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Paddlefish

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Description of the Species

Taxonomy

The American paddlefish *Polyodon spathula* (Walbaum) of the Mississippi River basin and its tributaries and adjacent Gulf Slope drainages and the Chinese paddlefish *Psephurus gladius* (Martens) of the Yangtze River are the only surviving species in the family Polyodontidae (Rochard et al. 1991; Birstein 1993; Mims et al. 1993). Two extinct genera, *Paleopsephurus wilsoni* (Cope 1883; Grande and Bemis 1991) and *Crossopholis magnicaudatus* (MacAlpin 1941, 1947; Grande and Bemis 1991) are represented in the family. Polyodontidae belongs to the order Acipenseriformes, superorder Chondrostei, subclass Actinopterygii, class Osteichthyes. In 1772, Walbaum first described paddlefish as *Squalus spathula*, originally considered to be a shark; however, by 1797, Lacepede revised this species in the genus *Polyodon* (Vasetskiy 1971). It was subsequently described under various names; complete synonymy can be found in Jordan and Evermann (1896).

Range

The historic range of the American paddlefish (hereafter referred to as paddlefish) was the Mississippi River basin and adjacent Gulf Slope drainages (Hocutt and Wiley 1986; Gengerke 1986), including 26 states of the United States, with a few records from the Great Lakes (Hubbs and Lagler 1958). The current distribution of paddlefish is within the Mississippi River basin and the Mobile River drainage, including 22 contiguous states. Paddlefish in the United States have been extirpated on the periphery of their range, which includes Maryland, New York, North Carolina, and Pennsylvania. Generally, it inhabits large rivers, but it occurs in reservoirs and natural lakes.

Paddlefish supported a large commercial fishery in the early 1900s, but the population declined in most areas of its range. Habitat destruction and river modification are the most obvious alterations affecting their distribution and abundance. Construction and operations of dams have eliminated traditional spawning grounds, affected natural spawning migrations, altered water flow patterns, and eliminated backwater areas that were important as nursery and feeding grounds (Sparrowe 1986; Unkenholtz 1986; Graham 1997). Further, industrial pollution, poaching adults for caviar, and overfishing by commercial and sport fishermen have adversely affected paddlefish populations (Pfielger 1975; Carlson and Bonislawsky 1981; Pasch and Alexander 1986). Despite a decline in the peripheral range, paddlefish populations are considered by resource agency personnel to be increasing in 3 states, stable in 14 states, declining in 2 states, and unknown in 3 states (for more details, see Graham 1997). Several states have been stocking paddlefish to restore them to their historic ranges.

Paddlefish have been introduced to other areas of the world. They were exported to Former Soviet Union (FSU) in 1974 by the Missouri Department of Conservation; 330,000 fry were shipped over the subsequent 4 years (Graham 1986). Paddlefish have been successfully propa-

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gated and cultured in FSU (Melchenkov et al. 1996; Vinogradov et al. 2003). Introduction into Hungary from the United States was also recorded in 1986 (ICLARM Fishbase 1986), although some transfer may have occurred via Russia under the umbrella of the former U.S.S.R. Introductions into China for culture have been made from a private fish farm in the United States since the late 1980s and as a part of a cooperative study (Mims and Shelton 1997a). The culture of paddlefish outside the United States may soon escalate, as live fish were exported for the aquarium trade to about 15 countries in the period from 1988 through 1996 (Hoover 1998).

Anatomy

General

The paddlefish has several nonderived morphological characteristics, including cartilaginous skeleton, a depressed, spatulate rostrum that extends up to one-third of its body length and a heterocercal caudal fin (Russell 1986; Epifanio et al. 1996; Figure 1a). It is a long-lived (up to 30 years), large fish that may reach more than 2 m in length and 90 kg. The body is naked except for few bony romboid-shaped, partially embedded ganoid scales on the sides of the caudal peduncle and opercular openings. Color is light gray to black dorsally, blending to whitish on lower sides and ventrally, with scattered melanistic irregular-shaped blotches on the belly. Mouth is very large, opening straight forward beneath the rostrum. Two minute barbels (in adult 3–4 mm, but nearly as long in larvae) are located in front of the nonprotrusible mouth on the ventral portion of the snout. The eyes are small. Gill covers extend caudad and narrow into posteriorly projecting flaps. Adult paddlefish have gill rakers that are about 5 cm in length with 550–600 rakers in the inner and outer rows of the first arch, which permit filter feeding. Spiracles, anterior to the functional gills, are present. Larval fish have two rows of conical teeth in the upper jaw and a single row in the lower jaw, whereas in adult fish (>25 kg), teeth are retained but are completely embedded in the jaw (Bemis et al. 1997). The digestion system has a pyloric caeca that forms a large mass with a single duct that leads to a spiral valve (Weisel 1973; Figure 1b). Although the skeleton is largely cartilaginous, the cranium is ossified dorsally. Dorsal fin rays number 50–56, anal fin 50–65, and vertebrae 45.

Electroreception

Electroreception is the dominant sensory system of paddlefish. The sense organs of this system are known as ampullary organs and are common not only to paddlefish and sturgeon, but to aquatic amphibians, lungfishes, and

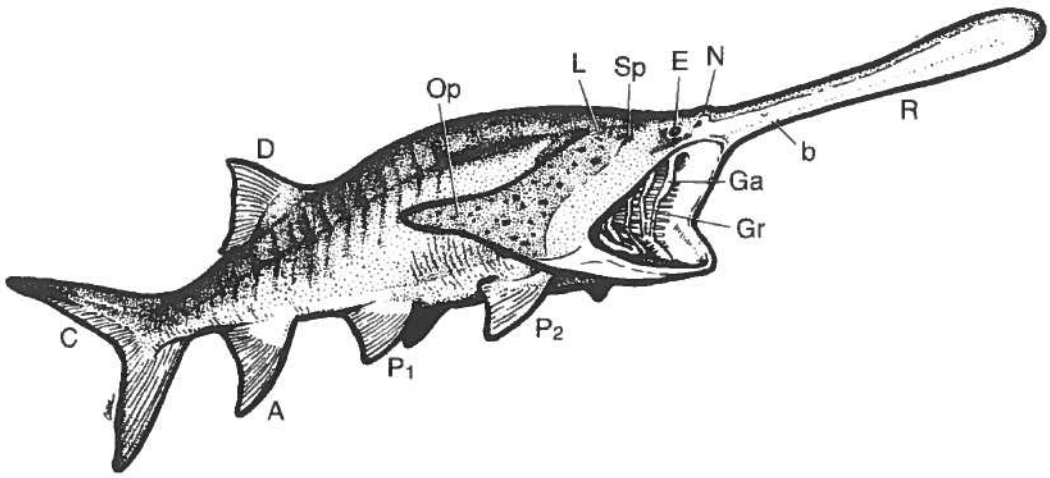

Figure 1a.— General morphology of paddlefish (A = anal fin; b = barbels; C = caudal fin; D = dorsal fin; E = eye; Ga = gill arch; Gr = gill rakers; L = pore of lateralis system; Op = opercular flap; P_2 = pectoral fin; P_1 = pelvic fin; R = rostrum; Sp = spiracle).

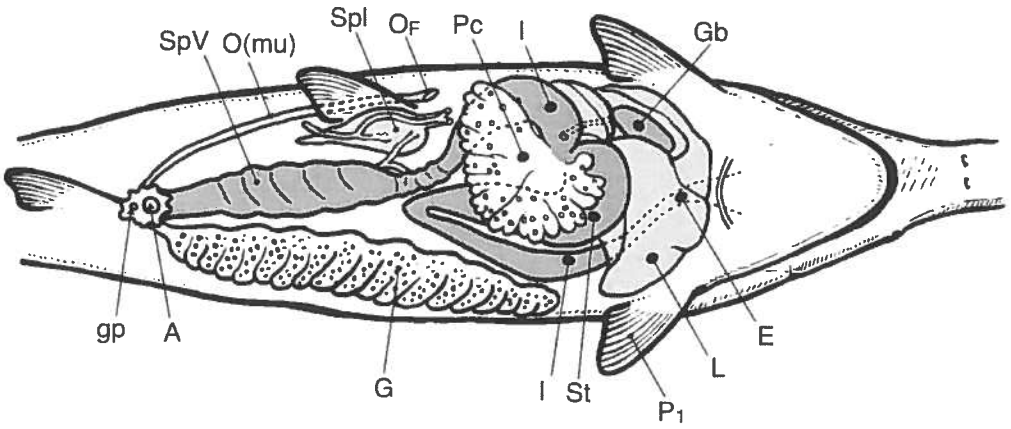

Figure 1b.— General internal anatomy, modified from Weisel (1973) (A = anus; E = esophagus; G = gonad, ovary; Gb = gallbladder; Gp = gonopore; I = intestine; L = liver; O = oviduct, Mullerian duct; Of = oviductal funnel; Pc = pyloric caecum; Spl = spleen; Spv = spiral valve; St = stomach).

polypterids. The ampullary organs of paddlefish are found mostly on the rostrum but are also located on the cheek and opercular flap. An adult fish is estimated to have 70,000 ampullary organs (Nachtrieb 1912). The number of organs increases throughout life by subdivision of existing organs. The origin and the function of the rostrum with passive electroreceptors is primarily as a sensory antenna for detecting planktonic food, but also detects and avoids obstacles with exposed metallic surfaces (Jorgenson et al. 1972 and Gurgens et al. 2000). Behavioral experiments conducted in the dark to eliminate vision showed that paddlefish could efficiently capture planktonic prey to distances up to 8–9 cm (Wilkens et al. 1997). Further, experiments demonstrated that swarms of *Daphnia* plankton are a natural source of electrical noise (Wilkens et al. 1997; Russell et al. 1999).

Ram Ventilation

Paddlefish respire by ram ventilation, which occurs when a fish swims with its mouth open so that water is forced across the gills. This type of respiration in paddlefish requires constant swimming as evidenced by the absence of a buccal valve and the inability to completely close either the mouth or buccal chamber (Bemis et al. 1997). Flattened gill arches, elongated gill rakers, and secondary fixation of the upper jaw to the neurocranium are specialized features associated with filter feeding and is only possible because of ram ventilation, where buccal-opercular pumping and branchial arch mediated respiratory movement is not necessary (Bemis et al. 1997). Because ram ventilation requires constant swimming, fish cannot be confined in small containers or stocked at high densities (see nursery section), which would hinder swimming and cause suffocation.

Cytogenetics

A more complete overview of cytogenetics of paddlefish can be reviewed in Birstein et al. 1997 and Wirgin et al. 1997. Paddlefish has a chromosome number of 120 and is considered to be tetraploid with four active nucleoli per nucleus (Dingerkus and Howell 1976). Chromosomes are divided in the following groups: 48 macrochromosomes and 72 microchromosomes; among macrochromosomes, there are 44 meta-/submetacentrics and 4 telocentrics. The paddlefish includes two divergent gene pools in the Mobile Bay drainage and the Mississippi River stocks (Epifanio et al. 1996); 20 loci have more than one allele while 42 are monomorphic based on allozyme analysis (Carlson et al. 1982). Using mitochodrial DNA analysis, Salanski et al. (2000) identified 22 polymorphic sites in a Missouri River population. In general, little cytogenetic change has occurred during the evolution of Polyodontidae.

Historical Overview

Culture of paddlefish was first initiated by Missouri Department of Conservation during the early 1960s through the early 1970s. Purkett (1963b) was the first to collect eggs and fertilize and hatch them. Needham (1965) is accredited for the first successful spawning of paddlefish induced with pituitary injections. Russell (1973) continued to develop a standard spawning technique and initiated rearing fry to fingerlings in ponds. The paddlefish program in Missouri was designed to reestablish paddlefish in the state and to develop a sport fishery in some of their impoundments. Semmens and Shelton (1986) were the first to initiate the development of paddlefish as a food fish. They also demonstrated that luteinizing hormone-releasing hormone analog (LHRH*a*) would induce ovulation and spermiation as described by Doroshov et al. (1983) for white sturgeon *Acipenser transmontanus*, and could permit consistent commercial production.

Since the mid-1980s, most of the research in the United States to develop and refine techniques for culture of paddlefish as a food fish has occurred at Kentucky State University Aquaculture Research Center in Frankfort. Mims et al. (1991, 1993, 1995a, 1995b) developed organic and inorganic fertilization schedules and the inoculation of *Daphnia* sp. to promote high survival (50–80%) and growth rates (2 cm/week) in nursery ponds for paddlefish fingerlings. Production strategies such as reservoir ranching (Onders et al. 2002) and pond culture with catfish (Mims et al. 1999) are being developed and refined for commercial production of meat and caviar. Further, a program to produce all-female offspring with sexually manipulated broodstock is being tested for development of the domestic caviar industry (Mims and Shelton 1998) and a procedure to cryopreserve sperm is being studied (Brown and Mims 1999; Mims et al. 2000). Processing and marketing studies at Kentucky State University have been conducted on paddlefish meat and caviar to increase potential of national and international commerce, including testing of refrigerated and frozen meat stability (Lou et al. 2000a), value-added products such as smoked paddlefish and surimi (Mims et al. 1999; Lou et al. 2000b), and consumer acceptability of paddlefish products (Wang et al. 1995; Mims et al. 1999).

Regulations and Permitting

Paddlefish, like all sturgeon species worldwide, are listed under the provisions of CITES, United Nation's Convention on International Trade of Endangered Species of Wild Fauna and Flora. In general, CITES provides an international mechanism for the maintenance of biodiversity by protecting listed species of wildlife and plants from over-exploitation through international trade. In 1989, the U.S. Fish and Wildlife Service (USFWS) was petitioned to include paddlefish on the list of Threatened and Endangered Species under the provisions of the endangered Species Act of 1973. After collecting supplemental data on paddlefish populations from the 22 states within its range, USFWS agreed that the listing of paddlefish as "threatened" was not justified. However, because the uncertainty of the species' status in several areas of its range, USFWS recommended to reclassify the paddlefish from category 3C (abundant and not subject to threat) to category 2 (potential endangered or threatened species, but needs more data to be conclusive). Further, in 1992, paddlefish were added to the CITES Appendix II, which requires that the exporting country must have a CITES export permit for international trade of paddlefish and their parts such as meat, caviar, and so forth. When an exporting country issues a permit for an Appendix II listed species, this indicates that law enforcement has made the finding that export is not detrimental to the species survival in the wild and that the species was legally acquired.

Within the United States, each state has its own specific regulations on the propagation, culture, and transport of paddlefish as a food fish. It is recommended that the culturists check with their natural resource conservation agency for proper permits and regulations before developing plans for paddlefish farming. In general, most broodstock must be captured from the wild population. This requires a license or special permit to capture the fish with commercial gear or buy fish from commercial fishermen. Since 1983–1994, the number of states that permitted commercial harvest went from 11 to 6 states, respectively (Graham 1997). Currently, there are only six states (Arkansas, Illinois, Kentucky, Missouri, Tennessee, and Mississippi) that permit restricted commercial harvest of paddlefish.

Culture Methods:

Facilities

Water Supply and Quality

A dependable supply of good quality water is essential to a successful paddlefish production hatchery. Groundwater is recommended over surface water supplies from ponds, reservoir, or streams. Groundwater tends to have a relatively minor seasonal temperature change. Groundwater temperatures in the United States range from about 26°C in southern Florida to 3°C in northern Minnesota (Soderburg 1994). For paddlefish, water temperature range for egg incubation is 15–20°C and for tank rearing of fish, 22–24°C. Because oxygen and biological processes are limited underground, groundwater typically contains few pathogens and little or no oxygen, but carbon dioxide and argon gases can be supersaturated. Therefore, groundwater must be pumped to an aerated storage tank to degas the carbon dioxide and argon gases and add oxygen before use in the hatchery. Other water quality characteristics such as alkalinity, hardness, and dissolved minerals should be tested since these characteristics can be very different from surface water. These parameters are discussed further in the Environmental Conditions section.

Egg Incubation

The most reliable hatching system is the McDonald hatching jar, commonly used for sturgeon and hybrid striped bass (*Morone chrysops* × *M. saxatilis*). The incubation jars are 8-L capacity, round bottom cylinders, 46 cm tall and 16 cm in diameter. The jar is made from an acrylic plastic that allows direct observation of the eggs and water flow patterns. The water enters the jar through a 2.5-cm diameter acrylic tube that has three wings attached to the bottom of the tube and a screen top to hold the tube firmly in place. This design provides adequate control of water flow and movement of the eggs, which fosters egg development and limits mortality from environmental stress and bacterial and fungus diseases. Each jar can hold between 70,000 and 100,000 eggs.

Water is circulated through the jar and allowed to discharge freely through the eggs. Water is generally supplied at the rate of 4 L per min. As the fry begin to hatch and "swim-up," the jar is positioned to discharge into an aquarium, floating screen baskets in a catch basin, and so forth. Water should not be recirculated in order to maintain good water quality and lower the chance of diseases.

Holding Tanks

Circular tanks are necessary for holding broodstock and for fingerling production. Broodstock must be held in tanks that have a diameter of greater or equal to 2.4 m, so the fish can swim continuously and aerate their gills (Mims et al. 1999; see ram ventilation). Tanks must be covered with netting and securely fastened around their perimeter to prevent fish from escaping. Fingerlings also should be raised in circular tanks with diameters 1.5 m and larger. Water exchange of 25% of the tank volume per day is recommended. Tanks should have a smooth internal surface to prevent physical damage to the fish by "rubbing and bumping" during their confinement. Fiberglass or plastic circular tanks are recommended, though painted metal stock tanks can be used. In the fingerling operation, circular tanks are beneficial because of the "vortex effect," by which excrement and excess feed move towards the drain in the center of the tanks and allows easy removal with a swimming pool vacuum system. Stainless steel or aluminum screen materials are recommended for the drain with mesh sizes varying from 0.8 mm (1/32 in) with newly hatched fry and increasing up to 6 mm with 12-cm and larger fish.

Broodstock

Broodstock are generally obtained from public waters because of the long maturation period (Mims et al. 1999); control of the adults in the context of a sportfish complicates access to broodstock for artificial propagation. Fish are captured in 13-cm or larger bar mesh gill nets that are set in rivers or lakes in late winter or early spring when water temperatures are less than 16°C (see Harvest section). Licensed commercial fishermen are a good source for obtaining broodstock; however, in some states special collection permits might have to be issued in order to obtain stock for propagation.

Males are generally smaller and are identified by minute tubercles on their head and opercular flaps; this is not fool-proof, as not all males are tuberculate and some females may have slight development. Females are mature at sizes larger than 9–15 kg (107–140 cm) and males larger than 5–9 kg (Mims et al. 1999), but somewhat smaller in the Mobile River drainage (females > 7–10 kg or 82–90 cm; males > 6–8 kg or 72–75 cm; Lein and DeVries 1998). Gravid females will have swollen abdomens; the gonopore areas may be distended and reddish in color.

Broodstock can be transported to hatchery facilities in transport tanks that have dimensions sufficient to accommodate the fish length; a loading rate of about 0.25 kg/L, supplemental oxygen or aeration with agitators, and the addition of sodium chloride (0.25–0.50%) are recommended. By appearance, paddlefish do not transport well; as soon as they are loaded in transport tanks, they float belly up in what appears to be a self-induced lethargy. The expectation is that the fish are immobilized by an acute physiological stress response, but in fact, the magnitude of increase of stress indicators in the plasma is less than for most teleosts (Barton et al. 1998). Furthermore, the fish survive surprisingly well despite this behavior and their poor capacity to operculate by branchial pump water movement. Upon arrival at the destination, fish will recover and swim normally with some "encouragement." Semmens (1986) demonstated that broodstock can be held in watershed ponds and repetitively develop eggs and ovulate in captive, not different from freshly captured fish. A broodstock registry has been established for paddlefish (Kincaid et al. 1999).

Natural Reproduction and Spawning Characteristics

Most statistics, such as growth, fecundity, spawning frequency, and age at sexual maturity are given for paddlefish from the Mississippi River drainage, but in fish from the Mobile River drainage, most of these characteristics are divergent (Lein and DeVries 1998). Sexual maturity is attained at about 7–14 years (>6 years in Mobile River system), for females at 9–15 kg or 107–140 cm in length, but somewhat earlier in males at 6–7 years (>5 years in Mobile River system) and smaller at 5–9 kg (Larimore 1950; Carlson and Bonislawsky 1981; Reed et al. 1992). Larimore (1950) studied gametogenesis. The testes extend along the dorsal body wall separately except in their caudal portion. Ventrally, the testes are embedded in a thick layer of fat (Meyer and Stevenson 1962). The ovaries are slightly more lateral, but in immature stages and during off-spawning years, they also are surrounded by fat. Gonads are undifferentiated during the first year of life and at sizes less than 565–710 mm total length (TL); ovaries develop primary oocytes at about 70 weeks of age (Mims et al. 1997). Both males and females possess Mullerian ducts, which are functional in mature females. Ovulated eggs pass from the body cavity through these "oviducts" to the genital vent (Conte et al. 1988).

Paddlefish move upstream during spring flooding under the impetus of increased flow at about 275 m^3/s and after the water temperature has warmed to about 10–11°C (Purkett 1961;Yeager and Wallus 1990). Paddlefish spawn over gravel substrate in the main current at about 1 m/s velocity, when water temperatures reach about 13–18°C, which is in mid-April near the center of its geographic range (Pasch et al. 1980; Wallus 1986). Spawning in the Mobile Bay system occurred at water temperatures of 12–17°C and 78–115 m^3/s (Lein and DeVries 1998). Spawning has been observed during high water at 16°C.

Ovary weight in mature females is about 15–20% of the body weight, and fecundity is in the range of about 12,000 eggs/kg (Vasetskiy 1971); Lein and DeVries (1998) measured about 15,000–23,000 eggs/kg in the Mobile River system, but Reed et al. (1992) reported only about 9,500 eggs/kg from the Atchafalaya River system in Louisiana. The diameter of mature eggs is between 2 and 2.5 mm to 2.7 mm, and is slightly oval and heavily pigmented with melanine (Ballard and Needham 1964; Shelton and Mims 1995). Mature ova have two investing membranes and the nucleus moves to the animal pole prior to ovulation (Larimore 1950). Nuclear migration and pigment redistribution are used in ova staging to monitor maturation and predict ovulation (Shelton and Mims 1995). The egg swells after contact with water and the outer membrane reacts causing adhesiveness as

described for sturgeon by Markov (1978) and Cherr and Clark (1985). The fertilized eggs are slightly larger at about 2.5–4.0 mm; eggs are adhesive and demersal, sticking to gravel (Purkett 1961, 1963a). Cleavage in the developing zygote is holoblastic (Ballard and Needham 1964).

Under natural variable temperature, larvae hatch in about 7 d at 18°C and 12 d at 13°C, respectively. During early posthatching, yolk sac larvae are about 9–10 mm and they swim vertically in the water column, then sink passively. This pattern is altered when enough yolk has been absorbed to improve swimming ability, at which time they swim continuously for the next 2–3 d near the water surface in erratic circular patterns. The oral plate is perforated, and the eyes and barbels are developed during this period; the paddle gradually develops after about 3 weeks at 50–55 mm.

Induced Spawning

Artificial propagation is a vital component for aquacultural development, but it also has been an effective management tool for maintaining some populations that were affected by environmental alterations, for example in the Osage River, Missouri. Some of the techniques used on paddlefish were modified from propagation techniques developed for sturgeon (Conte et al. 1988; Dettlaff et al. 1993).

Broodstock Selection

Paddlefish broodstock can be evaluated by ova staging to determine gonad maturity as has been done for sturgeon (Kazanskii et al. 1978; Doroshov et al. 1983). Ova are sampled through a small abdominal incision because a catheter cannot access the ovaries via the oviduct. Ova can be examined for distribution of pigmentation and to estimate the position of the germinal vesicle (Shelton and Mims 1995; Figure 2). The ova are placed in a vial in a small amount of water and boiled for 2 to 5 min until the yolk is hardened; then, several eggs are cut in half with a sharp blade, passing through the polar axes. If the nucleus is centrally located, hormonal injection will not likely succeed; however, if the nucleus (germinal vesicle—GV) has progressed well toward the animal pole (germinal vesicle migration—GVM), then ovulation probably can be stimulated (see illustration). Selected fish are held in circular tanks (about 2.5–3 m in diameter) so they can maintain continuous swimming. Water should be 16–18°C with a flow rate exchange of 25% of the total volume per hour and water saturated with oxygen (100%; about 10 mg/L at 16°C).

Injection Regimen

Gamete maturation is stimulated by intraperitoneal injection of LHRH*a* of des-Gly 10(D-Ala6) ethylamide (Mims et al. 1997, 1999). This hormone is currently used under an Investigational New Animal Drug (INAD) permit. Females are given a total dose of 100 µg/kg body weight administered in a priming injection (10 µg/kg) and a resolving injection (90 µg/kg) 12 h later. Ovulation is expected in 12–24 h at 17°C. Males are given a single dose of 50 µg/kg when the females receive the initial injection. They will spermiate within 24 h and continue for 3–4 d. The early conventional practice in the artificial propagation of paddlefish was to induce ovulation with a homoplastic injection of freshly collected paddlefish pituitaries; the glands were stored frozen, then thawed just prior to use. Dose for females is a single injection of two glands from donors of equivalent weight (Graham et al. 1986). The latent period is 30–36 h for females injected early in the spawning season, but 18–24 h later. Both Graham et al. (1986) and Semmens (1986) report that latency for females injected with LHRH*a* is somewhat shorter than for females injected with pituitaries. Pituitary glands were the primary means to induce spawning until other gonadotropic materials were developed; Clemens and Sneed (1962) reported the efficacy of various pituitary donor/recipient relationships. Common carp *Cyprinus carpio* became the usual donor and processed pituitaries were commercially available; however, Semmens (1986) found that common carp pituitary had a lower stimulating effectiveness than paddlefish pituitaries.

As the gonadotropin effects maturation, the GVM proceeds toward the animal pole; upon reaching the polar area, the nuclear wall disintegrates (germinal vesicle breakdown—GVBD), which signals the resumption of meiosis and the pending formation of the first polar body. Fe-

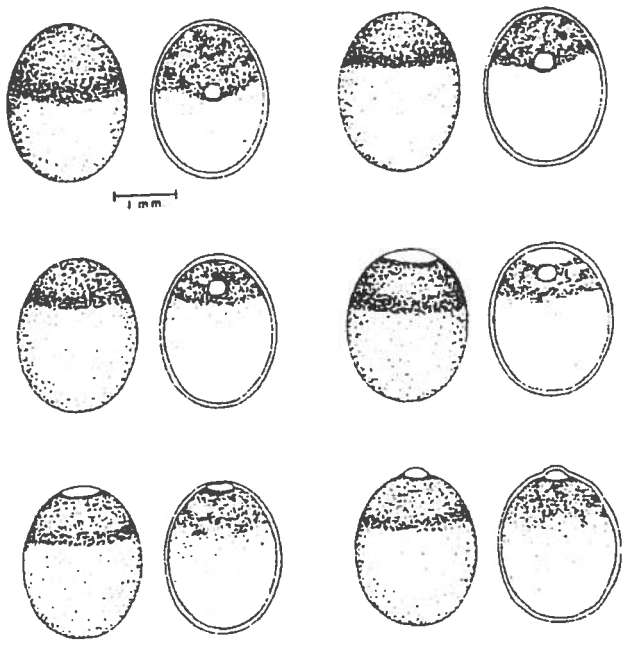

Figure 2.—Paddlefish oocyte stages (sequentially from upper left to lower right); left illustration of each pair is representative of the surface pigmentation and the right illustration of each pair is of bisected oocyte showing yolk distribution and germinal vesicle (GV) position (Shelton and Mims 1995).

males are checked periodically during the latency period; slight pressure on the abdomen will express a few eggs when ovulation has occurred, or some eggs may be seen adhering to the bottom of the holding tank. If eggs are to be stripped, then collection can begin, but if one of the surgical techniques is to be used, a delay of an hour or so will ensure more complete ovulation.

Collection of Gametes

After ovulation, conventional egg collection has been through multiple strippings of a few hundred milliliters of eggs at 30- to 60-min intervals over a 12- to 24-h period (Graham et al. 1986); eggs are ovulated into the peritoneal cavity and must enter the dorsally attached oviducts via mid-anteriad openings. More recently, ovulated eggs have been collected from fish via an abdominal incision, as practiced in artificial propagation of sturgeons (Conte et al. 1988). Surgical removal accelerates the collection of eggs compared to the labor-intensive and lengthy stripping procedure; however, in our experience, survival of broodstock has been poor, as it has been in the traditional stripping practice (Stech et al. 1999). Though surgical removal of eggs and subsequent closure of the incision with sutures or staples has been an improvement over the labor-intensive stripping protocol, the sutures usually pull through the tissue, leaving an unprotected wound. The muscular stress on the incision, unlike sturgeon, is due to the continuous swimming action of the fish. Currently, Stech et al. 1999 have demonstrated a minimally invasive surgical technique (MIST) that provides free-flowing eggs via a small incision through the ventral portion of the dorsally located common oviduct near the urogenital opening; the procedure requires only 10–15 min, egg collection is complete and the fish is returned to the water with minimal stress (Figure 3). This procedure has not caused short-term nor delayed mortality of fish. Second-time MIST spawners have been successfully ovulated in a subsequent year (Mims et al. 2004).

Eggs are demersal and adhesive (Yeager and Wallus 1982) and for incubation in McDonald jars, they must be treated to prevent clumping. Conventional treatment of sturgeon eggs is to coat them with river silt (Doroshov 1985; Conte et al. 1988; Dettlaff et al. 1993) or with a suspension of Fuller's earth at about 50–75 g/L; the latter has been the most widely applied to "destick" paddlefish eggs (Graham et al. 1986; Mims and

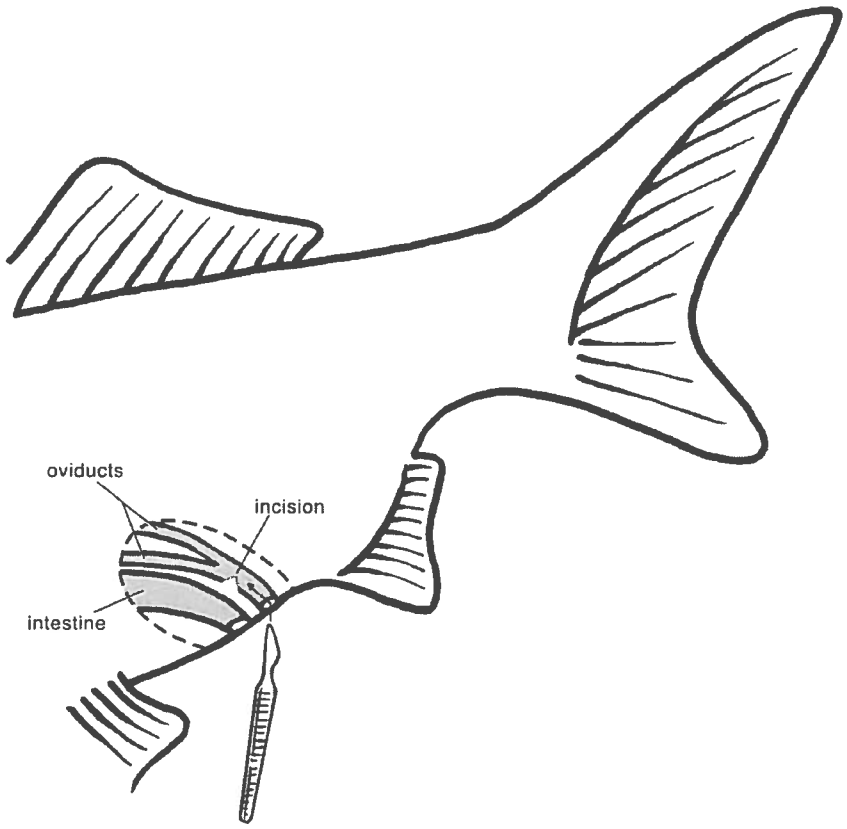

Figure 3.—Schematic illustration of the minimally invasive surgical technique (MIST) for removal of ovulated eggs from paddlefish.

Shelton 1998). Kowtal et al. (1986) reported that treatment with urea/salt/tannic acid would remove the adhesiveness and that hatch rate was comparable to silt treatment. Number of ovulated eggs varies with fish size and to a certain extent, population. Mims et al. (1999) report that females 9–36 kg will release 70,000–300,000 eggs while Graham et al. (1986) report that females (10–13 years old) 20–30 kg will release 300,000–400,000 eggs. Fecundity for paddlefish from the Mobile Bay drainage is 15,000–23,000 eggs/kg of body weight (Lein and DeVries 1998), but ovulation range is about 8,000–11,000 eggs/kg of body weight (Semmens 1986).

Paddlefish milt has a range of 0.2–1.7 × 10^9 spermatozoa/mL (Linhart et al. 2000). A positive correlation between concentration of spermatozoa and light transmittance using a spectrophotometer at a wavelength of 450 mm has been reported; the linear regression was sperm concentration × 109 mL-1 = $1.3244 \bullet x^{-0.9969}$ where x is the percentage of sperm transmittance (Linhart et al. 2000). Spermiating males can provide large volumes of milt up to 4.5 d. Milt is collected by inserting a short segment of Tygon tubing attached to a syringe into the urogential opening and applying light suction to withdraw a sample. Milt samples can be chilled on "wet" ice (ice held at room temperature until ice surface is wet) or held undiluted in a refrigerator (1–4°C) for short-term storage. Motility of spermatozoa should be checked microscopically before use. Milt is diluted in water (1:100–200) just prior to adding to the eggs to prevent polyspermy (Ginzburg 1968; Dettlaff et al. 1993); Chondrostei have multiple micropyles (Cherr and Clark 1985) permitting the probability of polyspermy. Milt is added to eggs at about 10–15 mL of undiluted milt/L of eggs and stirred for about 1 min. Volume of unfertilized eggs measures about 50,000/L (Mims and Shelton 1999). The Fuller's earth suspension is then added to the fertilized eggs, and stirred continuously for 20–30 min, usually with one

change of fresh suspension during this interval. The eggs are rinsed in freshwater prior to loading in the hatching jars.

Incubation

The standard 8-L McDonald hatching jars are commonly used for incubation. Fertilized eggs are loaded at about 70,000–100,000 eggs per jar (Graham et al. 1986; Mims and Shelton 1999). Water flow is about 4–8 L/min in order to maintain the eggs in motion.

Embryonic Development

Embryonic development for sturgeons is described by Dettlaff et al. (1993); paddlefish and sturgeon embryogeny coincide in almost all details. Cleavage is holoblastic; at 14°C, the early blastula is formed in 24 h, gastrulation is initiated by 32 h and neuralization, including optic vesicle formation, is evident in 90 h, although little increase in size of the eye occurs between 4 and 21 d (Ballard and Needham 1964). Time to first cleavage ranges from 148 to 215 min inversely within the temperature range of 14–21°, or about 2.5 times the interval between subsequent synchronous mitotic divisions (τ_0), 48–84 min, respectively (Rubinshtein et al. 1997; Shelton et al. 1997). During day 6, the tail bud is free from the yolk surface and active movement begins. Incubation period to hatching takes 155–166 h at 14–19°C (Figure 4). Hatching occurs after 6–7 d at 16°C (Bemis and Grande 1992). Swimming is initially vertical and intermittent, but subsequently is continuous, in wide random circles, close to the water surface. The yolk sac is absorbed at about 16–18 mm, 5–6 d after hatching. The mouth opening has developed by about 8–9 mm and the jaw becomes functional between 13 and 17 mm; barbels can be easily seen; and incisor-like teeth form in the upper and lower jaws. The paddle begins to form between 21 and 34 mm and fins begin to have definitive form, including heterocercal caudal fin (Yeager and Wallus 1990).

The mitotic interval or developmental duration (τ_0) for paddlefish in the range of 16–20°C is between 75 and 50 min, respectively, which is longer than that of the shovelnose sturgeon *Scaphirhynchus platorynchus* (Shelton et al. 1997) and for four species in FSU (Dettlaff et al. 1993). Time to hatching is 10–12 d at 11–12°C, 7–8 d at about 15°C, or 5–6 d at 18°C (Graham et al. 1986; Melchenkov et al. 1996; Mims and Shelton 1999;

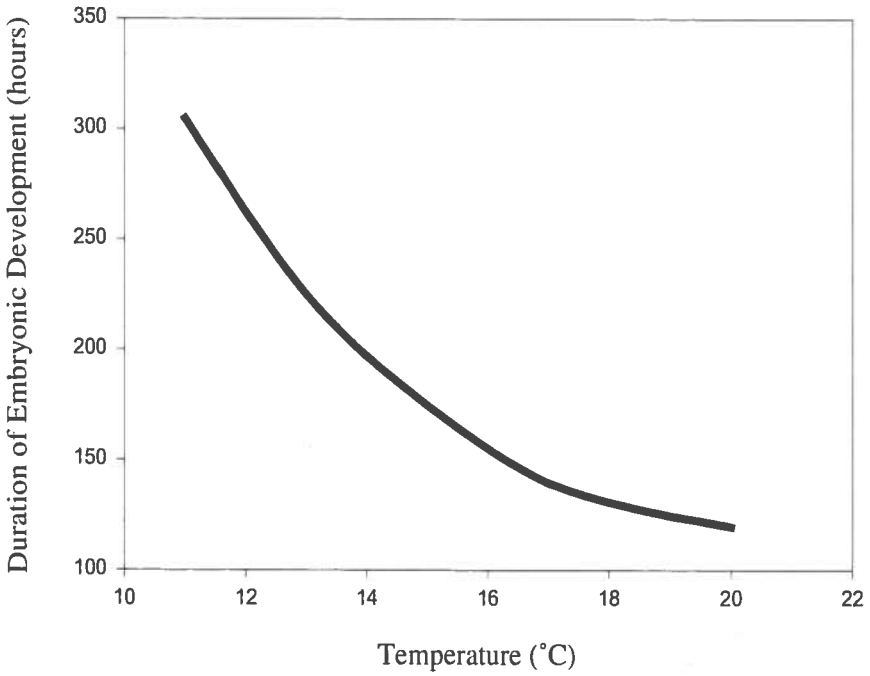

Figure 4.— Duration of embryonic development of paddlefish depending on water temperatures.

Vinogradov et al. 2003). Hatching may begin significantly sooner than the time to peak hatching. Yolk absorption requires about 5–6 d at 18°C; during this interval, the mouth and foregut develop. First feeding coincides with the appearance of darkly pigmented material in the gut and in the spiral valve. Larvae can be transported to nursery ponds before dawn in plastic bags up to 500–600/L of water with an atmosphere of oxygen; transient time can be up to 36 h (Graham et al. 1986; Mims and Durborow 1998).

Nursery Methods

Nursing of larval paddlefish in earthen ponds has been the primary method of raising paddlefish fingerlings and has been dependent upon managing large cladocerans as the food of choice for larval paddlefish (Ruelle and Hudson 1977; Rosen and Hales 1981; Michaletz et al. 1982; Webster et al. 1991; Mims et al. 1995a). Organic fertilizers have been the most effective in stimulating cladoceran populations (Michaletz et al. 1982; Graham et al. 1986; Mims et al. 1991,1995a, 1995b, 1999). A combination of rice bran and inorganic fertilizer has given best results in Kentucky (Table 1). Fertilized ponds should stand for about 2 weeks to permit growth of cladoceran populations and then, larvae stocked at a rate of 62,000/ha. Growth to about 150 g or 35 cm in 6 months can be expected. During the initial growth period, supplemental feed can be supplied (#00–03 salmon/trout crumbles; 50% protein) at 15–18 kg/ha; then at about 75 mm, fish can be trained to a 1.5-mm pellet with 45% protein (Mims et al. 1999). Feed conversion can be about 2:1–4:1. Dissolved oxygen should be maintained at greater than 3 mg/L, or somewhat higher than for typical catfish culture.

Table 1.—Quantities and application schedules.

Week	Rice bran[a] kg/ha	Inorganic fertilizer[b] L/ha
0[c]	1,410	37
1	310	4.6
2	160	9.3
3	160	9.3
4[d]	160	9.3

[a] Other organic fertilizers can be used based on a total application of 45 kg/ha of nitrogen.
[b] Inorganic fertilizer 10-34-0.
[c] Fertilizers were applied to filled ponds three times per week during a 2-week period before stocking.
[d] Fish should be offered extruded diet of 1.5 mm during week 4.

One major problem with pond culture is lack of large caladoceran. Variation in water temperature in late spring can greatly affect the growth or decline of large cladocera; and therefore, give variable fish growth and survival. Another problem with pond culture is aquatic bird predation. The surface orientation of larvae/fingerlings and their swimming behavior make them extremely vulnerable to birds such as cormorants and herons. Covering ponds (≤400 m^2) with netting has reduced losses, but is not practical or cost effective on large ponds. Survival in nursery ponds has ranged from about 30–80% (Michaletz et al. 1982, Mims et al. 1991, 1995a). Mims and Knaub (1993) stocked 8-d-old fry at 61,775/ha. After 40 d, they grew to an average of 125 mm in total length (TL) and 6.8 g in weight. Forty-seven-day-old fish (3.6 g, 120 mm) were stocked into earthen ponds in Kentucky at 4,940 or 9,880/ha, fed a sinking trout diet and reached 107 and 139 g in 131 d with survivals of 72% and 41%, respectively (Tidwell et al. 1991); the yield from these two ponds was between 380 and 580 kg/ha. Paddlefish juveniles of 38 cm (140 g) were stocked at 990/ha in catfish fingerling production ponds for a 209-d culture period and grew at an average rate of 2 g/d, and yields of about 400 kg/ha of paddlefish (Burke and Bayne 1986).

Recently, early training to a prepared diet has permitted the use of more intensive systems such as tanks and raceways. Selection of the optimum prepared diet is important, not only from a nutritional and energetic consideration, but also with reference to palatability. Paddlefish larvae and fingerlings have readily accepted trout and salmon prepared diets especially those made by Rangen, Inc. (Mims and Shelton 1998). In Texas, stocking rates in tanks or raceways has been successful at about 2/L for the first 2 weeks (to size of 5 cm), then to maintain good growth, stocking rate should be reduced by about half at biweekly intervals (10 and 15 cm) with harvest at 25 cm and stocked directly into lakes or river systems. Survival can be expected to be 50–80% (Mims and Durborow 1998). In Russia, Melchenkov et al. (1996) have reported using higher densities of paddlefish

fry fed prepared diets and raised in flow-through circular tanks to produce 2–4-g fish that were ca. 7.5–10 cm in TL (Table 2). As the rostrum develops, it becomes an impediment to particulate feeding on prepared diets; if floating pellets are used, fish need more room to rotate so the mouth is sideways to permit engulfing the feed (Graham et al. 1986). In Kentucky, once fish are averaging 10–14 g and trained on extruded pellets, they are stocked in ponds for further grow out on a floating diet. Further research studies are planned to optimize survival of paddlefish fingerlings using a combination of tank and pond culture methods.

Grow Out

Stocking rate and yield for meat fish are dependent on the type and fertility of the culture system. Fertilized farm ponds can be stocked with fingerlings (30–35 cm) at rates of 125–250/ha, and a yield of about 100–200 kg/ha can be expected. Polyculture with a primary species that is fed will permit stocking of about 250–615 fingerling/ha and about 340–550 kg/ha can be expected (Mims 1991a). Semmens and Shelton (1986) report stocking 1–2-month-old paddlefish at about 1,500/ha in channel catfish fingerling ponds. Stocking 1-year-old fish at about 250/ha in catfish production ponds should add about 450 kg/ha in paddlefish yield. Growth rate under these conditions can be expected to be 2–3 kg in 1–2 years.

Management for the production of fish for their roe (i.e., caviar) will require a different strategy. In intensive systems as in a polycul-ture with catfish at ca. 12,500/ha and paddlefish at 75/ha, growth to about 3 kg in 1 year can be expected, but egg maturity would require a greater time investment of several years. Alternatively, a reservoir ranching strategy might be considered. Reservoir ranching trials were conducted in watershed ponds in Kentucky (Onders et al. 2002). Fish 30–67 cm TL (0.17–0.33 kg) were stocked in flood control impoundments in January at about 10/ha and harvested in the fall after about 2 years. About 25% of the fish were recovered and average yield was about 14 kg/ha. Mean individual harvest weight was between 2.8 and 6.0 kg. Paddlefish stocked at 10–20/ha can reach 4–5 kg in 18 months and about 100 kg/ha can be harvested annually. Age-2 fish at 0.7 kg were stocked at 8/ha in a watershed pond in central Oklahoma; 2 years later, they had grown to about 11 kg. In either case, an all-female population would greatly increase the profit potential; the technology of this system is discussed below.

Table 2.—Density of paddlefish depending on weight and water flow in a flow-through system. (from Melchenkov et al. 1996)

Weight (mg)	Density flow (L/m^3)	Water flow (L/min)
20–50	30–35/L	12–15
51–100	20–25/L	12–15
101–500	10–12/L	15–17
501–2,000	2–3/L	20–25
2,001–4,000	<1/L	20–25

The concept of reservoir ranching is an extension of that already demonstrated for sport-fisheries management (Graham 1986). Stocking in large impoundments, primarily to support sport fisheries, provides growth information that can be considered in the reservoir ranching context. Graham (1986) reported stocking juvenile paddlefish (25–30 cm) into a 17,000-ha Missouri reservoir at the rate of 0.1–2.2/ha over a 6-year period; harvest began after 10 years, yielding fish of 13–18 kg and a total of 1,000–2,000 fish were removed over the next 3 years.

Monosex Culture

The culture of only female paddlefish would increase the potential profitability of reservoir ranching if roe production were the goal. Mims and Shelton (1998) report the status of this technology, which is patterned after the program developed for grass carp *Ctenopharyngodon idella* (Shelton 1986), where methyltestosterone (MT) capsules were implanted in gonadally undifferentiated females and induced the development of functional testes. Breeding for a monosex population using the neomales (XX-males) was described in the context of aquaculture by Shelton (1989).

An all-female population of paddlefish was initially produced by gynogenesis (Mims et al. 1997; Mims and Shelton 1997b), then these genetic females were sex reversed using MT implants to develop functional males that would produce only X-bearing spermatozoa (Mims et

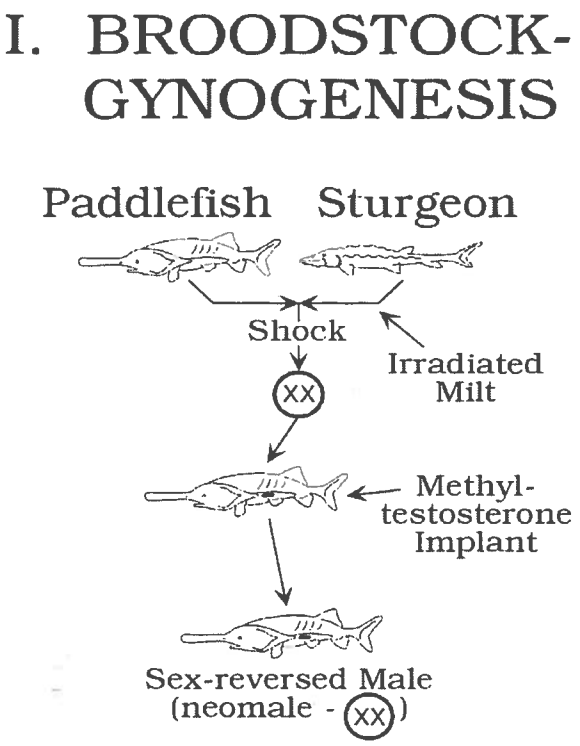

Figure 5a.—Schematic illustration of induced gynogenesis and sex-reversal for paddlefish.

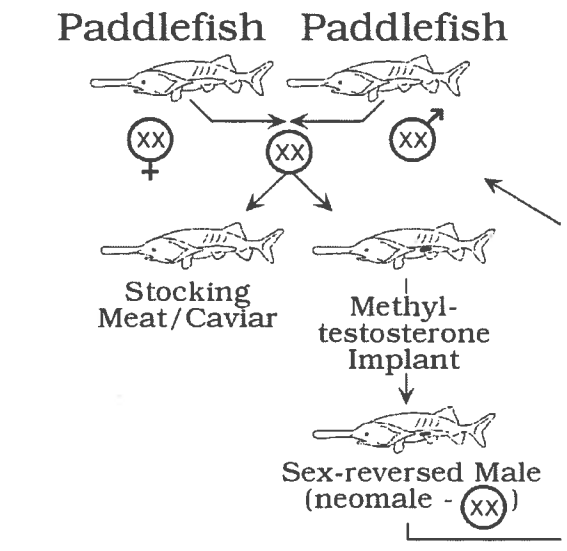

Figure 5b.—Schematic illustration of breeding program for production of all-female paddlefish for caviar and meat and broodstock continuation.

al. 1995c) (Figures 5a and 5b).

When the sex-reversed males mature, these will be used as milt donors for fertilizing eggs from any normal female to produce only female progeny. Commercial-level production of only female progeny can then proceed. Gynogenetic fish that were treated with steroid in 1995 have grown to maturity; these neomales will be progeny tested to verify that only female progeny will be produced when these sex-reversed males are used to fertilize eggs from untreated females. In the spring of 2003, we were able to get small amounts of milt (<30 mL/fish) from five neomales (XX-males) for testing breeding of all-female offspring. Fish from 2003 will be sacrificed and gonad histologically examined for ovarian tissue in fall 2004.

Mims et al. (1997) and Mims and Shelton (1998) developed the direct induction protocol for gynogenesis in paddlefish. Shovelnose sturgeon sperm was used to activate paddlefish eggs, but the male genome was inactivated with ultraviolet irradiation (Mims and Shelton 1997b). The inactivation of sturgeon DNA required different UV-dosages depending on the spermatozoan concentration, which was estimated using spectrophotometric transmittance at a wavelength of 450 mm. At a transmittance of 4.5–1.5% (sperm concentration range of 0.3–0.95 × 10^9/mL), 1,000–2,700 joules/m^2/s, respectively, were sufficient to inactivate the DNA, without eliminating motility. The linear regression is dosage (joules/m^2) = 3590.88–575x, where x = percent transmittance (Mims et al. 1997). Induction of diploidy by retention of the second meiotic polar body was with heat shock. Time of optimal induction of diploid gynogenotes used a thermal shock of 35°C, applied at 18 min after activation for 2 min; preshock incubation temperature was 18°C. If activated eggs are incubated at a different preshock temperature, application time must be adjusted according to the rate of mitotic developmental or tau (τ_o) units (Shelton et al. 1997). The rate of mitotic development is longer than most fishes, thus the polar body forms after 15 min in contrast to 2–5 min in warmwater fishes.

Gonadal differentiation in paddlefish is considerably delayed compared to most fishes. Cytological development of primary oogonia does not occur until fish are older than 62 weeks and about 500 g in body weight (Mims et al.

1997). To induce testes formation in genetic females (gynogenotes), two capsules, each containing 5 mg of MT were implanted intraperitoneally at 20 weeks of age, or at about 100 g in body weight; the treated fish were then stocked at 1,000–3,500/ha so as to grow rapidly through the period of gonadal differentiation. Testes were induced in more than 90% of the treated fish (Mims et al. 1995c). Only females have been identified in untreated gynogenotes (Mims et al. 1997), which suggests that female sex determination is based on homogamety (XX).

Duration of sperm motility varies with media ionic concentration; paddlefish sperm is motile for 76–110 s in distilled water, but to a maximum of 370 s in an optimal osmolality solution (10 mM of NaCl with a 20 mM TRIS-HCl, pH 8.5) (Linhart et al. 1995). Storage of gametes is important for artificial propagation and for conservation efforts (Mims et al. 2000). Cryobanking of spermatozoa with unique genetic characteristics, such as X-bearing sperm or from genetically modified individuals can be used in technology transfer. Paddlefish spermatozoa have been evaluated using dark-field microscopy and motility characteristics with stroboscopic analysis (Cosson et al. 2000); these motility characteristics prior to freezing will be used to correlate with fertilization effectiveness in cryopreserved samples.

Activation and short-term storage solutions were first reported for paddlefish by Mims (1991b). Later, Linhart et al. (1995) described a solution for short-term storage of paddlefish milt that was 100–150 mM glucose + 20 mM TRIS-HCl at pH of 8.5. Cosson and Linhart (1996) further reported a modified short-term storage for paddlefish spermatozoa to be composed of a solution with 5 mM KCl and 20 mM TRIS-HCl buffered at pH of 8.

Cryopreservation of paddlefish sperm does not follow that of most fishes because of the relatively low concentration of sperm cells and because chondrostean spermatozoa have an acrosome, which is sensitive to activation (Brown and Mims 1999; Mims et al. 2000). Sperm cell concentration is generally in the range of $0.2–1.7 \times 10^9$ cells/mL (Mims and Shelton 1997; Brown and Mims 1999; Linhart et al. 2000). Paddlefish sperm was mixed with the cryoprotectant dimethyl sulfoxide (DMSO) and a saline extender (3:1, milt:medium), stored in 5.0-mL straws and frozen on dry ice for 15 min then in liquid nitrogen (Brown and Mims 1999). Samples were thawed in a 20°C water bath and evaluated for motility and by fertilizing freshly ovulated eggs. Motility decreased to between 25% and 50% in frozen and thawed samples compared to 100% in fresh sperm; hatching of eggs fertilized with treated sperms was about 16% compared to 91% for control.

Tsvetkova et al. (1999) is the only other known researcher on paddlefish sperm cryopreservation. Paddlefish sperm was mixed in a ratio of 1:1 with a cryoprotective media containing a buffer solution of tris (oximethyl) amino-methan (pH 8.0), 7% saccharose, 12% DMSO, and 15% egg yolk. The sperm, diluted with cryoprotective media, was manually frozen using the following three-step procedure: from 5°C to –15°C at a rate of 2–5°C/min, from –15°C to 70°C at 15–20°C/min with subsequent slow submerging to liquid nitrogen. The sperm was thawed in a water bath at 38–40°C for 1 min. Thawed sperm were used for insemination of large batches (400 g) of eggs. Fertilization rate was 24% compared to 40% in control (fresh sperm fertilized with eggs taken from the same females; relative mean hatching rate for cryopreserved and fresh spermatozoa were 22% and 100%, respectively. Further developments are described and compared to techniques developed for sturgeon (Mims et al. 2000).

Nutrition

Vitamin C (ascorbic acid) is essential to most fish, but some primitive Actinopterigian fishes such as paddlefish, sturgeons (Acipenserid), bowfin *Amia calva* and gars (*Lepisosteus* sp.) have the enzyme gulonolactone oxidase, a catalyst for synthesizing ascorbic acid (Dabrowski 1994; Papp et al. 1999; Moreau and Dabrowski 2000). Vitamin C is necessary for collagen synthesis and dietary deficiency results in scurvy, biochemical disorders, reduced resistance to bacterial diseases, and mortality (Dabrowski 1994; Lovell 1998). Paddlefish have an advantage of ascorbate synthesis compared to teleost fish, which must depend on a food-chain transfer or prepared dietary supplementation of ascorbic acid (Dabrowski 1994).

The rest of the literature that is available on paddlefish nutrition has focused on feeding trials using commercially available prepared diets, specifically trout and salmon diets, which are high in protein (>40%) and fat (>10%). This is similar to what is being practiced with white sturgeon (Conte et al. 1988). However, morphological and behavioral differences, such as rostrum and filtering feeding mechanism of the paddlefish compared to sturgeon, complicate nutrition studies. The proper experimental tanks (i.e., circular) to maintain an environment suitable for paddlefish to survive in and feed properly have limited the interest to work with this fish. Ottinger et al. (1992) maintained the growth of 11 juvenile paddlefish (2 month old) in 378-L tanks and reported up to 0.33 g/d on a trout crumbles diet, which was slower than pond-reared fish in the same general age-group (Burke and Bayne 1986). Kroll et al. (1992, 1994) reported that larval paddlefish raised at a water temperature of 20°C and fed a prepared diet with high protein (>40%) and fat content (14–21%) had survival ranging from 14% to 40%, TL of 21–27 mm, and weight of 167–178 mg after 30 d. At Kentucky State University in Frankfort during the spring of 2004, Rangen trout diets (i.e., crumbles # 0, 1, and 2; protein 50% and fat 16%) and an extruded pellet (1.5 mm; protein 45% and fat 16%), which were distributed by a belt feeder to larval paddlefish contained in a flow-through circular tank system, (22–24%) gave high survival (>80%) and obtained 15-cm fish averaging 10 g in 30 d (see nursery section for more details). Additional research is needed in developing cost-effective prepared diets for larval/juvenile paddlefish.

Environmental Conditions

Dissolved oxygen is particularly important; a daily oxygen-monitoring program is necessary to achieve maximum yields. Because paddlefish have a rostrum, they are unable to obtain oxygen from the surface film of water such as catfish can when oxygen is low (less than 2 mg/L). Mims et al. (1999) recommends that the dissolved oxygen be kept above 30% of saturation at any given water temperature.

Paddlefish can survive a wide range of water temperatures from 1°C to about 35°C. Water temperatures for optimum fish growth are 18–27°C. However, Mims and Clark (1991) reported that paddlefish demonstrated over a 70% weight gain in polyculture with catfish fingerlings during the winter period (November to the mid of April; mean water temperature of 8.1 ± 0.1°C) in Kentucky. Other water quality parameters are similar to those required by catfish: pH 6–9; unionized ammonia less than 0.2 mg/L as nitrogen; and nitrite level dependent upon chloride level (Mims et al. 1999). Further studies are needed on environmental requirements and tolerances in tank and pond-rearing conditions.

Diseases and Predators

Diseases have not appeared to be a problem in the production of paddlefish in ponds and reservoirs, probably because of low stocking densities. However, under intensive culture conditions, paddlefish have been vulnerable to common fish diseases and parasites of warmwater fish species and have even been affected by the salmonid disease furunculosis, *Aeromonas salmonicida* (Fries and Villarreal 1998). Rostrum degenerative disease was described by Fries and Villarreal (1998) and causes deformity of the rostrum including a narrowing and/or downward curvature. Both *Aeromonas* and *Columnaris* have been isolated from the rostrum and are believed to cause this disease. Treatment with Chloramine-T or halamide at a rate of 20 mg/L for 1–3 h may be the treatment of choice to control these external bacteria, though they are not currently improved for food fish.

Paddlefish have been known to have the parasitic infection called "ICH" or *Ichthyophithirius multifilis*. Treating with 0.3 g/L of iodine-free sodium chloride and raising the temperature to 30°C for several days have been successful in eliminating this parasite from the fish in tank culture.

Paddlefish are parasitized by the cestode *Marsipometra hastata*, but little apparent harm appears to result (Purkett 1963a; Hoffman 1970). A coelenterate (hydroid) *Polypodium hydriforme* parasite infests eggs (Raikova et al. 1979; Choudhury and Dick 1991). Suppes and Meyer (1975) reported nearly 90% infestation of females in the Osage River, Missouri and about 0.04–0.4%

of the eggs were affected. Parasitized eggs are two to three times larger than normal, are often called "water blisters" by commercial fishermen, and are not viable eggs for fertilization.

Young paddlefish (<30 cm in TL) are most vulnerable to fish and aquatic bird predation. Tidwell and Mims (1990) reported that there was no survival of juvenile paddlefish (mean weight, 4.6 g; mean TL, 13 cm) when stocked in polyculture with large catfish (mean weight, 586 g; mean TL, 40 cm). Mims (1999) found that stocking 30-cm fingerlings gave greater than 90% survival in polyculture with channel catfish. In reservoir ranching, paddlefish should be greater than 30 cm to lower the risk of fish predation (Graham 1986; Onders et al. 2002).

Aquatic bird predation is one of the major causes of fish loss in U.S. aquaculture. Cormorants and other diving birds are efficient predators in catfish ponds causing large monetary losses in catfish and large expenditures in control (Tucker and Robinson 1990). Also, wading birds such as great blue herons and great egrets cause significant loss of fish, but are limited to feeding along the shoreline. Young paddlefish are relatively easy prey to aquatic birds. Netting has controlled bird predation over small nursery ponds (2,000 m^2), but probably is not cost effective on larger ponds.

Rapid growth to sizes larger than these predators can consume is the advantage that paddlefish have over aquatic birds.

Harvest

Paddlefish are relatively easy to harvest with seines or gill nets. Bag seines are best for harvesting paddlefish in ponds with over 90% catch efficiency (Semmens and Shelton 1986). If paddlefish are polycultured in catfish fingerling ponds, a large mesh (greater than 2.5 cm) seine will allow the fingerlings to swim through and selectively retain the larger paddlefish (Semmens and Shelton 1986). Paddlefish in polyculture with grow-out catfish can be easily sorted; paddlefish are docile and the rostrum can be used as a convenient handle.

In large ponds, lakes, and reservoirs, gill nets are the best choice for harvesting paddlefish. A gill net is a wall of netting made of fine nylon (monofilament or braided) filament in various bar mesh sizes depending on the target-size fish that are being captured. Bar mesh sizes of 10–15 cm is recommended for harvesting fish with weights of 5–25 kg and total lengths of 50–83 cm and mesh sizes larger than 18 cm for fish greater than 25 kg and length greater than 80 cm. (Mims and Durborow 1998; Paukert and Fisher 1999). The mesh size for the target fish should be small enough to retain the fish, but large enough to allow the fish to respire and stay alive. The netting is suspended vertically by a floatline and a leadline. For a gill net to be efficient in harvesting paddlefish, the net must have considerable slack. This is accomplished by weaving vertical lines known as "tied downs" through the mesh and tying to the floatline and the leadline. The length of the tied downs should be about 20% shorter than the depth of the net to permit "bagging" (Lund 1995). Tie downs are usually placed every 2.5 m down the length of the gill net. Onders et al. (2001) reported that most paddlefish (90% mean efficiency) could be captured and harvested with monofilament gill nets in reservoirs (14–40 ha in size) within 24–36 h.

Processing

Meat

Paddlefish meat is firm, white, and boneless with similar taste and texture to sturgeon meat (Mims and Shelton 1998). Paddlefish will yield 57% in bullet form (decapitated, eviscerated, and fins removed) and 27% in fillet form (red meat and skin removed) (Melchenkov et al. 1996; Lou et al. 2000a; Vinogradov et al. 2003). Paddlefish are classified as a low-fat fish ranging from 1% to 4.5%; fat content increases with body weight (Lou et al. 2000a). The meat is relatively stable and can be preserved for up to 7 d under refrigerated storage and 7 months under frozen storage. Protein solubility and texture has been reported to decline initially and then remain stable during the remaining refrigerated and frozen storage periods (Lou et al. 2000a). Lipid oxidation was significantly low during these storage periods.

Two valued-added paddlefish meat products, hot-smoked and surimi, are currently being studied to develop procedural techniques. The following recipe is suggested for hot-

smoked paddlefish in compliance with U.S. Department of Agriculture (USDA) Hazard Analysis Critical Control Point (HACCP). Hot smoked paddlefish is processed by placing raw fillets in 90–95° salinometer brine for 1.5–2.5 h depending on size and thickness. Then, fillets are rinsed in freshwater to remove excess salt, slime, and debris. They are placed on oiled wire-mesh trays and air-dried at about 21°C for 1–2 h until a pellicle forms. Air drying continues and smoke is increased for 3–4 h. Temperature of smoker is raised to 79.4°C for an additional 1–2 h until the internal temperature of the fillets reaches 65°C. The smoker is adjusted to maintain a constant temperature for 30 min. Smoked fillets are cooled and refrigerated (Jarvis 1987; Wang et al. 1995). Besides internal temperature, the finished hot-smoked fillets must have a water-phase salt level of 3.5% or higher to protect against toxin formation by *Clostridium botulinum* type E and nonproteolytic type B and F.

Surimi, a Japanese term referring to the intermediate product manufacturing by washing ground fish meat (Lee 1986), is used primarily to produce products such as imitation crab meat, lobster tails, and other seafood analogs. Gel formation is one of the most important attributes of surimi affected by fish species, formulations, and cooking procedures (Lee 1986). The best process for paddlefish surimi was preincubation at 70°C for 30 min followed by cooking at 90°C for 30 min; the addition of beef plasma powder gave the best gel strength and texture (Lou et al. 2000b).

Caviar

Historically, caviar was defined as salted sturgeon roe from fish caught in the Caspian Sea. However, black caviar can be obtained from two families of fishes: sturgeon, Acipenseridae, and paddlefish, Polyodontidae. Currently, fish must be sacrificed to obtain high quality caviar (Waldman and Secor 1998). Unovulated eggs must be processed to separate individual eggs from the ovarian connective tissue. Ovaries are cut into small sections (10–15 cm long) and placed onto a stainless steel 6-mm wire screen. Pressure is applied to the egg mass so as to gently force the eggs through the screen, leaving the connective tissue behind. The screened eggs are weighed, and canning salt (without iodine) is added at a rate of 14–28 g/kg of roe. Eggs and salt should be thoroughly mixed by hand for 5–8 min until foam appears on the top of the egg mass. The mass should stand about 20 min. Then the caviar is packed into plastic tubs with tight fitting covers and stored at –2°C (Jarvis 1987).

Marketing

Meat

Fresh paddlefish meat is being tested for consumer acceptability. Historically, sturgeon meat was familiar to and accepted by early immigrants of European descent in the United States in the late 1800s, but paddlefish was less appreciated. Today, paddlefish meat is often sold as a "boneless catfish," to associate the product with a fish already popular in the southern United States. As a result, paddlefish meat has remained unfamiliar to the majority of consumers and the market has remained limited (Wang et al. 1995). Recent testing of fresh paddlefish meat by fine dining chefs in Louisville, Kentucky has indicated that it is unique and versatile for preparation and presentation. The chefs indicated the firm texture was a laudable attribute. They valued this product between 50% and 75% of their "gold standards" (e.g., sea bass and dover sole range in price from US$30 to $40/kg). Further, hot-smoked paddlefish meat has been well received in fine dining restaurants and gourmet shops (Wang et al. 1995; Kaminsky 1998). The price of hot-smoked paddlefish ranges from $28 to $55/kg. Surimi is not being marketed at this time.

Caviar

Most paddlefish caviar is still supplied through the capture fisheries. Chlordane and PCBs in eggs of paddlefish have been of particular concern, although no samples from the Ohio River exceeded U.S. Food and Drug Administration's action limit concentration (1 mg/L) for PCBs, but some egg samples were above the action limit (0.3 mg/L) for chlordane (Gundersen et al. 1998, 2000). Current wholesale prices range from $90 to $143/kg, with

retail prices of more than $330/kg. Eggs from paddlefish raised in ponds and reservoirs have provided a caviar with a richer, more buttery taste (eggs with higher fat content) than eggs from wild caught paddlefish. Further studies are needed in developing markets for the meat and caviar with cultured paddlefish.

Future

Paddlefish have had a variable history as a food fish. More recently, popularity has increased through value-added products and the demand for caviar has placed considerable stress on the natural populations. The development of culture techniques have included improved artificial propagation protocol, intensive nursery production, pond and tank culture options, and advances in monosex production. Culture in the United States may develop as a component of the catfish industry, but some form of reservoir ranching is more likely to be the system that develops. Culture of the paddlefish outside of its native range has the greatest practicable potential. The latent elements for rapid expansion already exist in China and Russia. Mixed species culture in the expansive system of reservoirs in China can immediately utilize a new component in that niche; the meat will have an immediate acceptance in their food market. This eventuality only awaits the application of artificial propagation techniques into their repertoire. Concerning Russia, adoption is already underway; propagation and production are an established fact. Under the plummeting supply of Caspian Sea caviar, the Russians will logically opt for egg production. If our system of all-female production through breeding is verified, we anticipate that it will be immediately applied in other countries. We will be purchasing paddlefish caviar from overseas, like many other native species aquaculture products(e.g. rainbow trout *Oncorhynchus mykiss* and salmon) now being grown in other countries rather than at home. It is important that federal and state agencies and the aquaculture industry work together to develop farm-raised paddlefish in the United States in order to provide a reliable supply of caviar and meat for commerce.

Research is needed in nutrition with the development of a larval diet and in disease management for treatment of bacterial infections of fish reared in tank systems. Also, research is needed in molecular biology for stock identification and milt cryobiology.

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