ancient group of actinopterygians that also includes paddlefish (Bemis *et al.*, 1997). They have been present throughout the Holoarctic region since the Jurassic and there are currently 25 species (Bemis *et al.*, 1997). The genus *Scaphirhynchus* describes a group of freshwater sturgeon that are restricted to North America (Bailey & Cross, 1953).

The shovelnose sturgeon (*Scaphirhynchus platorynchus* Rafinesque) was first described in 1820 from specimens caught in the Ohio, Wabash and Cumberland Rivers (Rafinesque, 1820). It was originally placed in the genus *Accipenser*; however, this was revised in 1858 when Girard proposed the name *Scaphirhynchus platirhynchus* (Girard, 1858; cited in Bailey & Cross, 1953). The current nomenclemature (*Scaphirhynchus platorynchus*) was not adopted until 1952 (Cross & Moore, 1952). The shovelnose sturgeon is also known as the sand sturgeon, hackleback, switchtail and flathead sturgeon (Monson & Greenback, 1947; Keenlyne, 1997; Williamson, 2003). It is considered vulnerable within its entire range (Birstein, 1993; CITES, 2003; IUCN, 2003), although is not federally listed.

The genus *Scaphirhynchus* also contains two additional species; the pallid sturgeon (*S. albus* Forbes & Richardson) and the Alabama shovelnose sturgeon (*S. suttkusi* Williams & Clemmer). There is little genetic variation between the three species (Phelps & Allendorf, 1983; Simons *et al.*, 2001) and this is thought to be due to the slow rate of molecular evolution in sturgeons (Simons *et al.*, 2001). However, shovelnose x pallid hybrids are relatively common

(Carlson *et al.*, 1985; Phelps & Allendorf, 1983; Simons *et al.*, 2001) and this hybridization may have also contributed to the genetic similarities.

Historically shovelnose sturgeon were found throughout the Mississippi and Rio Grande Basins (Figure 2.1; Bailey & Cross, 1953; Sublette *et al.*, 1990). However, they have not been recorded in the Rio Grande since 1874 (Bailey & Cross, 1953). Shovelnose sturgeon have also been reported in the Tombigbee River, Alabama (Chermock, 1955), although it seems likely that these were probably Alabama shovelnose sturgeon. While shovelnose sturgeon may be locally common, their distribution within the Mississippi drainage has shrunk considerably over the past century and this has been attributed to changes in habitat quality and pressure from commercial fisheries (Bailey & Cross, 1953; Keenlyne, 1997; Simons *et al.*, 2001; Everett *et al.*, 2003; Williamson, 2003). Population density estimates for shovelnose sturgeon vary from 100 individuals per river kilometer (Christenson, 1975) to approximately 2500 per river kilometer (Schmulbach, 1975). It is thought that this is a function of river size and habitat quality (Keenlyne, 1997).

Morphology

The shovelnose sturgeon is the smallest of the sturgeons found in North America, rarely exceeding one meter in length and reaching a maximum weight of 4.5kg (Figure 2.2; Carlander, 1969; Keenlyne, 1997). The snout is extremely depressed, broad and shovel-like, and has fringed barbels (Jordan & Evermann, 1896; Bailey & Cross, 1953; Williams & Clemmer, 1991). A long filament extends from the upper lobe of the caudal fin and is thought to help individuals orientate in the current (Weisel, 1978). However, it is often abraded on older specimens. The dorsal surface is typically buff to brown, while the ventral surface is pale white to cream (Bailey & Cross, 1953). Injured individuals, including those with severed caudal and pectoral fins, and rostrums, have been noted in a number of studies. Possible causes include propeller strikes

and rubberbands (Helms, 1973; Christenson, 1975; Moos, 1978; Keenlyne, 1997; Gutreuter *et al.*, 2003; Parsons *et al.*, 2003). Moos (1978) also noted several individuals that had epidermal tissue covering one eye.

While shovelnose sturgeon are morphologically similar to both pallid and Alabama shovelnose sturgeon, a range of morphometric and meristic ratios have been calculated to help distinguish between the species (Bailey & Cross, 1953; Williams & Clemmer, 1991; Dryer & Sandvol, 1993, Keenlyne *et al.*, 1994). However, several studies have concluded that the Alabama shovelnose sturgeon is morphometrically identical to shovelnose sturgeon (Howell *et al.*, 1994; Bartolucci *et al.*, 1998) and this controversy has yet to be resolved.

Age, Growth & Natural Mortality

Sturgeon are slow growing and extremely long-lived compared to most teleost fishes (Tsepkin & Sokolov, 1971; Birstein, 1993; Beamesderfer & Farr, 1997; Berry, 2002). They are generally aged by examining annual growth rings on the first pectoral fin ray (Currier, 1951; Brennan & Caillet, 1989; Collins & Smith, 1996), although this method has been found to underestimate the age of white sturgeon (*Acipenser transmontanus*; Rien & Beamesderfer, 1994; Paragamian & Beamesderfer, 2003). Shovelnose sturgeon have been known to live for up to 43 years (Everett *et al.*, 2003), although the maximum age estimates for many populations are generally much lower and vary geographically (Helms, 1973; Hopfar & Peters, 1997; Morrow *et al.*, 1998; Quist & Guy, 1999; Everett *et al.*, 2003; Quist *et al.*, 2002). Considerable geographic differences have also been noted in their growth rates (Figure 2.3; Bailey & Cross, 1953; Zweiacker, 1967; Keenlyne, 1997; Quist & Guy, 1999; Everett *et al.*, 2003; Quist *et al.*, 2003; Quist *et al.*, 2002). Keenlyne (1997) compared data collected by Carlander (1969) and Helms (1973), and found that populations in the Missouri River had lower growth rates than those in the Mississippi River. In addition, shovelnose sturgeon in the Yellowstone River had higher growth rates than

those in the Missouri River and this was attributed to better quality habitat (Everett *et al.*, 2003). Sprague (1960) and Zweiacker (1967) both suggested that the growth of individuals almost ceased and their condition declined after the construction of dams on the upper Missouri River. Females also tend to grow faster and larger than males (Everett *et al.*, 2003).

Little research has been done on the natural mortality rates of shovelnose sturgeon. Farabee (1979) suggested that the total annual mortality rate in the Upper Mississippi River was nearly 60% but estimated that between 5% and 25% of this could be attributed to fishing mortality. A catch-curve analysis of the data collected by Everett *et al.* (2003) suggests that the annual natural mortality rate in the Yellowstone River is around 8.6% (Figure 2.4) and this is comparable to estimates of rates for other North American species of sturgeon, which range from 7% to 16% (Boreman, 1997; Pine *et al.*, 2001; Gross *et al.*, 2002). Lake sturgeon less than 40cm in total length (TL) are thought to have a higher risk of predation due to a lack of fullydeveloped scutes (Auer & Baker, 2002) and Pine *et al.* (2001) calculated that the juvenile mortality rate of Gulf of Mexico sturgeon (*A. oxyrinchus desotoi*) is approximately 25%. Larval sturgeon have a much higher natural mortality rate than adults (Boreman, 1997), although there are very few studies on wild specimens and none on shovelnose sturgeon. Pine *et al.* (2001) estimated that the annual egg-to-age1 mortality rate for Gulf of Mexico sturgeon was between 99.96% and 100%, while Gross *et al.* (2002) predicted similar mortality rates for shortnose, Atlantic and white sturgeon less than one year old (young-of-year; YOY).

Habitat & Movements

Shovelnose sturgeon are typically associated with deep, main channel habitats, however they are not uniformly distributed within the river channel (Carlson *et al.*, 1985; Schuldt *et al.*, 1986; Hurley *et al.*, 1987; Quist & Guy, 1999; Quist *et al.*, 1999). They tend to concentrate in channel-crossover habitats, where the main channel crosses from one lateral bend to another

(Quist & Guy, 1999, Quist *et al.*, 1999). When individuals are found on the outside of a bend, they tend to be associated with areas of low velocity, such as shallow pools downstream of sandbars or islands (Carlson *et al.*, 1985; Schuldt *et al.*, 1986; Quist & Guy, 1999; Quist *et al.*, 1999; Bramblett & White, 2001). A number of studies have found that shovelnose sturgeon are often found in deep scour pools downstream of wing and closing dams (Carlson *et al.*, 1985; Hurley *et al.*, 1987; Curtis *et al.*, 1997; Quist & Guy, 1999) and it is thought that these might act as replacements for sandbars which have been lost in many rivers due to alterations to the hydrologic regime (Hurley *et al.*, 1987). Little is known about the habitat requirements of larval shovelnose sturgeon, although it is thought that they predominantly occur in main channel habitats (Adams *et al.*, 2000).

Benthic water velocity appears to be important in the distribution of adult and juvenile shovelnose sturgeon and typically ranges from $0.2 - 0.5 \text{ ms}^{-1}$ (Hurley *et al.*, 1987; Curtis *et al.*, 1997, Quist *et al.*, 1999). They have been found in depths ranging from less than 1m to greater than 12m, and mean depth values tend to vary considerably between studies (1.2 - 5.3 m; Schuldt *et al.*, 1986; Curtis *et al.*, 1997; Quist *et al.*, 1999; Bramblett & White, 2001). This is probably a function of differences in available habitat between study sites and suggests that depth is not particularly important in structuring shovelnose sturgeon distributions. Shovelnose sturgeon occur most frequently over sand and gravel substrates (Hurley *et al.*, 1987; Curtis *et al.*, 1997; Quist *et al.*, 1999) and this is probably linked to the availability of invertebrate prey (Quist & Guy, 1999).

There is some evidence of seasonal differences in habitat use (Curtis *et al.*, 1997; Quist & Guy, 1999; Quist *et al.*, 1999). Shovelnose sturgeon in the Kansas River were found over coarser substrates in the spring and summer than during the winter months and this was linked to the abundance of invertebrates (Quist & Guy, 1999; Quist *et al.*, 1999). Edge habitats and tributaries are also more commonly frequented during the spring and this is probably related in part to spawning behavior (Hurley & Nickum, 1984).

Mark-recapture studies of shovelnose sturgeon have suggested that they tend to move randomly throughout the river and do not occupy a distinct home range area (Christenson, 1975; Moos, 1978). This movement is often multi-directional and typically occurs over short distances. The distance that an individual is recaptured from the release point tends to increase as time at large increases and this is probably a function of random movement patterns. Moos (1978) noted that most shovelnose sturgeon were found within 13.6 km of their release point after two years, although three individuals did move over 500 km downstream in a 9 to 24 month period. A number of authors have noted small upstream movements during the spring that are thought to coincide with spawning events, although this has not been confirmed to date (Helms, 1972; Bemis & Kynard, 1997; Keenlyne, 1997).

Food Habits & Feeding

Shovelnose sturgeon are opportunistic benthic invertivores (Modde & Schmulbach, 1977; Berry, 2002) that are well adapted to feed in fast-flowing water (Weisel, 1979). They detect prey with electroreceptors and tastebuds on the ventral surface of the rostrum (Weisel, 1978; Weisel, 1979). They also have been observed using the rostrum to disturb the sediment (Forbes & Richardson, 1920, cited in Moos, 1978). Shovelnose sturgeon feed by extending their fleshy lips and expanding the buccal cavity (Held, 1969; Weisel, 1979). This draws water and particles from the substrate into the mouth. The gill rakers have a high density of tastebuds and presumably help to filter out inedible particles (Weisel, 1979).

Shovelnose sturgeon feed on a wide range of prey, including aquatic and terrestrial invertebrates, and larval fish (Modde & Schmulbach, 1977; Berry, 2002). However, they predominantly eat aquatic invertebrates from up to 17 Orders (Hoopes, 1960; Carlander, 1969; Held, 1969; Modde & Schmulbach, 1977; Carlson *et al.*, 1985; Hopfar & Peters, 1997; Berry, 2002). The composition of their diet varies seasonally (Modde & Schmulbach, 1977) and tends

to reflect the availability of particular taxonomic groups. The average biomass of stomach contents tends to increase as the density of invertebrates in the drift increases. In comparison, higher discharge levels reduce stomach biomass and can alter the composition of the diet (Modde & Schmulbach, 1977). These patterns suggest that shovelnose sturgeon utilize optimal foraging patterns (Modde & Schmulbach, 1977; Berry, 2002).

Reproduction

Shovelnose sturgeon are potadromous, making short upstream migrations to riverine spawning sites (Bemis & Kynard, 1997). These have been difficult to identify and are typically inferred by the presence of a number of ripe and/or spent individuals (Hurley & Nickum, 1984). However, it appears that preferred sites occur along the edge of main channel habitats or closely associated with wing dams. Spawning may also occur at the mouth of tributary rivers or in dam tailwaters (Farabee, 1979; Hurley & Nickum, 1984). Spawning typically occurs over gravel substrates in areas of relatively high flow (Hurley & Nickum, 1984). While little is known about the spawning site fidelity of individuals, it appears that the same areas are used for spawning every year.

The availability of spawning habitat has been reduced throughout the Mississippi River Basin by the construction of dams and reservoirs. Dams effectively block upstream spawning migrations and change the hydrology and sediment transport regimes. Flowing water is important to ensure dispersal and hatching of sturgeon eggs, however much of the riverine habitat has been converted to slow-flowing reservoirs. It also is thought that seasonal floods and the corresponding changes in water temperature may act as reproductive cues (Moos, 1978; Beamesderfer & Farr, 1997; Hopfar & Peters, 1997; USACE, 2003). Reproductive problems have been noted in some areas. Follicular atresia, where the ovarian follicules degenerate and are resorped before they reach maturity, was noted in approximately 52% of

females in a Mississippi River reservoir. While the exact causes were unknown, it was suggested that this was linked to unfavorable spawning conditions (June, 1977). The presence of hermaphrodites has also been noted in a number of studies, with estimates ranging from 1.6 – 29% of the local population (June, 1977; Moos, 1978; Carlson et al., 1985; Harshbarger et al., 2000). This is usually rare in sturgeons (Van Eenennaam & Doroshov, 1998) and has been recently been attributed in part to high environmental concentrations of organochlorines (Harshbarger et al., 2000). The observed hybridization between pallid and shovelnose sturgeon is thought to be linked in part to a reduction of available spawning habitat (Simons et al., 2001).

The age of sexual maturity in shovelnose sturgeon differs between the sexes with males becoming sexually mature at approximately 5 years and females maturing at 7 years (Helms, 1973; Hurley & Nickum, 1984). Size at maturity appears to vary considerably among populations (Carlander, 1969; Christenson, 1975; Moos, 1978; Keenlyne, 1997) and is probably a function of habitat quality. Shovelnose sturgeon do not typically spawn on an annual basis. Instead approximately 65 – 71% of males and 33% of females may spawn in a given year (Moos, 1978; Hurley & Nickum, 1984). Males are thought to be on a 1 - 2 year reproductive cycle, while individual females spawn every 2 - 3 years (Moos, 1978). However, it is not known whether individuals remain on the same cycle throughout their lifetime. Spawning occurs between April and July in water temperatures from 15° C to 24° C. The beginning of the spawning period varies geographically, with northern populations typically spawning later (Christenson, 1975; June, 1977; Moos, 1978; Hurley & Nickum, 1984). Temporal differences have also been noted for particular sites (Moos, 1978), suggesting that environmental cues, particularly temperature, may be important.

Estimates of fecundity vary considerably, ranging from approximately 4,000 (Henry & Ruelle, 1992) to 51,000 eggs (Helms, 1973) per female. Analysis of available data suggests that these differences may be related to the condition of an individual, with the lower values coming from fish in poor condition. The total number and weight of eggs increases as a function

of female body size and individuals produce approximately 17,000 eggs per kilogram body weight (Figure 2.5; Zweiacker, 1967; Helms, 1973; Christenson, 1975; Henry & Ruelle, 1992). Shovelnose sturgeon eggs are black and approximately 2.5mm in diameter (Christenson, 1975; Moos, 1978; Henry & Ruelle, 1992). They are adhesive and attach to the substrate as they drift downstream (Moos, 1978). They hatch in approximately 7 – 10 days, producing larvae that are 7 – 9mm TL (Snyder, 2002). These are virtually indistinguishable from pallid sturgeon larvae until they are greater than 10mm TL (Snyder, 2002).

Fishery

Sturgeon species worldwide have been exploited for many centuries as a source of flesh and caviar. Commercial harvesting for sturgeon in North America began around the 1750s and concentrated primarily on Atlantic (*A. oxyrhynchus*) and white sturgeon (Bledsloe *et al.*, 2003). Shovelnose sturgeon were not initially considered valuable and were often destroyed in large numbers in the late 1800's by fishers who considered them a pest species (Coker, 1930). However, by the turn of the 20th Century, serious population declines were noted for the commercially valuable species and harvests of shovelnose sturgeon began to increase. Shovelnose meat was popular smoked and the roe made into high quality caviar (Coker, 1930).

Catch records for the early period of the fishery are sporadic at best (Sullivan, 1971). An estimated 84,900kg of shovelnose sturgeon were harvested from the Upper Mississippi River (Illinois, Iowa and Missouri) in 1899. Declines were first noted in the 1920s and harvests had dropped as low as 13,600kg by 1946 (Barnickol & Starret, 1951). The Upper Mississippi River Conservation Commission was established in 1943 and has collected annual harvest records for a range of commercial fishes from Illinois, Iowa, Minnesota, Missouri and Wisconsin. The lowest recorded harvest for shovelnose sturgeon since their records began occurred in 1952, yielding 4,200kg. In comparison, a harvest of 54,600kg was recorded in 1956. The mean

annual harvest between 1947 and 1996 was 21,500kg. Annual harvests have fluctuated considerably during this time and this may be due to changes in fishing effort, methods and demand for shovelnose sturgeon products (Sullivan, 1971; Williamson, 2003). Rasmussen (1979) suggested that the commercial fishery of the time was having no impact on the abundance of shovelnose sturgeon in the Upper Mississippi River. He did, however, recommend a 22-inch length limit to allow individuals to reach adulthood and complete the period of maximum growth (Rasmussen, 1979).

The dramatic population declines of many European sturgeon species and the resulting restrictions on international trade in sturgeon products (Raymakers, 2002) lead to an increased demand for caviar from other sources. The United States currently catches approximately 14% of the total worldwide sturgeon harvest and contributes 27% of the global sturgeon aguaculture production (Raymakers, 2002). These figures are predominantly comprised of Atlantic and white sturgeon, although commercial harvests for shovelnose sturgeon are locally important. Such harvests are currently legal in eight states (Arkansas, Illinois, Indiana, Iowa, Kentucky, Missouri, Tennessee, Wisconsin) and include harvest of roe and fresh or smoked meat (Keenlyne, 1997; Williamson, 2003). Harvest records for Illinois show a dramatic increase from 4,000kg harvested in 1990 to over 29,600kg in 2001. Annual roe harvest rates were relatively steady at approximately 100kg during the early 1990s but have since increased to 3,700kg in 2001 (Figure 2.6; Williamson, 2003). Harvest data for the other states is more sporadic, although improved reporting requirements for commercial fishers have now been adopted due to the inclusion of shovelnose sturgeon in Appendix II of CITES in 1998 (CITES, 2003; Williamson, 2003). The rate of underreporting of harvests and poaching is unknown but is of concern, particularly as demand for shovelnose sturgeon products increases (Williamson, 2003).

Commercial fishers typically catch shovelnose sturgeon with trammel or hoop nets and target them during the spring as they make their upstream spawning migrations (R. Maher,

Illinois DNR, Personal Communication.). Drifting trammel nets catch considerably more shovelnose sturgeon than other methods (Starret & Barnickol, 1955), although they are illegal in some states (i.e. Illinois Administrative Code Section 830.40). Shovelnose sturgeon do not show external sexual dimorphism of the genital tract (Moos, 1978), so a small incision is typically made in the ventral surface of captured fish to determine if they contain mature eggs. On average, ripe individuals yield approximately 2.3kg of roe (Illinois DNR, unpublished data). Shovelnose sturgeon caviar is prized for its nutty, subtle flavor and usually retails for around \$10 per ounce (Birstein, 1993; Williamson, 2003). This is considerably cheaper than imported black caviar, which can exceed \$125 an ounce (Bledsloe *et al.*, 2003). Shovelnose sturgeon caviar is often marketed as American or hackleback caviar, although cases of intentional mislabeling as "Russian" caviar have been noted (Williamson, 2003). Shovelnose sturgeon have never been particularly valued as a sport fish and most catches are probably accidental (Keenlyne, 1997).

To date, there has been little active management of the shovelnose sturgeon fishery and little is known about the past or present status of most commercially exploited populations (Table 2.1; Sullivan, 1971; Keenlyne, 1997; Williamson, 2003). Several states have introduced harvest restrictions, including gear, season, site, and length restrictions (Williamson, 2003). Boreman (1997) investigated the sensitivity of North American sturgeon to harvest and concluded that reducing fishing pressure may be the best method for restoring depleted sturgeon populations. Quist *et al.* (2002) noted that shovelnose sturgeon are prone to both growth and recruitment overfishing and that this could be avoided by establishing minimum length limits. Maximum size limits would also to help increase spawner survival (Caron *et al.*, 2002).

Harvesting for caviar removes breeding females from the population and this may significantly contribute to population declines. Therefore, the introduction of a non-fatal method for removing roe from adult females, allowing their subsequent return to the wild, could greatly reduce the risk of unsustainable harvest. Recent work has looked at techniques for stripping

roe from live female paddlefish (*Polydon spathula*; Štěch *et al.*, 1999; Mims *et al.*, 2004), although these have focused on roe removal for hatchery purposes rather than caviar production. Aquaculture is also becoming a valuable tool for sturgeon management and is currently utilized for Siberian (*A. baeri*) and white sturgeon (Logan *et al.*, 1995; Gisbert & Williot, 1997; Sanders *et al.*, 2003). Recent work with shovelnose sturgeon suggests that this has considerable potential (Mims & Shelton, 1998). Such alternative methods to the traditional caviar harvest will become increasingly important, particularly if demand for caviar products continues to rise.

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Table 2.1. The population classification, status and associated commercial harvest restrictions in states within the range of shovelnose sturgeon (Keenlyne, 1997; Williamson, 2003).

State	Classification	Status	Commercial Harvest Restrictions
Alabama	Extirpated	Unknown	
Arkansas	Commercial/Sport	Unknown	Gear, License, Season, Site
Illinois	Commercial/Sport	Unknown	Gear
Indiana	Commercial/Sport	Unknown	
lowa	Commercial/Sport	Stable	
Kansas	Sport	Unknown	
Kentucky	Commercial/Sport	Unknown	
Louisiana	Special Concern	Unknown	
Minnesota	Sport	Stable	
Mississippi	Rare	Unknown	
Missouri	Commercial/Sport	Unknown	Gear, License, Site, Size
Montana	Sport	Stable	
Nebraska	Sport	Stable	
New Mexico	Extirpated	Extinct	
North Dakota	Protected	Stable	
Ohio	Endangered	Unknown	
Oklahoma	Sport	Unknown	
Pennsylvania	Extirpated	Unknown	
South Dakota	Protected	Unknown	
Tennessee	Commercial/Sport	Unknown	Gear, License, Season, Site, Size
Texas	Threatened	Unknown	
West Virginia	Protected	Unknown	
Wisconsin	Commercial/Sport	Unknown	
Wyoming	Sport	Stable	



Figure 2.1. The current (solid line) and historical (•) distribution of shovelnose sturgeon. (Redrawn from Bailey & Cross, 1953 and Keenlyne, 1997).


Figure 2.2. Shovelnose sturgeon (Scaphirhynchus platorynchus Rafinesque). (Illustration by Paul Vecsei, used with permission.)



Figure 2.3. The mean length of shovelnose sturgeon for a given age from different populations within the Mississippi River drainage. The data were taken from available literature and are shown as Von Bertalanffy relationships (solid lines) or averages (points). Each series extends to the oldest recorded individual in that particular study. (1). Yellowstone River – Females (Everett *et al.*, 2003). (2). Yellowstone River (Everett *et al.*, 2003). (3). Lower Mississippi River (Morrow *et al.*, 1998). (4). Yellowstone River – Males (Everett *et al.*, 2003). (5). Missouri River (Quist *et al.*, 2002). (6). Missouri River (Everett *et al.*, 2003). (•). Upper Mississippi (Helms, 1973). (▲). Mississippi & Missouri Rivers (Carlson *et al.*, 1985). (+). Missouri (Zweiacker, 1967). (■). Minnesota River (Durkee *et al.*, 1979).



Figure 2.4. Catch-curve analysis of an unharvested population of shovelnose sturgeon in the Yellowstone River. (Data from Everett *et al.*, 2003).



Figure 2.5. Relationship between total body weight (g) and number of eggs (g) in shovelnose sturgeon throughout the Mississippi River drainage. The data represent averages taken from available literature. (▲). Missouri River (Zweiacker, 1967). (■). Upper Mississippi River (Helms, 1973). (♦). Red Cedar & Chippewa Rivers (Christenson, 1975). (●). Minnesota River (Henry & Ruelle, 1992).



Figure 2.6. Reported commercial harvest for shovelnose sturgeon flesh (solid line) and roe (dotted line) in Illinois from 1990 to 2001 (Williamson, 2003).

A LEFKOVITCH MATRIX MODEL FOR SHOVELNOSE STURGEON (SCAPHIRHYNCHUS PLATORYNCHUS) IN THE WABASH RIVER, ILLINOIS1

¹ Whitehead, A.L., M.J. Conroy & J.T. Peterson. To be submitted to *Canadian Journal of Fisheries and Aquatic Sciences*.

Introduction

A large number of species around the world are now under some kind of management regime, whether it is for the purpose of conservation, harvest or control. The method by which such management regimes are determined varies from case to case, but often predictions of population growth rates and the possible impact of different management options are incorporated into the decision process. Population models can be used to generate such predictions and typically incorporate most or all of the available demographic data for the population in question. Such models, depending on the system, can be very simple or incredibly complex.

Population matrix models have been successfully used in ecological research to help estimate population growth rates and predict the potential effects of different management decisions for a wide array of organisms (i.e. sea turtles – Crouse *et al.*, 1987; Heppell *et al.*, 1996; killer whales – Braust & Caswell, 1993; tortoises – Doak *et al.*, 1994; red-cockaded woodpeckers - Heppell *et al.*, 1994; palms – Olmsted & Alvarez-Buylla, 1995; sturgeon – Gross *et al.*, 2002). They are capable of modeling relatively complex systems (Heppell *et al.*, 1994) but can also cope with sparse datasets (Heppell *et al.*, 2000).

The Wabash River originates in western Ohio and flows through Indiana before forming the lower Illinois-Indiana border (Figure 3.1). At approximately 750km in length, it is the longest free-flowing river east of the Mississippi Basin and is a major tributary to the Ohio River. The lower 320km are under the jurisdiction of the Illinois Department of Natural Resources (DNR) and host an active caviar fishery for shovelnose sturgeon. However, little is known about the population dynamics of shovelnose sturgeon in the Wabash River. Ripe-and-running females are targeted by the fishery while males and unripe or immature females are returned to the river. There is little information on historic catches in this region, although the fishing intensity has increased over the past few years and this trend is expected to continue as the demand for new

sources of caviar rises. The Illinois DNR began tagging shovelnose sturgeon in the Wabash River in 2000 but still has insufficient data to determine the status of the shovelnose sturgeon stocks in the Wabash River (R. Maher, Illinois DNR, personal communication).

In this chapter I use available demographic data for shovelnose sturgeon to develop a stage-based Lefkovitch matrix model for an unharvested population. I then compare the sensitivity of the model to changes in parameter values and look at the potential effects of different rates of a caviar harvest.

Matrix Model Development

Population projection matrices typically take the form

$$n_{t+1} = An_t \tag{3.1}$$

or

$$\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_s \end{bmatrix}_{t+1} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1s} \\ a_{21} & a_{22} & \cdots & a_{2s} \\ \vdots & \vdots & \ddots & \vdots \\ a_{s1} & a_{s2} & \cdots & a_{ss} \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_s \end{bmatrix}_{t}$$
(3.2)

where n_t is the abundance of individuals in a particular life stage at time t, and s denotes the final stage (Leslie, 1945). A is the transition matrix that describes the number of individuals in each stage that survive from one time period to the next. In addition, it characterizes the number of offspring produced by each stage within a given time period. The dominant eigenvalue λ of the transition matrix is equal to e^r , where r is the intrinsic rate of increase of the population in the equation

$$N_t = N_0 e^{rt} \tag{3.3}$$

at the stable stage distribution. Therefore, if $\lambda = e^r = 1$, then r = 0, and the population is stationary. The stable age distribution is represented by the right eigenvector *w* such that

$$Aw = \lambda w. \tag{3.4}$$

The expected reproductive contribution of each stage to population growth is represented by the left eigenvector v and is defined by

$$v'A = \lambda v' . \tag{3.5}$$

Leslie matrices typically have annual time steps where individuals are structured into discrete age classes and require estimates of age-specific rates of survival and fecundity (Leslie, 1945). In comparison, stage-based matrices (Lefkovitch, 1967) allow individuals to remain in a given stage from one time period to the next. Individuals within a stage are subject to the same mortality, growth and fecundity rates, although these can vary between stages. In addition, the duration of stages can differ. A Lefkovitch matrix requires stage-specific estimates of fecundity (F_i), the probability of surviving and remaining in the same stage (P_i), and the probability of surviving and growing into the next stage (G_i). While these models require considerably fewer data than Leslie matrices, they have been found to give relatively similar results (Crouse *et al.*, 1987; Brault & Caswell, 1993; Heppell *et al.*, 2000). When the duration of each stage is fixed, the annual probability of an individual growing into the next stage (γ_i) is calculated by

$$\gamma_{i} = \frac{\left(\frac{\sigma_{i}}{\lambda}\right)^{T_{i}} - \left(\frac{\sigma_{i}}{\lambda}\right)^{T_{i}-1}}{\left(\frac{\sigma_{i}}{\lambda}\right)^{T_{i}} - 1}$$
(3.6)

where σ_i is the stage-specific survivorship and T_i is the stage duration. The value of λ is calculated by iteration using the dominant eigenvalue from the matrix until the initial λ and final λ are equal to the fourth decimal place. The transition matrix parameters can then be estimated using Equations 3.7 and 3.8:

$$G_i = \sigma_i \gamma_i \tag{3.7}$$

$$P_i = \sigma_i (1 - \gamma_i) \tag{3.8}$$

The resulting matrix takes the form

$$A = \begin{bmatrix} P_1 & F_2 & \cdots & F_{s-1} & F_s \\ G_1 & P_2 & \cdots & 0 & 0 \\ 0 & G_2 & \ddots & 0 & 0 \\ 0 & 0 & \ddots & P_{s-1} & 0 \\ 0 & 0 & \cdots & G_{s-1} & P_s \end{bmatrix}.$$
 (3.9)

There is currently little demographic data available for shovelnose sturgeon, particularly for Wabash River. Therefore, the data used in the following matrix models are a combination of direct estimates from field data collected from the Wabash River by the Illinois DNR, estimates from other populations of shovelnose sturgeon and similar sturgeon species, and expert opinion. The life history diagram for shovelnose sturgeon is shown in Figure 3.2. Survival rates for juvenile and adult shovelnose sturgeon are not known, although it is thought that these may be as high as 90% (D.L. Peterson, UGA, personal communication). The YOY survival rate is also unknown but is thought to be in the order of 0.1% (D.L. Peterson, UGA, personal These rates are similar to those proposed for other sturgeon species communication). (Boreman, 1997; Jager et al., 2002; Pine et al., 2001; Gross et al., 2002). Females mature at age seven (Helms, 1973; Hurley & Nickum, 1984), although there are currently no direct estimates of the age-fecundity relationship for shovelnose sturgeon. Therefore, this relationship was estimated from known von Bertalanffy growth, length-weight and weight-fecundity relationships by simulation (Table 3.1, Figure 3.3). The average number of eggs produced in a given time step per individual was then estimated from

$$F_{age} = 19331\ln(age) - 20324 \tag{3.10}$$

and adjusted for a three-year spawning periodicity and the expected proportion of females in each age class. The number of female YOY produced was estimated from the number of eggs using a 10% hatch rate and a sex ratio of 1:1.

To examine the female population dynamics of shovelnose sturgeon, I created a deterministic 3 x 3 post-breeding Lefkovitch matrix using the data in Table 3.2. A stage-based Lefkovitch model was considered to be more suitable for shovelnose sturgeon than an age-based model because of the limited amount of demographic data available. All analyses were conducted using SAS v.8.02 and the code is provided in the appendices. Because the maximum age of the population in the Wabash River is unknown, I did not truncate the adult stage ($P_3 = 0.9$; Crowder *et al.*, 1994). The resulting transition matrix is shown below

$$A = \begin{bmatrix} 0 & 0 & 200 \\ 0.001 & 0.7879 & 0 \\ 0 & 0.1121 & 0.9 \end{bmatrix}$$
(3.11)

and is referred to as the "baseline" model for the remainder of this chapter.

The baseline model makes a number of assumptions and these are listed below:

- 1. Females have a fixed spawning periodicity and age at maturity.
- 2. An average number of females spawn in a given year.
- 3. The population dynamics are not regulated by density-dependent factors
- 4. Males would be present in sufficient numbers to facilitate successful reproduction.

The estimated growth rate for the baseline matrix model is $\lambda = 1.0036$. The right eigenvector (*w*) of the transition matrix represents the stable age distribution of the population (Table 3.3). This suggests that shovelnose sturgeon populations are dominated by YOY, with adults comprising approximately 0.5%. The stage-specific reproductive values are given by the left eigenvector (*v*) of the matrix (Table 3.3). These represent the estimated per capita contribution of individuals in each stage to population growth, with adult shovelnose sturgeon making the greatest reproductive contribution.

Elasticity Analysis

A matrix model provides the researcher with a set of demographic statistics that are based on age- or stage-specific survival rates and fecundities. However, what happens to these statistics if one or more of the vital rates should change? Elasticity analysis calculates the *proportional* change in λ due to an infinitesimal *proportional* change in the matrix element a_{ij} when all other elements of the transition matrix are held constant during partial differentiation (de Kroon *et al.*, 2000; Caswell, 2001). It is derived from Caswell's (1978) sensitivity index

$$s_{ij} = \frac{\partial \lambda}{\partial a_{ij}} = \frac{v_i w_j}{\langle w, v \rangle}, \qquad (3.12)$$

where w and v are the right and left eigenvectors of the transition matrix respectively. Elasticities are calculated by

$$\varepsilon_{ij} = \frac{\partial(\log \lambda)}{\partial(\log a_{ij})} = \frac{a_{ij}}{\lambda} \frac{\partial \lambda}{\partial a_{ij}}$$
(3.13)

and can be used to predict the proportional change in λ due to a proportional change in one or more of the vital rates. For example, if the elasticity of λ to the survival of adults is 10%, then a 5% increase in adult survival will result in a 0.5% (10% x 5%) increase in the population growth rate, changing $\lambda = 1$ to $\lambda = 1.05$ (Gross *et al.*, 2002). Because elasticities measure the proportional changes, they sum to one (de Kroon *et al.*, 1986; Mesterton-Gibbons, 1993). This means that they can also measure the contribution of a_{ij} to λ , allowing for comparison of the relative importance of different transitions within the life cycle (Caswell, 2001). The dimensionless characteristic of elasticities allows transitions measured in different scales, such as survival and fecundity, to be compared (de Kroon *et al.*, 1986; Mesterton-Gibbons, 1993). The elasticity of λ to changes in the stage-specific survival and fecundity rates is shown in Figure 3.4. In general, the elasticity of λ decreases as the value of each parameter decreases. It appears that the population growth rate is most sensitive to changes in adult survival, followed by juvenile survival. In comparison, YOY survival and fecundity contribute little to the population growth rate.

Although estimates of age at maturity and spawning periodicity of shovelnose sturgeon are thought to be relatively robust, it is possible that changes in these parameters may impact the population growth rate and elasticity values. Therefore, I calculated four additional transition matrices using values one year either side of those in the baseline matrix for each parameter. The maximum age of shovelnose sturgeon in the Wabash River is currently unknown. Maximum age appears to vary considerably between populations, although Chapman (1999) gave an average estimate of 27 years. Therefore, I also re-evaluated the baseline matrix by truncating the adult survival rate to account for a maximum age of 27 years using Equation 3.8.

Decreasing the spawning periodicity and age at maturity independently, lead to an increase in the intrinsic rate of increase ($r = \log \lambda$; Figure 3.5). In comparison, increasing the spawning periodicity and age at maturity, and truncating the maximum age, resulted in a decrease in the intrinsic rate of increase. Similar changes occurred to the elasticity values, although these amounted to less than 5% in all cases.

Effects of Harvest

Finally, I performed a series of simulations to calculate the effects of a caviar harvest on the population growth rate. Individuals were harvested before reproducing by

$$n_{t+1} = A \Big[n_t - (n_t h_t) \Big]$$
(3.14)

where h_t is a vector containing the harvest rate. The first two elements of the vector are set to zero as no YOY or juveniles are susceptible to harvest. Element three takes a proportion of the adult females that are reproductively active in period t. Figure 3.6 suggests that up to 2% of the female population could potentially be harvested without causing a decline in yield, and therefore, population growth rate for a given initial population size. However, it is important to note that this model is deterministic and assumes additive harvest effects. The effects of stochastic demographic and environmental changes on shovelnose sturgeon populations are currently unknown, therefore the above harvest rate should be considered with caution. A more sophisticated approach to modeling optimal harvest rates is examined in Chapter Four.

Discussion

It has been recognized for over a century that harvest can have detrimental effects on sturgeon populations. Almost all commercial sturgeon fisheries rapidly declined within 20 years of initiation, and most populations still exist at much lower densities than they once did (Saffron, 2002). These trends are probably linked to the life history strategies of sturgeon: low YOY survival, delayed sexual maturity, multi-year spawning periodicity, high juvenile and adult survival, and high fecundity rates. Previous studies have shown that species with similar demographic patterns are susceptible to high juvenile and adult mortality rates (Crouse *et al.*, 1987; Brault & Caswell, 1993; Congdon *et al.*, 1993; Heppell *et al.*, 2000; Gross *et al.*, 2002).

The high elasticity of the population growth rate to adult and juvenile survival suggests that shovelnose sturgeon would be vulnerable to a caviar harvest that targets these stage classes. Many other long-lived species with similar life history traits show similar elasticity patterns. For example, populations of long-lived desert tortoises in the western Mojave desert are in decline because of high adult female mortality (Doak *et al.*, 1994). Improving the survival rate of this stage class would reverse the decline; however, similar increases in the survival of

younger stages, alone, would not be sufficient to improve the status of the population (Doak et al., 1994). Gross et al. (2002) concluded that improving the YOY survival of several North American sturgeon species would produce the greatest contribution to the population growth This interpretation was based on the fact that adult and juvenile survival rates are rate. approximately 90% and, therefore, would be difficult to increase any further. In comparison, YOY survival rates were estimated to be less than 0.001% and could potentially be increased through hatchery production. In comparison, however, several studies of loggerhead sea turtles have suggested that boosting hatchling survival is unlikely to increase the overall population growth rate unless it occurs in conjunction with a decrease in juvenile and adult mortality (Crouse et al., 1987; Crowder et al., 1994; Heppell et al., 1996). Similar conclusions have been drawn for populations of desert tortoises (Doak et al., 1994), Mexican palms (Olmsted & Alvarez-Buylla, 1995) and killer whales (Brault & Caswell, 1993). These species all have very similar life history strategies to shovelnose sturgeon. This suggests that the conclusions of Gross et al. (2002) may be incorrect and that shovelnose sturgeon populations may not greatly benefit from an increase in YOY survival rates.

The long life span of sturgeon means that adults are exposed to the fishery for an extended period of time and this makes them vulnerable to overfishing (Beamesderfer & Farr, 1997; Boreman, 1997). Length restrictions have been proposed by a number of researchers to allow a greater number of individuals to spawn before becoming susceptible to harvest (Rasmussen, 1979; Boreman, 1997; Caron *et al.*, 2002; Gross *et al.*, 2002; Quist *et al.*, 2002). Such restrictions are currently in place for commercial shovelnose sturgeon harvests in Missouri and Tennessee (Williamson, 2003), although there has been no published analysis of their effectiveness to date.

In researching this chapter, I became aware of how little we actually know about the population dynamics of shovelnose sturgeon, which suggests that it is extremely difficult to make informed management decisions about populations. Matrix models have been found to

be relatively robust, even when there is very little available demographic data (Heppell *et al.*, 2000). However, inaccurate or biased estimates of adult survival rates and the age at maturity can have a large effect on elasticity patterns. In comparison, juvenile survival and fecundity rates appear to be less influential (Heppell *et al.*, 2000). Therefore, matrices can also be useful in identifying areas where future research should be focused (Doak *et al.*, 1994; Olmsted & Alvarez-Buylla, 1995).

Juvenile and adult shovelnose sturgeon make a considerable contribution to the population growth rate. However, the current estimates of their survival rates are poor, particularly for young juveniles who may be more susceptible to predation (Auer & Baker, 2002). Further information is also needed on the fecundity-age relationship of shovelnose sturgeon. Previous studies have found considerable geographic differences in fecundity (Zweiacker, 1967; Helms, 1973; Christenson, 1975; Henry & Ruelle, 1992), indicating that this should be evaluated on a population-by-population basis. However, Gross *et al.* (2002) found that changing the shape of this relationship for shortnose sturgeon did not greatly affect the elasticity patterns, suggesting that this is perhaps not a high priority.

The low elasticity to fecundity, however, suggests that a non-fatal caviar harvest should not have a great impact on the population growth rate, assuming that the females are not harmed during the harvest process (Gross *et al.*, 2002). The ability to take roe and then return the adult females to the wild would help to reduce the risk of a population decline. Recent work has looked at techniques for stripping roe from live female paddlefish (Štěch *et al.*, 1999; Mims *et al.*, 2004), although these have focused on roe removal for hatchery purposes rather than caviar production.

The factors affecting the transition parameters in the matrix model also need to be better evaluated. Changes to the spawning periodicity altered the population growth rate, with an increase of one year between spawning events leading to a population decline. In addition, the elasticity of the population growth rate to adult survival increased with increasing time between

spawning events. While there seems to be a general consensus between researchers that the spawning periodicity for shovelnose sturgeon is approximately three years (Moos, 1978; Hurley & Nickum, 1984), it is not known if this period is fixed throughout the lifespan of an individual. Nor do we know if all individuals follow the same pattern or if this differs between populations. Such information is necessary in order to make informed management decisions. The possibility of irregular but synchronous spawning could also alter the population dynamics and, therefore, change the susceptibility to harvest (Gross *et al.*, 2002).

Information about the maximum age of reproductive females in the population is important. While there is no evidence that reproductive senescence occurs in sturgeon, a decrease in age restricts the number of adult females available to breed. Truncating the maximum age of individuals in the baseline model to 27 years (Chapman, 1999) resulted in a slight decline in the population growth rate, which may alter the appropriate harvest decision.

The baseline matrix model suggests that there is hope for shovelnose sturgeon populations in the absence of harvest. However, harvest rates greater than 2% appear to put the population at risk of extinction. It is important to remember that this model is deterministic and does not incorporate stochastic or environmental events. In addition, it contains no density-dependent recruitment factors. Therefore, we should avoid making decisions based on the absolute results of this model, but rather examine the trends that result from changes in a population's vital rates. In addition, it can be updated as additional information becomes available and this will help to improve its realism. However, it currently provides valuable information based on the available data that can be incorporated into management plans.

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Table 3.1.	Relationships	used to	calculate	the	average	fecundity-age	relationship	of	female
shovelnose	sturgeon.								

Parameter	Equation	Source		
von Bertalanffy growth equation	$L_t = 858 (1 - \exp^{(-0.13(t+2.7))})$	Everett <i>et al</i> ., 2003		
Length-weight relationship	$\ln weight = -12.727 + 3.0448 \ln(length)$	Illinois DNR		
Fecundity-weight relationship	<i>Fecundity</i> = -175.9 + 16.797 <i>weight</i>	Zweiacker, 1967		
		Helms, 1973		
		Christenson, 1975		
		Henry & Ruelle, 1992		
		Illinois DNR		

Table 3.2. Life history stages of female shovelnose sturgeon life and the stage-specific parameters used to calculate the baseline Lefkovitch transition matrix. The data are based on available literature and expert opinion.

Stage	Duration (years)	Annual Survival	Annual Fecundity
YOY	1	0.001	0
Juveniles	6	0.9	0
Adults	>21	0.9	200*

* Average number of female YOY produced based on a three-year spawning periodicity, 10% hatch rate and a 1:1 sex ratio.

Table 3.3. Stable age distribution (w) and reproductive value (v) for the baseline Lefkovitch matrix created for an unharvested population of shovelnose sturgeon in the Wabash River, Illinois.

Stage	Stable Age Distribution (%)	Reproductive Value
YOY	99.04	1
Juveniles	0.46	1004
Adults	0.50	1930



Figure 3.1. Location of the Wabash River. The solid lines represent the jurisdictional boundaries of the Illinois Department of Natural Resources.



Figure 3.2. Life history diagram for shovelnose sturgeon. Females spend approximately 6 years in the juvenile stage, while the maximum age of adults is unknown.



Figure 3.3. The average age-specific fecundity of female shovelnose sturgeon. This was estimated by a 5000-iteration simulation model using known Von Bertalanffy, length-weight and weight fecundity relationships for shovelnose sturgeon throughout the Mississippi River drainage.



Figure 3.4. The elasticity of lambda to changes in a) adult (dotted line) and juvenile (solid line) survival, b) YOY survival and c) fecundity, while all other values in the matrix were held constant. The vertical bars represent the values used in the baseline Lefkovitch matrix.



Figure 3.5. Changes to the intrinsic rate of increase (\square) for an unharvested population of shovelnose sturgeon in the Wabash River when life history parameters in the matrix are varied. The \square -value for the baseline Lefkovitch matrix is represented by the dotted line, while the spawning periodicity is equal to four (SP4) or two years (SP2), age at maturity is equal to eight (AM8) or six years (AM6), and the maximum age is 27 years (MA27). All other values in the matrix were held constant.



Figure 3.6. The potential yield of roe from a population of shovelnose sturgeon in the final year of harvesting, as expected after harvesting for 200 years at a fixed rate. A range of initial population sizes were simulated using the parameters specified for the baseline Lefkovitch matrix. The contours represent the initial number of adult females in the population, with the heavy lines indicating intervals of approximately 1000 individuals.

OPTIMAL HARVEST OF SHOVELNOSE STURGEON (SCAPHIRHYNCHUS PLATORYNCHUS) IN THE WABASH RIVER, ILLINOIS 2

² Whitehead, A.L., M.J. Conroy & J.T. Peterson. To be submitted to *Fisheries*.

Introduction

Dynamic programming is a mathematical optimization technique that can be used to optimize an objective function under a sequence of decisions (Lubow, 1995). It has become increasingly popular in ecological research and has been applied to a wide range of scenarios, from behavioral analyses (Clarke & Mangel, 2000) to harvest management (Johnson *et al.*, 1997; Milner-Gulland, 1997). It is often used in natural resource problems where a manager must make decisions that involve tradeoffs between the benefits, such as increases in yield, and costs, including decreases in resource availability and economic costs.

Shovelnose sturgeon are taken from the Wabash River, Illinois, for a commercial caviar harvest where only ripe-and-running females are targeted. Little is known about the status of the population and it is not currently under active management. Recent research by the Illinois DNR has begun to examine the population status with regards to formulating a management plan, but to date they have insufficient information. The objective of this chapter is to evaluate the optimal harvest policy for a population of shovelnose sturgeon in the Wabash River, Illinois, using available demographic data.

Stochastic Dynamic Programming

Stochastic dynamic programming is a discrete-time, optimization method that uses backwards iteration to find the long-term optimal strategy to a decision problem (Lubow, 1995; Williams *et al.*, 2002). It is based on the principle of optimality, which states that, if the best sequence of decisions is known from the next step onward, then the best decision for the current step depends only on the immediate consequences of the current decision (Bellman, 1957; Lubow, 1995). A terminal reward function $V_T[N_T]$ is assumed for the final time period T,

depending on the state of the system, N. If $V_T[N_T]$ is known, then $V_{T-1}[N_{T-1}]$, the reward one period earlier, can be calculated depending on the strategy adopted and the outcome of stochastic events. The optimal strategy, which maximizes $V_{T-1}[N_{T-1}]$, can then be found. If this process is continued for sufficient iterations, the terminal reward function no longer affects the optimal strategy, which remains constant as the time from T increases.

The shovelnose sturgeon model is similar to the baseline Lefkovitch matrix model described in Chapter Three (Equation 3.11) and examines only the female population dynamics. The system dynamics can be described by

$$\underline{N}_{t+1} = \underline{N}_t + f_t(\underline{N}_t, \underline{d}_t, \underline{Z}_t)$$
(4.1)

where \underline{N}_t is the vector of system states, \underline{d}_t is a vector of management decisions, \underline{Z}_t are random variables, and f is a model. When population growth is unconstrained, the optimal decision is to always delay harvest until immediately before the end of time, when the maximum yield can be achieved. Therefore, in order to construct a realistic model, a Beverton-Holt stock recruitment function was added to restrict the maximum population size. This is given by

$$R = \frac{Y}{1 - A(1 - Y/K_Y)}$$
(4.2)

where *R* is the actual number of YOY produced, *Y* is the potential number of YOY produced, *A* is the shape parameter of the curve, and K_y is the number of YOY produced at equilibrium (Ricker, 1975; Riemann & Beamesderfer, 1990). There is currently insufficient data to accurately predict the number of shovelnose sturgeon at equilibrium in the Wabash River. Therefore, I used two arbitrarily selected K_y -values of 1,000,000 and 4,000,000 YOY at equilibrium, representing approximately 1200 and 4800 adult females respectively under conditions of no harvest (Figure 4.1 & Figure 4.2). According to the stable age distribution calculated in Chapter Three, these values are equivalent to total populations of approximately 5,000 and 20,000 individuals respectively, which is within the range predicted for the 320km stretch of river under the jurisdiction of the Illinois DNR (Christenson, 1975; Schmulbach, 1975). The two models are referred to as the "low-density" and "high-density" scenarios from this point forward. While it is unknown whether these equilibrium population sizes are realistic, they provide the opportunity to examine trends in optimal harvest rates and population growth, and can easily be updated as more detailed information comes to hand. All models were optimized using ASDP v3.1.02 (Lubow, 2001).

Each year is assumed to start with a decision about the proportion of spawning females to be taken in the caviar harvest. Harvest affects the population size and structure both directly, by reducing population size, and indirectly, through recruitment. Immediately after harvesting, spawning occurs and is followed by survival and growth prior to the harvest decision in the next time step. Adult and juvenile survival rates were modeled as stochastic variables drawn from a discrete parameterization of the beta distribution, while YOY survival remained constant. In addition, fecundity rates were drawn from a discrete parameterization of the normal distribution.

The objective function aims to maximize the harvest yield

$$Y = \pi(F_t) \tag{4.3}$$

where F_t is the number of spawning adult females harvested and π is the average weight of roe produced per individual (2.3kg; Illinois DNR, unpublished data). Therefore, the value $V[\cdot]$, of any decision strategy \underline{D}_t , is the sum of the expected yields over the time horizon $\tau = t, t + 1, ... T$ associated with every possible system state \underline{N}_t such that

$$V(\underline{D}_t|N_t) = E\left\{\sum_{\tau=t}^T Y(\underline{d}_{\tau}|\underline{N}_{\tau}) \Big| N_t\right\}.$$
(4.4)

This can be shown as the current and future value by

$$V(\underline{D}_{t}|N_{t}) = E\left\{Y(d_{t}|N_{t}) + \sum_{\tau=t+1}^{T} Y(\underline{d}_{\tau}|\underline{N}_{\tau}|\underline{N}_{t})\right\}$$

= $Y(d_{t}|N_{t}) + \sum_{N_{t+1}} p(N_{t+1}|N_{t},d_{t}) E\left\{\sum_{\tau=t+1}^{T} Y(\underline{d}_{\tau}|\underline{N}_{\tau})|\underline{N}_{t+1}\right\}$
= $Y(d_{t}|N_{t}) + \sum_{N_{t+1}} p(N_{t+1}|N_{t},d_{t}) V(D_{t+1}|N_{t+1}).$ (4.5)

This objective function is maximized by solving the recursive formula

$$V^{*}(N_{t}) = \max_{d_{t}} \left\{ Y(d_{t}|N_{t}) + \sum_{N_{t+1}} p(N_{t+1}|N_{t}, d_{t}) V^{*}(N_{t+1}) \right\}.$$
(4.6)

The terminal reward function $V_T[N_T]$ for the final year of the simulation must be specified in order for the back-calculation to be possible. However, its value has no effect on the optimal strategy when sufficiently far from the terminal date. Therefore, the expected future yield at time *T* was assumed to be 0.

To calculate the optimal harvest strategy and the expected long-term yield associated with this strategy, the following steps are performed for each year:

- The model loops through a grid of all possible combinations of the three system states, giving a systematic coverage of all possible population structures at the spring census just after spawning. The range of parameter values is shown in Table 4.1.
- 2. For each set of state values, the model loops through a grid of possible harvest decisions and calculates the expected yield from Equation 4.3.
- The population undergoes spawning and mortality, and the size and structure of the population at the end of the year is calculated.
- 4. The expectation of the return in time period t is then calculated by Equation 4.6.

The resulting optimal policy is shown as a series of colored contour plots. Because fourdimensional graphs can be difficult to create and comprehend, I constructed three plots for both scenarios, each showing the optimal policy for a pair of system states averaged over the third system state. For example, the optimal strategy for the low-density scenario is shown in Figure 4.3a, where optimal harvest rates for different combinations of YOY and juvenile population sizes were averaged over the range of adult population sizes examined in the model.

Once the optimal harvest strategies were determined, I ran a series of simulations for each scenario to determine the effects of such a strategy on populations with different initial starting sizes over a 400-year period. It was assumed that all populations started at a stable age distribution. Because the equilibrium values used in each of the scenarios were selected arbitrarily, the use of different population sizes for the simulations allows us to examine trends in population growth, harvest rate and yield over time.

Results

The optimal strategy for a shovelnose sturgeon caviar harvest was calculated for each combination of the three system states for each scenario. This resulted in two sets of 1331 long-term optimal strategies, depending on the census results in a given year. It is important to remember that the optimal harvest rate refers to the proportion of spawning adult females to be harvested, not a proportion of the total population. Harvest rates typically increased with increasing population size, although they appear to be predominantly driven by the number of adult females in the population (Figure 4.3 & Figure 4.4). Each plot represents the optimal harvest strategy based on two system states averaged over the third state. This can make interpretation of the overall strategy somewhat difficult but is considerably easier than producing (and comprehending) a four-dimensional plot. Note also that the colored contour scales differ between plots. The three plots for the low-density scenario show optimal harvest rates ranging from 0% to 93.9% (Figure 4.3). Due to the grid intervals in the model, it is not possible to determine the minimum number of adult females required for harvest. However, it is probably less than 500 individuals. Harvest rates rapidly increase and are greater than 60% for populations with more than 2000 adult females (Figure 4.3b & 4.3c). In comparison, the three
plots for the high-density scenario show optimal harvest rates ranging from 0% to 71.4% (Figure 4.4). The minimum number of adult females required to harvest is approximately 1000 individuals (Figure 4.4b & 4.4c). Once the population exceeds 5000 individuals, the level of harvest reaches rates of greater than 50%. Figures 4.3c and 4.4c would probably be the most appropriate plots for managers to use in determining the optimal strategy for harvest in a given year as they are more likely to be able to estimate the abundances of juveniles and adults than YOY.

Once the optimal strategy was determined for each scenario, populations with different initial densities were followed forwards over time to determine the effects of the optimal harvest policy. Trajectories of population growth, cumulative yield and harvest rate for each initial density were plotted over a 400-year period. In addition, the population trajectories for a range of unharvested populations were also plotted and are shown in Figure 4.2. When unharvested, populations constrained at a low density stabilized at approximately 1200 adult females (Figure 4.2b), while the same populations converged at 800 individuals when harvested at the optimal rate (Figure 4.5a). In the high-density scenario populations begin to converge and stabilize at approximately 4800 adult females when unharvested (Figure 4.2b). In comparison, the same populations stabilized at approximately 3500 individuals when subjected to the optimal harvest strategy (Figure 4.5b).

The average rate at which these populations were harvested is shown in Figure 4.6. High harvest rates were initially noted in the low-density scenario, with almost 77% of spawning females harvested in the first year when the initial female adult population was equal to 3000 individuals (Figure 4.6a). In comparison, very low harvest rates were initially used for populations that began below the unharvested equilibrium for adult females. Under high-density constraints, large initial populations were subjected to high harvest rates (38.2% of spawning females for an initial adult female population of 6000 individuals; Figure 4.6b). In comparison, small populations were not harvested at all for a period of time (9 years and 19 years for initial

adult female populations of 2000 and 1000 individuals respectively). The harvest rates for both scenarios converged to approximately 2.7% of spawning females, although they continued to fluctuate due to the stochastic nature of the population dynamics.

The average yield of roe recovered from the population in a given year was directly proportional to the optimal harvest rate and the equilibrium population size (Figure 4.7). In both scenarios, high yields were initially gathered from populations above the equilibrium, while smaller populations did not produce any roe for the first few years. The yield stabilized at approximately 26kg per year in the low-density scenario and 100kg per year for the high-density scenario.

The cumulative yield over the 400-year harvesting period is shown in Figure 4.8. Large populations produced a greater cumulative yield in both scenarios, due to higher harvesting rates during the first few years. However, once the populations reached equilibrium, the associated cumulative yield increased at the same rate for all populations as expected. Overall, the high-density scenario produced approximately three times more roe after 400 years than the low-density scenario.

After sufficient time, a stationary distribution for population growth and structure is reached, regardless of the initial population size. At this point only a subset of the possible harvest strategies are utilized. The stochastic nature of the population dynamics means that the trajectory of a given population cannot be easily predicted due to random variations from the expected value. However, probability distributions for population size can give us an indication of possible outcomes. The predicted number of adult females in an unharvested population after 400 years is significantly lower when modeled using the low-density scenario (Figure 4.9). This ranges from approximately 300 to 3500 individuals, compared to between 1000 and 14000 individuals predicted using the high-density scenario. Similarly, a low-density scenario population harvested using the optimal harvest strategy would probably contain between 200

and 1450 adult females, compared to between 900 and 6000 for the high-density scenario (Figure 4.10).

The range of harvest strategies employed in the 400th year of harvesting at the optimal strategy is shown in Figure 4.11. Approximately 70% of populations were harvested at rates of less than 2.5% when simulated using the low-density scenario (Figure 4.11a). In comparison, almost 40% of populations in the high-density scenario had a zero-harvest policy at the 400th year. A further 29% were subject to harvest rates less than 2.5%. Correspondingly, the return of roe in the 400th year ranged from 0.2kg to 350kg for the low-density scenario, and 0kg to 800kg at the high-density scenario (Figure 4.12). However, there was at least an 80% chance for both scenarios that the yield would be less than 200kg in a given year. It seems likely that, while such yields might be ecologically sustainable, they would not be viable economically.

Discussion

Based on the results of this study, it appears that the long-term optimal strategy for a caviar harvest of shovelnose sturgeon is to harvest approximately 2.7% of spawning adult females annually. This rate of harvest appears to be independent of the parameterization of the Beverton-Holt stock recruitment relationship. While it seems likely that this is the most appropriate recruitment model for use with sturgeon species (Riemann & Beamesderfer, 1990; Pine *et al.*, 2001; Quist *et al.*, 2002), the functional form of such relationships can have a large impact on the results of stochastic dynamic programming models (Runge & Johnson, 2002). Therefore, the simulations shown here represent only one possible set of outcomes and caution should be taken when interpreting the results. It seems unlikely that the number of shovelnose sturgeon in the Wabash River is above or close to the equilibrium level, due to the susceptibility of sturgeon populations to harvest and the history of unrestricted harvesting in the area. However, the degree to which they are below this level will directly influence the management

policy. Populations that are close to equilibrium should stabilize more quickly and potentially provide a more consistent harvest, with fewer years when not harvesting is the optimal policy. However, a low equilibrium value will limit the maximum yield that can be obtained from the population and may influence the economic viability of the harvest. Therefore, it is important that managers select conservative harvest levels to prevent a possible collapse of the fishery until a more accurate assessment of the appropriate stock recruitment function, its corresponding equilibrium, and the actual population size can be determined. This is particularly important when there are other factors that may affect the health of a population. Several authors have contributed declining populations of North American sturgeon to reductions in habitat quality (Boreman, 1997; Keenlyne, 1997) and changes in natural mortality rates will directly affect the optimal harvest strategy.

Morrow *et al.* (1998) suggested that shovelnose sturgeon are probably less vulnerable to harvest than other sturgeon species because of their relatively fast growth and early maturation. However, the harvest rates predicted by the current model are similar to those previously suggested for North American sturgeon. Riemann & Beamesderfer (1990) predicted that white sturgeon stocks would show a reduction in yield at harvest levels greater than 5%, while a 10% harvest would lead to a collapse of the fishery. Similarly, Quist *et al.* (2002) suggested that shovelnose sturgeon would suffer from recruitment overfishing if populations were subjected to exploitation rates of greater than 10%. It is important to note that these studies included harvesting for flesh as well as caviar, and therefore, these rates are taken from the entire population rather than just the spawning adult females. In addition, stochastic dynamic programming often produces optimal harvesting rates that are more conservative than those predicted by other methods, particularly when stochastic variables have not been incorporated.

While the average harvest rate at the stationary optimal strategy is approximately 2.7%, the actual rate varies on an annual basis depending on the stochastic variations in the population dynamics. The probability of not being allowed to harvest in a given year is high,

which makes it difficult for those in the industry to ensure that they can meet consumer demand, and maintain the required staff and infrastructure. In addition, the low yields obtained when harvest is allowable suggest that such a caviar harvest may not be viable economically. The optimization criteria for the caviar harvest model maximizes yield in terms of roe and does not contain an economic component. While this may make the model somewhat simplistic, it is appropriate for use by the Illinois DNR who wish to determine the maximum level of harvest that is biologically sustainable. Further analysis into the viability of the harvest from an economic standpoint is also necessary. However, this was not the goal of the current study. It is also important to remember that this model does not consider the harvest of shovelnose sturgeon for flesh. It is likely that this would increase the pressure on the population as immature and mature but non-spawning females, as well as males, would also be vulnerable to harvest. At present, there is no significant demand for shovelnose sturgeon flesh (Williamson, 2003). However, the current model could easily be restructured should such a harvest become desirable and this would be necessary to ensure that the population is harvested sustainably.

The use of length restrictions has been proposed by a number of authors to reduce the effects of harvest on sturgeon populations (Rasmussen, 1979; Riemann & Beamesderfer, 1990; Caron *et al.*, 2002; Quist *et al.*, 2002). Such a restriction could take the form of maximum allowable lengths or slot restrictions, both allowing a greater number of individuals to produce offspring. The current study did not examine length restrictions with regard to the optimal strategy due to model constraints. However, the adoption of such a policy could potentially lead to increased yields (Quist *et al.*, 2002) and reduce the risk of detrimental population declines. Therefore, further research needs to be conducted in this area.

It is not possible to say for certain that the current harvest regime is unsustainable as there is insufficient evidence to determine the current population size. However, harvest rates have been rapidly increasing over the past few years (Williamson, 2003) and it is thought that demand for North American caviar will continue to increase as sturgeon stocks in the Caspian

Sea become further depleted. Therefore, it would be prudent to utilize conservative management policies until we have more information about the status of shovelnose sturgeon in the Wabash River.

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Variable	Grid Points	Minimum value	Maximum value	Increment
YOY	10	0	1000000	1000000
Juveniles	10	0	10000	1000
Adults	10	0	10000	1000
Harvest Mortality	500	0	1	0.005

Table 4.1. Grid size for the state and decision variables in the stochastic dynamic programming model for the optimal harvest of caviar from shovelnose sturgeon in the Wabash River, Illinois.



Figure 4.1. The Beverton-Holt stock recruitment relationship for shovelnose sturgeon used in the stochastic dynamic programming model. The Pr-values are 1,000,000 (solid line) and 4,000,000 (dotted line) YOY, while A = 0.7. See Equation 4.2 for further details.



Figure 4.2. The average population size for adult female shovelnose sturgeon over a 400-year period based on 100 stochastic dynamic programming simulations of unharvested populations with different initial starting sizes, under the a) low density and b) high density scenarios.



Figure 4.3. Contour plots of optimal harvest rates for spawning female shovelnose sturgeon for the low density scenario. Harvest rates are averaged across the range of a) adult, b) juvenile and c) YOY female population sizes.



Figure 4.4. Contour plot of optimal harvest rates for spawning female shovelnose sturgeon for the high density scenario. Harvest rates are averaged across the range of a) adult, b) juvenile and c) YOY female population sizes.



Figure 4.5. Average population growth for shovelnose sturgeon over a 400-year period based on 100 stochastic dynamic programming simulations for optimally harvested populations with different initial starting sizes, under the a) low density and b) high density scenarios.



Figure 4.6. Change in average optimal harvest rate over a 400-year period harvesting period based on 100 stochastic dynamic programming simulations for populations of shovelnose sturgeon with different initial sizes, under the a) low density and b) high density scenarios.



Figure 4.7. Average yield of roe in a given year over a 400-year harvesting period based on 100 simulations stochastic dynamic programming for shovelnose sturgeon populations with different initial starting sizes, under the a) low density and b) high density scenarios.



Figure 4.8. Average cumulative yield of roe over a 400-year harvesting period based on 100 stochastic dynamic programming simulations for shovelnose sturgeon populations with different initial starting sizes, under the a) low density and b) high density scenarios.



Figure 4.9. Probability distribution of the number of adult female shovelnose sturgeon present at the long-term optimum, under the a) low density and b) high density scenarios.



Figure 4.10. Probability distribution of the number of adult female shovelnose sturgeon present at the long-term optimum, under the a) low density and b) high density scenarios.



Figure 4.11. Probability distribution of harvest rates for spawning shovelnose sturgeon females followed at the long-term optimum, under the a) low density and b) high density scenarios.



Figure 4.12. Probability distribution of the amount of roe harvested from a shovelnose sturgeon population in a given season at the long-term optimum, under the a) low density and b) high density scenarios.

CONCLUSIONS AND RECOMMENDATIONS

Harvest for shovelnose sturgeon is currently unregulated in the Wabash River, Illinois, and catch records have shown a marked increase in demand over the past few years (Williamson, 2003). Sturgeon are particularly vulnerable to harvest because of their life history strategies: they live for many years, mature at a late age and do not spawn annually (Boreman, 1997). The models constructed for this thesis suggest that harvest rates greater than 2.7% of adult spawning females will lead to a declining population, particularly when the population is already below the natural equilibrium. Although this equilibrium value and the current population size are unknown, it is probable that the population is below this level due to the history of harvest in the Wabash River (Williamson, 2003). Therefore, the continuation of the current management policy should be viewed with caution.

It is apparent that better information is needed in order to successfully manage a caviar harvest for shovelnose sturgeon in the Wabash River. While research is currently being conducted by the Illinois DNR, they have been unsuccessful to date in collecting sufficient data to estimate either the population size or factors that influence the population dynamics. This may be in part due to the methods that are currently being utilized in the shovelnose sturgeon surveys. Below are a number of recommendations that may help to improve the recapture efficiency of shovelnose sturgeon in the Wabash River.

 Standardize sampling locations Harvesting and electroshocking surveys for shovelnose sturgeon currently occur throughout the 320km stretch of the Wabash River that is under the jurisdiction of the Illinois DNR, and the same locations are not always used from year

to year. DNR staff have identified three sites, with good historic catches, that could be used as potential sampling sites: Darwin, IL; Russelville, IL; and Vincennes, IN (Figure 5.1). Restricting sampling to these sites could reduce sampling effort, provide more consistent data and help to reduce the violation of assumptions made under standard mark-recapture models (Williams *et al.*, 2002). The addition of a southern sampling site would provide a better estimate of the population status within this stretch of river.

- 2. Concentration of sampling period to spawning run The current DNR sampling period runs from May to November, while harvesting occurs from October to June. While this extended period theoretically would provide more data, it is inefficient and renders any data collected unsuitable for mark-recapture analysis by violating a number of assumptions (Williams *et al.*, 2001). Conducting an intensive sampling regime for a short period during the spawning run (April to July; Williamson, 2003) would be more cost-effective and provide data better suited to mark-recapture analysis. It would also make use of the natural movement of shovelnose sturgeon, which may lead to higher capture rates.
- 3. Use stationary gill nets Due to limited resources, Illinois DNR staff currently sample shovelnose sturgeon as part of a general fish census of the Wabash River. Sampling occurs from May to November using AC and DC electroshocking. However, the use of electroshocking for sturgeon species has been discontinued throughout almost all of the United States and is currently illegal in Michigan (D.L. Peterson, UGA, *personal communication*). Starret & Barnickol (1955) and Grady *et al.* (2001) showed that drifting trammel nets and stationary gill nets are the most effective gear choices for shovelnose sturgeon in the lower Missouri and middle Mississippi Rivers. While the use of trammel nets is currently illegal in the Wabash River (Illinois Administrative Code Section 830.40), stationary gill nets are permitted. The placement of such nets across the river at specified sites during the annual spawning runs would greatly improve the capture

efficiency. This technique would also reduce the required sampling effort as they can be set once per day, left overnight, and checked in the morning. Sturgeon mortality in gill nets is generally low (D. Peterson, UGA, *personal communication*) and caught fish can be tagged and released above the nets to continue their upstream migration.

4. Improve tag retention and readability Most captured individuals are marked with PIT tags which typically have a very high retention rate. However, a large number of marked individuals may be processed through the commercial fishery without "recapture" because most of the fishing crews do not have access to PIT tag scanners. The use of double marking may go some way to avoid this problem and has been used during some marking periods by DNR staff. However, monel tags have typically been used as the secondary tags and these are known to have a low retention rate in some sturgeon species (Smith *et al.*, 1990). In comparison, Carlin tags attached at the base of the dorsal fin had a retention rate greater than 80% in shortnose sturgeon (Smith *et al.*, 1990) and these external tags would be clearly visible to fishers. This would allow the DNR to collect recovery data from a greater number of fishing vessels and hopefully lead to a better estimate of population size.

Both the matrix and optimal harvest models assume that the level of bycatch associated with a caviar harvest has no effect on survival rates. While only ripe-and-running females are taken in the harvest, it is not currently possible to determine the sex of an individual by examining the external morphology. Therefore, harvesters typically make a small cut in the abdomen to determine the presence of ripe eggs. Individuals with abdominal scars are often recaught in subsequent years, suggesting that there is no significant decrease in survival. However, the ability to determine an individual's sex without such invasive practices may be an advantage to both the harvester, by reducing processing time, and the caught-and-released sturgeon, by reducing stress. A recent study by Vescei *et al.* (2003) found that several species of North American sturgeon do exhibit slight sexual dimorphism of the external genitalia and this

can be easily used in the field to determine the sex of an individual. It is possible that similar characteristics are present in shovelnose sturgeon.

Caviar is a highly sought-after commodity and, as such, the industry is often associated with poaching. While most cases of poaching occur within the sturgeon stocks of the Caspian Sea, several high-profile cases have been noted for North American species in recent years (Saffron, 2002; Williamson, 2003). To date, there has been no evidence of poaching for shovelnose sturgeon (Williamson, 2003) but that does not mean that it does not, or will not, occur. The potential risk of this additional pressure on sturgeon stocks means that management policies should tend towards the conservative. The population models in this thesis have not included the possibility of poaching but this can easily be incorporated should it be deemed necessary.

The main priority of the Illinois DNR should be to determine the approximate population size of shovelnose sturgeon in the Wabash River, as well as obtaining better estimates of the factors that may influence population dynamics. In addition, conservative harvest restrictions should be put in place to ensure that the population is not at risk. The use of length restrictions should also be investigated. As more detailed information about the population becomes available, it should be incorporated into models similar to those examined in this thesis to enable managers to make informed decisions about the appropriate management policy.

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Figure 5.1. Potential sites for sampling shovelnose sturgeon on the stretch of the Wabash River under the jurisdiction of the Illinois Department of Natural Resources.



APPENDICES

```
Appendix 3.1. SAS code for fecundity simulation
```

```
%macro fecund(runs = ,);
proc datasets; delete combo;
options nomprint;
%do xx = 1 %to &runs;
data runs;
     %let max_age = 27;
     %do z = 7 %to &max_age;
     leng\&z = 858*(1-exp(-0.13*(\&z+2.7))) + (98.5*normal(0));
     lleng&z = log(leng&z);
     lweight&z = -12.727 + 3.0448*lleng&z + (0.1517*normal(0));
     weight&z = exp(lweight&z);
     FECUND&z = int(175.9 + 16.797*weight&z + 4594.9*normal(0));
     if fecund&z le 0 then fecund&z = 0; else fecund&z = fecund&z;
     %end;
     output;
*** output data ***;
keep fecund7 fecund8 fecund9 fecund10 fecund11 fecund12 fecund13
fecund14 fecund15 fecund16 fecund17 fecund18 fecund19 fecund20
fecund21 fecund22 fecund23 fecund24 fecund25 fecund26 fecund27;
run;
proc append base = combo data = runs force;
%end;
proc means noprint data=combo; var fecund7 fecund8 fecund9 fecund10
fecund11 fecund12 fecund13 fecund14 fecund15 fecund16 fecund17
fecund18 fecund19 fecund20 fecund21 fecund22 fecund23 fecund24
fecund25 fecund26 fecund27;
output out=means mean = fecund7 fecund8 fecund9 fecund10 fecund11
fecund12 fecund13 fecund14 fecund15 fecund16 fecund17 fecund18
fecund19 fecund20 fecund21 fecund22 fecund23 fecund24 fecund25
fecund26 fecund27;
%mend fecund;
run;
*** Number of iterations ***;
fecund(runs = 5000);
run;
```

Appendix 3.2. SAS code for calculation of initial λ and transition matrix parameters for the

shovelnose sturgeon baseline Lefkovitch model

```
proc iml;
print 'shovelnose sturgeon baseline Lefkovitch matrix model';
*** initial parameter values ***;
pi = {0.001 0.9 0.9};
                                  *** state-specific survival rates;
d = \{1 \ 6 \ 21\};
                                   *** stage durations;
R = \{0 \ 0 \ 200\};
                                   *** Fecundity;
lambda= 1.0031;
                                   *** initial estimate of lambda;
print pi lambda;
*** calculate transition matrix parameters ***;
gamma=j(1,3);
P=j(1,3);
G=j(1,3);
do i = 1 to 3;
gamma[i]= (((pi[i]/lambda)**d[i])-((pi[i]/lambda)**(d[i]-1)))
/(((pi[i]/lambda)**d[i])-1);
P[i]=(pi[i]*(1-gamma[i])); *** stage-specific survival;
G[i]=pi[i]*gamma[i]; *** stage-specific growth;
G[i]=pi[i]*gamma[i];
                                  *** stage-specific growth;
end;
print gamma P G;
A= (P[1] | F[2] | F[3])//
    (G[1]||P[2]||0)//
    (0||G[2]||pi[3]);
print A;
*** eigen analysis ***;
call eigen(val,rvec,A) vecl="lvec";
v=lvec[,3];
w=rvec[,3];
lambda=round(max(val[]), 0.0001);
N=w;
tot=sum(N);
age=N/tot;
Reprod=v;
R=sum(Reprod);
R_value=Reprod/R;
print lambda age R_value;
```

```
*** recalculate transition matrix parameters based on new lambda value
***;
do i = 1 to 3;
gamma[i]= (((pi[i]/lambda)**d[i])-((pi[i]/lambda)**(d[i]-1)))
/(((pi[i]/lambda)**d[i])-1);
P[i]=(pi[i]*(1-gamma[i]));
C[i]=pi[i]*gamma[i];
                                *** stage-specific survival;
                                *** stage-specific growth;
G[i]=pi[i]*gamma[i];
F[i]=(R[i]*P[i])+(R[i+1]*G[i]); *** stage-specific fecundity;
end;
print gamma P G F;
*** elasticity analysis ***;
S = (v*w)/(v*w);
Elast=S#A/lambda;
print Elast;
quit;
```

Appendix 3.3. SAS code for calculation of the effects of a caviar harvest on shovelnose

sturgeon

```
proc iml;
print 'sturgeon Lefkovitch matrix with harvest';
do pop_size = 10000 to 1000000 by 50000; *** total population size;
*** calculate transition matrix parameters ***;
pi = \{0.001 \ 0.9 \ 0.9\};
d = \{1 \ 6 \ 21\};
                                      *** state-specific survival;
R = \{0 \ 0 \ 200\};
                                      *** Fecundity;
do harvest = 0 to 0.2 by 0.01; *** harvest rate;
lambda= 1.0031; *** initial estimate of lambda;
gamma=j(1,3);
P=j(1,3);
G=j(1,3);
do i = 1 to 3;
gamma[i]=(((pi[i]/lambda)**d[i])-((pi[i]/lambda)**(d[i]-
1)))/(((pi[i]/lambda)**d[i])-1);
P[i]=(pi[i]*(1-gamma[i]));
                                      *** stage-specific survival;
                                       *** stage-specific growth;
G[i]=pi[i]*gamma[i];
end;
A= (P[1] | F[2] | F[3])//
    (G[1]||P[2]||0)//
    (0||G[2]||pi[3]);
pop=shape({0.9904,0.0049,0.0049},3,1);*** stable age distribution;
N=pop*pop_size;
int_adult=N[3];
                                       *** initial number of adults;
abund=sum(N);
age=N/abund;
yield = 0;
cum_yield=0;
time = 0;
do time =1 to 200;
h2=N[2]*(harvest*G[2]);
h3=N[3]*(harvest/3);
yield=round(2.3*(h2+h3), 0.001);
                                            *** yield of roe (kg);
cum yield=round(cum yield+yield, 0.001); *** cumulative yield (kg);
N[2]=N[2] - h2;
N[3]=N[3] - h3;
N= int(A*N);
```

```
abund1=sum(N);
age=N/abund1;
lambda=abund1/abund;
abund=abund1;
adult=N[3];
end;
print int_adult time lambda adult harvest yield cum_yield;
end;
end;
```

Appendix 4.1 ASDP code for optimal caviar harvest of shovelnose sturgeon.

```
#include "dyn_prog.h"
#define num_states scenario.num_state_vars
#define num_decs scenario.num_dec_vars
#define num_models scenario.num_models
#define INT static int
#define DECIMAL static REAL
DECIMAL result = 0;
REAL sd fcn (
               SM INDEX const iter num,
               SM_INDEX const stage_num,
               SM_INDEX const rep_num,
               XSM INDEX const model num,
                        const dec[],
               REAL
               REAL
                        const outcome[],
               XSM_INDEX const num_rvs,
               REAL const cur_state[],
               REAL
                        const nxt_state[],
               REAL
                         const prior[])
Shovelnose Sturgeon Caviar Harvest Optimization: State Dynamics
The state dynamics follow a postbreeding Lefkovitch matrix model
with harvest occurring prior to spawning
{
INT age=0;
double N[3], spawn, non;
for (age=0;age<3;age++) {</pre>
     N[age]=cur state[age];}
spawn=N[2]/3.;
non=N[2]-spawn;
 /*** calculate the number of spawners harvested ***/
 spawn = max(0.0, spawn*(1.-dec[0]));
 /*** calculate the size of the states in the next time step ***/
nxt_state[0]= (spawn*outcome[1])/(1-0.7*(1-
(spawn*outcome[1]/4000000)));
```

```
nxt_state[1] = (N[0]*0.001)+(N[1]*(exp(5*log(outcome[0]))*(1-
0.1249314)));
nxt state[2]= (N[1]*outcome[0]*0.1249314)+((spawn+non)*outcome[0]);
for (age=0;age<3;age++)</pre>
     if(nxt_state[age]<1.0) nxt_state[age]=0;</pre>
 return;
}
Shovelnose sturgeon caviar harvest optimization: Objective Function
The reward is the weight of roe (kg) harvested from the population
which is a function of the decision and the minimum allowable
population size
#define num_states scenario.num_state_vars
#define num_decs scenario.num_dec_vars
#define num_models scenario.num_models
#define INT
                 static int
#define DECIMAL
                 static REAL
REAL sd_fcn (
             SM_INDEX const iter_num,
             SM_INDEX const stage_num,
             SM_INDEX const rep_num,
             XSM_INDEX const model_num,
                  const dec[],
             REAL
             REAL
                     const outcome[],
             XSM_INDEX const num_rvs,
             REAL const cur_state[],
             REAL
                    const nxt_state[],
             REAL const prior[])
{
DECIMAL obj = 0;
obj=cur_state[2]/3*dec[0];
}
/*_____
         ----*/
return(obj);
}
Shovelnose sturgeon caviar harvest optimization: Terminal Value
Function.
```

```
No terminal values are assigned.
REAL tv_fcn ( REAL const state[],
          REAL const distrib[])
{
DECIMAL result = 0.0;
/*_____*/
result=0;
/*_____*/
return(result);
}
Decision Strategy Lookup Function Declaration -- DO NOT MODIFY !!!
*******
REAL * get_dec (
          SM INDEX
               const stage_num,
          REAL
               const * cur_state,
          REAL
               const * cur distrib)
/*_____
  Decision Strategy Lookup Function Definition -- MODIFIABLE
_____/
{
/*_____
To obtain optimal decision, leave call to "get_opt_dec", otherwise
compute one yourself.
-----*/
return (get opt dec (
             stage num,
             cur_state,
             cur distrib));
```

}