Interim Progress Report to:

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Distribution and Population Dynamics of Asian Carp in the Upper Mississippi River

Submitted By

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Project Highlights:

Egg densities (all fish taxa) across sampling sites peaked during May 30, 2017, but a second pulse of eggs was also detected on July 25. Larval fish densities (all fish taxa) were highest on June 16th and 27th, shortly after the initial peak in egg densities. Age-0 fish from 2017 were identified to family. Cyprinidae, Sciaenidae, and Centrarchidae were the most abundant in our samples, and peak densities of all taxa occurred during June 16th. Invasive Asian carp larvae were collected in pools 18, 19, and 20 of the Mississippi River between May 18 and July 26, 2017. Mean Grass Carp densities across all sites by session were higher than Bighead and Silver Carp densities throughout 2017. The largest density of Grass Carp (18.41 per 100m^3 ± 9.10 SE) and Silver and Bighead Carp (3.59 per 100m^3 ± 2.51 SE) occurred during July 25th. No Age-0 Asian carp were caught within the major tributaries of the Mississippi River during 2017. Asian carp larval densities were generally higher upstream of the major tributaries than below the confluence of the Des Moines River but not at the Skunk and Iowa rivers. Presence of larval Asian carp from 2017 coincided with both falling (May 18 and June 8) and rising (May 3 and July 26) discharge.

Only adult Silver Carp and Grass Carp were captured in 2017 whereas adult Silver Carp, Grass Carp, and Bighead Carp were captured in 2018 with boat electrofishing. Silver Carp were captured as far north as pool 18 in 2017 and 2018 near the mouth of the Iowa River. Grass Carp were captured as far north as pool 16 in 2017, but only as far north as pool 18 in 2018. Relative abundance of Silver Carp was higher than Grass or Bighead Carp in the UMR during both years of sampling. Relative abundance tended to decrease with increasing latitude, but catch rates were higher below Lock and Dam 19 than above. Average size of Silver Carp in 2017 was 699 mm and 3.99 kg and average age was 7 years. Average size of Silver Carp in 2018 was slightly smaller at 691 mm and 3.463 kg.

Introduction

Ecological communities worldwide are becoming more uniform through the introduction and subsequent establishment of non-native species into novel areas through anthropogenic activities (Rahel 2002). Intentional introductions commonly occur to provide societal benefits such as food, recreation, and biological control (Pimentel et al. 2000). Additionally, advancements in transportation and worldwide commerce have increased unintentional introductions (Rahel 2002). A single non-native species can alter ecosystem structure and function and have costly economic consequences (Macisaac 1996, Pimentel et al. 2005, Weber and Brown 2009), but in the United States, approximately 50,000 non-native species introductions have occurred with varying success and impacts (Pimentel et al. 2005, Sagoff 2005).Economic losses due to non-native introductions are estimated at US$120 billion a year; however, actual costs are likely much higher because monetary costs associated from species extinctions, loss of ecosystem services, and aesthetic values are not easily assessed (Pimentel et al. 2005). Likewise, ecological costs may be much greater than economic costs but are difficult to quantify and assess because of lag times between invasion and empirically confirmed impacts to the environment (Gido and Brown 1999, Stohlgren and Schnase 2006).

Non-native fishes are one of the most introduced groups of aquatic animals that have resulted in negative ecological effects in riverine ecosystems (Gozlan 2008). Rivers naturally provide an invasion highway for fishes to expand from the point of introduction. Furthermore, modifications to rivers for navigation have connected previously separate waterways, facilitating inter-basin movement and the spread of invaders into additional novel habitats (Leuven et al. 2009). For example, the Mississippi River Basin covers approximately 40% of the lower 48 U.S. states with thousands of river miles (USACE 2011) and connects to the previously separated Great Lakes basin via the Chicago Area Waterway System, the Ohio-Erie Canal, and other man-made structures (USACE 2014).

At least 83 non-native fishes have become established in the Upper Mississippi River Basin (UMRB) as a result of dispersal from other basins or by direct introduction from anthropogenic activities (Rasmussen 2002). Two of the more recent and widely recognized invaders to the UMRB are Silver Carp (*Hypophthalmichthys molotrix*) and Bighead Carp (*H.*

nobilis; collectively referred to as Bigheaded Carp). These species have become abundant and threaten the integrity of the UMRB and any connected aquatic ecosystems (Irons et al. 2009). Asian carp were imported during the 1970s into the United States for food consumption and biological control in aquaculture facilities (Freeze and Henderson 1982). In the 1970s, individuals thought to have escaped during flooding events were observed in several rivers within Arkansas. Due to their high reproductive capabilities and long distance migrations (DeGrandchamp et al. 2008), these fish quickly became established and now inhabit more than 20 states throughout the Mississippi, Missouri, Ohio, and Illinois river basins (Kolar et al. 2007, Baerwaldt et al. 2013, Deters et al. 2013). By the mid-1980s, Asian carp were caught in the pooled sections of the UMRB (Kolar et al. 2007) with the first observations of Asian carp in Iowa occurring in 1986 when Silver Carp were captured in the UMRB below lock and dam 19 (LD19) near Keokuk (Irons et al. 2009). A year later, Bighead Carp were captured near the mouth of Yellow Springs Creek north of Burlington, IA (Irons et al. 2009). Since the initial observations in Iowa, Asian carp adults have been sighted in several additional UMRB tributaries in Iowa such as the Des Moines, Skunk, Iowa, and Cedar rivers (Bruce 1990, United Press International 2011, Irons 2012, Camacho 2016, Sullivan 2016).

Currently, southeastern Iowa appears to be on the leading edge of Asian carp expansion in the UMRB. Substantially higher adult catch rates of both Silver and Bighead Carp occur below LD19 than above, suggesting this structure and other lock and dams on the Mississippi River may serve as a partial migration barriers (Wilcox et al. 2004). For example, the UMRB water level is regulated at each dam in order to maintain a navigation channel by reducing or eliminating the amount of water discharged, leaving passage through the locks as the only means of fish movement during low river discharge periods. However, dam gates are lifted during higher discharge events that facilitate fish passage (Garvey et al. 2010). It is also during these high discharge events that Asian carp exhibit some of their highest movement rates, especially during annual spring runoff and associated peak discharge events when temperatures are below or within the spawning optimum, suggesting movement may be associated with spawning migration behavior (Jennings 1988, Peters et al. 2006, DeGrandchamp et al. 2008). Furthermore, Asian carp can quickly make long distance migrations

(DeGrandchamp et al. 2008), indicating that these fish are capable of dispersal into new locations.

Although Asian carp may be able to navigate lock and dams on the UMRB, pooled sections between these structures may provide unsuitable spawning habitats for these species. Asian carp are highly fecund (up to 3.5 million eggs per female; Garvey et al. 2006) and have short gestation periods (Chapman and George 2011). Thus, only a few adult individuals may be needed to quickly establish an abundant population (Crawley et al. 1986). Despite adult Asian carp being detected above LD19 up to St. Paul, MN, USA, their populations have remained low, suggesting reproduction may be limited in these reaches. Pooled sections associated with lock and dams exhibit reservoir-like characteristics that are more lentic in nature resulting in lower Asian carp reproduction than in unregulated sections where lock and dams are absent (Lohmeyer and Garvey 2009). In contrast, established Asian carp populations in tributary systems, such as the Illinois River, can have high recruitment and adult populations have increased exponentially in abundance within a decade (Sass et al. 2010). Yet, Asian carp abundance in the tributaries of the UMRB are much lower compared to the Illinois River and little is known regarding Asian carp reproduction ecology within these systems, which may be limiting adult population abundance.

Successful Asian carp spawning depends on adults finding suitable habitat of sustained, high flow or increasing discharge when water temperatures are between 17 and 30°C (Kolar et al. 2007). Continuous river flow of at least 25 km may be necessary to suspend the semi-buoyant eggs for a 24 h period or until larvae successfully hatch (Krykhtin and Gorbach 1981, George and Chapman 2013, Murphy and Jackson 2013). In most areas of the UMRB, reaches between dams with sufficient sustained velocities of 0.3 to 3.0 m/s and turbulence to keep eggs in suspension do not exist or are poorly suited for egg survival (Lohmeyer and Garvey 2009). However, age-0 Asian carp have been documented in tributaries such as the Cache River (a tributary to the Ohio River; Burr et al. 1996) and the Illinois River (a tributary to the Mississippi River; DeGrandchamp et al. 2007). Additionally, tributaries are associated with Asian carp spawning activity in their native range in the Yangtze River (Yi et al. 1988) and in varying capacities in the Missouri River (Schrank et al. 2001) and Illinois River (DeGrandchamp et al.

2007) where they are introduced. Successful establishment and reproduction in tributaries could provide sources of recruitment for pooled sections of the UMRB and other areas of poor reproduction.

Successful expansion and establishment of Asian carp populations within the UMRB depends on the ability of adults to find adequate conditions of temperature and long fetches of sustained, high flow. Despite perceived poor conditions for successful Asian carp reproduction in the Upper Mississippi River, tributaries could provide adequate conditions for reproduction, resulting in population expansion along the leading edge of the invasion. Reproductive success on an invasion front can increase exponentially through time (Chick and Pegg 2001, Sass et al. 2001) until establishment occurs (Hayer et al. 2014). Some systems where Asian carp are starting to establish can have sporadic reproduction (Irons et al. 2011), leading to either a surge or decline in the population. Evaluating factors affecting reproduction and recruitment in tributaries of the Mississippi River in association with annual variation in environmental conditions is needed to better understand Asian carp population dynamics in these systems and potentially develop management strategies for these invasive fishes. By understanding more about factors affecting reproduction and recruitment within the tributaries of the UMRB, potential increases of Asian carp presence, or newly established residence in UMR could be detected early. Spatial and temporal distribution of Asian carp eggs and larvae will help to locate spawning habitat, determine reproductive cues, and provide insight between environmental variables and reproduction.

Project Objectives:

1) Evaluate Asian carp reproduction in pools 14, 15, 16, 17, 18, 19, 20 and the contribution of the Wapsipinicon, Rock, Iowa, Skunk, and Des Moines rivers to Asian carp reproduction (egg, larval, and juvenile densities).

2) Evaluate adult population characteristics (abundance, distribution, size structure, condition) and dynamics (recruitment, growth, mortality) of Asian carp in pools 14, 15, 16, 17, 18, 19, and 20 of the Upper Mississippi River.

Methods:

Egg and Age-0 Fish Sampling

Asian carp eggs and age-0 fish were sampled in 2017 and 2018 at 18 locations (Figure 1) approximately every 10 days depending upon river conditions from beginning of May until the end of August (12 sessions, 18 sites, 3 habitats equating to 54 tows per session, or 648 larval tows per year). Sampling sites are abbreviated to distinguish tributary sites from sites within the Mississippi River upstream and downstream from the tributary site (Table 1). Sampling was not conducted when water levels were too high for safe boating or too low for boat access. Ichthyoplankton tows (0.5 m diameter net, 500 µm mesh) were conducted at the surface at a constant boat speed relative to the shoreline up to four minutes depending on debris load. A General Oceanics flowmeter (Model 2030R) was attached in the mouth of the net to estimate volume (m^3) of water filtered during each tow. Three tows were conducted at each site parallel to river flow: the first tow was in the main thalweg for drifting eggs and larvae (<24 hours post fertilization), the second tow occurred near channel borders where water velocity is moving downstream slower than the thalweg, and the third was in an adjacent backwater area for mobile larvae (>24 hours post fertilization). After each tow, ichthyoplankton net contents were rinsed toward the cod end, placed in sample jars, and preserved in 95% ethanol.

In the laboratory, eggs and age-0 fish (larvae and juveniles) were separated from debris. Due to the high number of larval fish collected in 2017, large samples were subsampled. Samples containing ≥200 larvae were subsampled so that at least 25% (minimum 100 fish) were identified. Asian carp larvae are difficult to distinguish among species and are being identified to genus using meristic and morphometric characteristics (Chapman 2006, Chapman and George 2011). Age-0 fishes were first categorized as larval or juveniles based on fin development. Fish recognized as having a full complement of fins are categorized as juvenile fish. All age-0 fish from 2017 have been identified to the lowest possible taxa using morphometric and meristic characteristics described in literature (Auer 1982). Age-0 fish collected in 2018 are currently being identified.

Adult Asian Carp Sampling

Sampling for adult Asian carp took place in September - November of 2017 and 2018 in Pools 14 – 20 of the UMR, including the mouths of five (Des Moines, Skunk, Iowa, Rock, and Wapsipinicon Rivers) major tributaries and one site upstream in the Des Moines River at Keosauqua (Figure 1). Sites were chosen so that samples were obtained from upstream, downstream, and within the mouths of each of the major tributaries, as well as at least one site in every UMR Pool within our study reach. Daytime boat electrofishing (pulsed DC; amps 4-13, voltage 100-500) was used to target backwater and channel border habitats generally less than 4 meters deep. Electrofishing transects (varying effort and transect numbers) are conducted until approximately 150 Silver Carp are captured (Pool 20) or until all available habitat at the site is sampled.

Adult Asian carp were identified as Silver, Bighead, or Silver x Bighead Carp hybrid using meristic and morphometric features, weighed (0.001 kg), measured (total length; 1 mm), and the first pectoral fin spine on each side and lapillus otoliths (up to 150 fish/site) were removed for age and growth analysis. Sex was determined based on visual inspection of gonads (male, female, immature, or unknown). Lapillus otoliths were air dried at room temperature for at least four weeks following collection before being mounted in epoxy. A 1-mm thick cross section at the nucleus was cut using a Buehler Isomet low-speed saw (Isomet Corporation, Springfield, VA) with the anterior portion of the otolith oriented perpendicular to the blade. Wetted 2,000-grit sandpaper was used to polish each side of the cross section. The section was then placed in immersion oil to improve clarity and annuli viewed under a dissecting microscope with transmitted light. Lapillus otoliths were independently aged by two experienced readers with no knowledge of fish length, estimated age of other structure, or source river. If the readers disagreed, then a common age was decided in unison.

Results and Discussion:

Eggs and Age-0 Fish

A total of 627 ichthyoplankton tows were completed in 2017. Eggs were collected during every sampling session for a total of 8,619 eggs in 2017. The largest numbers of eggs were collected during the third sampling event (May 30th - June 1st; 226.39 per 100m^3 ± 116.28 SE), with a total of 3,243 eggs across all sites except the backwater habitat of the Wapsipinicon mouth (Figure 2). A total of 429 tows were conducted in the Mississippi River that collected a total of 5,569 eggs. An additional 201 tows were taken within the tributary mouths that captured 3,050 eggs (Keosauqua = 421 eggs, Des Moines = 577 eggs, Skunk = 272 eggs, Iowa = 117 eggs, Rock = 1,656 eggs, Wapsipinicon = 7 eggs). Egg density appeared highest within the Rock River and lowest within the Mississippi River upstream of the Des Moines River (Figure 3). Across all habitats and sites, the highest egg density (474.39 per 100m^3 ± 470.61 SE) was within the thalweg of the Rock River mouth (Figure 4), although catches at this site throughout the year were highly variable.

A total of 72,405 age-0 fish (larvae and juveniles) were captured in 2017. The highest densities of age-0 fish were collected on June 16th (1,754.76 per 100m^3 ± 312.79 SE; 22,888 fish), June 27th (1,554.34 per 100m^3 ± 853.80 SE; 16,079 fish), and August 12th (1,355.44 per 100m^3 ± 956.36 SE, 8,666 fish; Figure 2). The two sampling sessions with the highest mean density of age-0 fish were captured within thirty days of the highest egg density in 2017. The sampling session with the lowest density of age-0 fish captured in 2017 (17.06 per 100m^3 ± 2.67 SE) occurred May 10th.

Age-0 fish were sampled from every river during 2017. The majority of age-0 fish (70,152 fish) were collected from sites downstream of tributaries within the Mississippi River, whereas fewer individuals (2,253) were collected from within tributaries. Age-0 fish densities tended to be higher in the Mississippi River downstream of tributaries than within its tributaries (Figure 3). Larval densities tended to be highest within the backwater or channel border throughout 2017 (Figure 4), although no age-0 fish were collected from the backwater at the mouth of the Wapsipinicon River . The thalweg of the Wapsipinicon River also had the lowest density of age-0 fish collected in 2017 (0.48 per 100m^3 ± 0.004 SE; Figure 4).

Ichthyoplankton from 2017 have been sorted into categories of yolk-sac larvae, larvae, and juveniles, and identified to family except for invasive carp that were identified to genus. Of the non-Asian carp fish larvae, Cyprinidae were most abundant, followed by Centrarchidae, Sciaenidae, Percidae, Clupeidae, and Lepisosteidae (Figure 5). Other families present but at low densities include Atherinopsidae, Catostomidae, Esocidae, Ictaluridae, and Moronidae. Across taxa, larval densities of most families peaked between May 30th and June 26th (Figure 5). Cyprinid larval density peaked three times during June 16th (48.03 per 100m^3 ± 9.47 SE), June 27th (34.18 per 100m^3 ± 16.26 SE), and August 12th (34.06 per 100m^3 ± 23.32 SE; Figure 5). Sciaenidae (0.99 per 100m^3 ± 0.24 SE) and Centrarchidae (1.23 per 100m^3 ± 0.83 SE) also had their highest densities during the June 16th sampling session (Figure 5).

A total of 366 age-0 Grass Carp and 67 age-0 Bighead and Silver carp were collected in 2017. Age-0 Grass Carp consisted of 360 yolk-sac larvae and six mesolarvae whereas all 67 Bighead and Silver Carp were yolk-sac larvae. Mean larval Grass Carp densities were generally higher than Bighead and Silver Carp by session throughout 2017 (Figure 6). Early peak larval densities occurred on May 19th for Grass Carp (5.40 per 100m^3 ± 3.97 SE; 103 fish) with Silver and Bighead Carp having a lower density (0.79 per 100m^3 ± 0.66 SE; 17 fish). A second, larger peak occurred late in the season during July 25th, with higher densities of Grass Carp (18.41 per 100m^3 ± 9.09 SE; 261 fish) than Bighead and Silver Carp (3.59 per 100m^3 ± 2.51 SE, 48 fish; Figure 6). Peak densities of all larval fish by session (Figure 2) did not overlap with invasive Asian carp densities (Figure 6).

No age-0 Asian carp were collected within tributaries in 2017. Mean densities across habitats by sampling date of all Asian carp species within the Mississippi River tended to be higher upstream than downstream of the Des Moines River (Figure 7). However, larval Grass Carp densities were nearly three times higher downstream (89.04 per 100m^3 ± SE 56.93) than upstream (33.92 per 100m^3 ± 17.61 SE) of the Skunk River on July 26, whereas densities were similar upstream versus downstream on other dates (Figure 7). The earliest reproduction events occurred during falling limbs of discharge (May 18 and May 31) whereas the largest Asian carp reproduction event in 2017 occurred later than previous years and coincided during a rising limb of discharge (Figure 7). Asian carp reproduction was detected more often at the

Des Moines River compared to other locations upstream of Lock and Dam 19. Additionally, Asian carp larval densities across habitats by sampling dates tended to be lower above Lock and Dam 19 than below (Figure 7). Larval Asian carp were found on four sampling events. Larval Asian carp were found in multiple pools on May 18 and July 26 whereas they were only found in one pool on May 31 and June 8 (Figure 7).

In 2018, a total of 627 ichthyoplankton tows were conducted across 12 sampling sessions. Enumeration and identification of eggs and larvae from 2018 is still in progress. Spawning behavior by Silver Carp was observed on May 14, 2018 and June 28, 2018 at the mouth of the Des Moines River. Additionally, we discovered evidence of Asian carp recruitment to the juvenile stage (~120mm) in a backwater near the mouth of the Skunk River where receding water levels of the Skunk River had left a substantial number of age-0 fish of many species in this backwater area that was separated from the river. We collected >150 Silver Carp, 1 Bighead Carp, and 2 Grass Carp with a cast net, as well as many other species (Common Carp, Gizzard Shad, Longnose Gar, Shortnose Gar, Bigmouth Buffalo, Smallmouth Buffalo, Quillback Carpsucker, Channel Catfish, Orangespotted Sunfish, Bluegill Sunfish, Green Sunfish, and Largemouth Bass). This finding is only the third documented occurrence of successful Asian carp recruitment to the juvenile stage above Lock and Dam 19.

Adult Asian Carp Population Characteristics and Dynamics

In 2017, a total of 161 Asian carp were collected from the Des Moines, Iowa, and Rock river confluences as well as pool 17 during a cumulative 7.03 hours of electrofishing across all sites (Table 2). Adult Asian carp were not sampled at Keosauqua on the Des Moines River due to low flows throughout fall 2017. The Des Moines River accounted for 94% (152 fish) of all Asian carp captures, while the Iowa River accounted for 4% (6 fish), the Rock River accounted for 1% (2 fish), and pool 17 accounted for 1% (1 fish). Silver Carp made up 96% (154 individuals) of total Asian carp captures across all sites, and Grass Carp made up 4% (7 individuals). No Bighead Carp or Black Carp were captured in 2017. Catch per unit effort (CPUE; fish/hr) for both Silver Carp and Grass Carp was highest at the Des Moines River (Table 2). Catches of Grass Carp were low and similar across sites but did not show any spatial trend.

Silver Carp CPUE was very high below Lock and Dam 19 (LD19) but no fish were captured above LD19 during 2017 except at the Iowa River. Of the 154 Silver Carp captured across all sites in 2017, 97% (150 individuals) came from the Des Moines River, while the other 3% (4 individuals) came from the Iowa River. Although no Silver Carp were captured at the Skunk River, approximately 30 individuals were observed jumping out of reach of the netters. Additionally, approximately 10 other Silver Carp were observed jumping at the Iowa River.

Silver Carp in 2017 ranged in size from 427 mm to 966 mm (mean = 699 mm) and from 0.836 kg to 10.120 kg (mean = 3.99 kg; Figure 8). Silver Carp size structure was lower at the Iowa River than the Des Moines River, but low sample size at Iowa River (n=4) should be taken into consideration. Sizes of Grass Carp captured was relatively similar across sites, but showed a slight increasing trend with latitude (Des Moines = 802 mm, Iowa = 837 mm, pool 17 = 928 mm,) except for the Rock River (643 mm; Figure 9). Silver Carp ages ranged from 1 to 11 years (Figure 10) and mean age at the Des Moines River (mean = 6.9 years old) was higher than the individuals captured at the Iowa River (1 year old). Grass Carp mean age tended to decrease with increasing latitude (Figure 11).

In 2018, a total of 225 Asian carp were collected from Keosauqua and the Des Moines, Skunk, and Iowa river mouths during a cumulative 7.36 hours of electrofishing across all sites. The Des Moines River accounted for 84% (188 fish) of total Asian carp captures, while Keosauqua accounted for 11% (26 fish), the Skunk River accounted for 3% (7 fish), and the Iowa River accounted for 2% (4 fish). Silver Carp accounted for 95% (214 fish) of the total Asian carp catch, Grass Carp made up 4% (8 fish), and Bighead Carp made up 1% (3 fish). No Black Carp were captured across any of the sites in 2018. Silver Carp were captured at Keosauqua and the Des Moines, Skunk, and Iowa rivers. Relative abundance was highest at the Des Moines River and tended to decrease both with latitude in the Mississippi River and upstream in the Des Moines River at Keosauqua (Table 2). Although few Silver Carp were captured at sites other than the Des Moines River, many Silver Carp were observed jumping out of reach of the netters (Skunk River ≈ 68; Iowa River ≈ 40). Grass Carp were captured at two sites (Keosauqua and Iowa River) and Bighead Carp were only captured at Keosauqua in 2018.

Silver Carp in 2018 ranged in size from 525 mm to 850 mm (mean = 691 mm) and from 1.534 kg to 6.812 kg (mean = 3.463 kg). Silver Carp size structure was largest at the Iowa River followed by the Des Moines River, Keosauqua, and the Skunk River (Figure 8). However, few individuals were captured at Keosauqua (n = 16) and the Skunk (n = 7) and Iowa (n = 3) rivers. Bighead Carp ranged in size from 632 mm to 738 mm (mean = 679 mm) and from 2.312 kg to 4.063 kg (mean = 3.130 kg; Figure 12). Grass Carp ranged in size from 601 mm to 930 mm (mean = 763 mm) and from 2.343 kg to 8.267 kg (mean = 5.133 kg; Figure 9). Grass Carp size structure is difficult to compare spatially given the low sample size at both sites where Grass Carp were detected (Keosauqua, n = 7; Iowa River, n = 1). Asian carp ages from 2018 are still being processed.

Tracking reproduction and recruitment is important to gage the long-term success of harvest, identify large reproductive events, identify recruitment sources and habitat, and monitor the reproductive front upstream. Assessing reproduction along the invasion front should continue to identify environmental (e.g., floods) or human (e.g., harvest) factors that may result in large year-classes, subsequently leading to population growth and expansion.

Publications resulting from this project to date:

Fritts, AK, BC Knights, J Amberg, JH Larson, JJ Amberg, C Merkes, T Tajioui, SE Butler, MJ Diana, DH Wahl, MJ Weber, and JD Waters. *In press.* Development of a quantitative PCR method for screening ichthyoplankton samples for bigheaded carps. Biological Invasions.

Whitledge GW, B Knights, J Vallazza, JH Larson, MJ Weber, JT Lamer, QE Phelps, and JD Norman. *In press.* Identification of Bighead Carp and Silver Carp early-life environments and inferring Lock and Dam 19 passage in the Upper Mississippi River: insights from otolith chemistry. Biological Invasions.

Sullivan, CJ, CA Camacho, MJ Weber, and CL Pierce. *In press.* Grass Carp detection and occupancy rates in the Upper Mississippi River. River Research and Application.

Sullivan, CJ, MJ Weber, CA Camacho, DH Wahl, R Columbo, and CL Pierce. 2018. Factors regulating year-class strength of Silver Carp throughout the Mississippi River basin. Transactions of the American Fisheries Society 147: 541-553.

Sullivan, CJ, CA Camacho, MJ Weber, and CL Pierce. 2017. Intra-annual variability of Silver Carp populations in the Des Moines River, USA. North American Journal of Fisheries Management 37: 836-849.

Sullivan, CJ. 2016. Asian Carp population characteristics and dynamics in the Mississippi River watershed. MS thesis, Iowa State University.

Camacho, C. 2016. Asian Carp reproductive ecology along the Upper Mississippi River invasion front. MS thesis, Iowa State University.

In prep

Camacho, CA, CJ Sullivan, MJ Weber, and CL Pierce. In prep. Suitability of an Upper Mississippi River Tributary for Asian carp reproduction. To be submitted to North American Journal of Fisheries Management.

Camacho, CA, CJ Sullivan, MJ Weber, and CL Pierce. In prep. Asian Carp reproduction in the tributaries of the Upper Mississippi River. To be submitted to River Research and Application.

Camacho, CA, CJ Sullivan, MJ Weber, and CL Pierce. In prep. Morphological identification of Asian Carp eggs using random forests machine learning classification. To be submitted to Canadian Journal of Fisheries and Aquatic Sciences.

Cozzola, A, N Tillotson, CJ Sullivan, MJ Weber, and CL Pierce. In prep. Spatiotemporal variation in Silver Carp populations across the leading edge of the invasion of the Upper Mississippi River. To be submitted to Biological Invasions.

Matthews, A, MJ Weber, and CL Pierce. In prep. Bigheaded carp reproduction output is associated with environmental influences but not adult abundance. To be submitted to Biological Invasions.

Matthews, A, MJ Weber, and CL Pierce. In prep. Assessment of random forest model ability to identify fish eggs based on morphological characteristics. To be submitted to Canadian Journal of Fisheries and Aquatic Sciences.

Sullivan, CJ, MJ Weber, and CL Pierce. In prep. Spatial variation in Silver Carp populations across their existing distribution in North America. To be submitted to Ecology of Freshwater Fish.

Sullivan, CJ, CA Camacho, MJ Weber, and CL Pierce. In prep. Spatial variation in Grass Carp populations across their existing distribution. To be submitted to North American Journal of Fisheries Management.

References:

Auer, N. A. (ed). 1982. Identification of larval fishes of the Great Lakes basin with emphasis on the Lake Michigan drainage. Great Lakes Fishery Commission, Ann Arbor, MI 48105. Special Pub 82-3:744 pp.

Baerwaldt, K., A. Benson, and K. Irons. 2013. Asian carp distribution in North America. Report to the Asian carp Regional Coordinating Committee.

Bruce, J. 1990. Bighead Carp (*Hypophthalmichthys nobilis*). Nonindigenous Aquatic Species Database, Gainesville, FL. http://nas.er.usgs.gov/queries/SpecimenViewer.aspx?SpecimenID=33085, January 08, 2014. http://nas.er.usgs.gov/queries/SpecimenViewer.aspx?SpecimenID=33085.

Burr, B. M., D. J. Eisenhour, K. M. Cook, C. A. Taylor, G. L. Seegert, R. W. Sauer, and E. R. Atwood. 1996. Nonnative fishes in Illinois waters: what do the records reveal. Transactions of the Illinois State Academy of Science 89(1):73–91.

Camacho, C. A. 2016. Asian carp reproductive ecology along the Upper Mississippi River invasion front. Masters thesis, Iowa State University.

Chapman, D. C. 2006. Early development of four cyprinids native to the Yangtze River, China: U.S. Geological Survey Data Series 239.

Chapman, D. C., and A. E. George. 2011. Developmental rate and behavior of early life stages of Bighead Carp and Silver Carp: U.S. Geological Survey Scientific Investigations Report 2011–5076.

Chick, J. H., and M. A. Pegg. 2001. Invasive carp in the Mississippi River basin. Science 292(5525):2250-2251.

Crawley, M. J., H. Kornberg, J. H. Lawton, M. B. Usher, R. Southwood, R. J. O'Connor, and A. Gibbs. 1986. The population biology of invaders (and discussion). Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 314(1167):711–731.

DeGrandchamp, K. L., J. E. Garvey, and R. E. Colombo. 2008. Movement and habitat selection by invasive Asian carps in a large river. Transactions of the American Fisheries Society 137(1):45–56.

Deters, J. E., D. C. Chapman, and B. McElroy. 2013. Location and timing of Asian carp spawning in the Lower Missouri River. Environmental Biology of Fishes 96(5):617–629.

Freeze, M., and S. Henderson. 1982. Distribution and status of the Bighead Carp and Silver Carp in Arkansas. North American Journal of Fisheries Management 2(2):197–200.

Garvey, J., B. Dugger, M. Whiles, S. Adams, M. Flinn, B. Burr, and R. Sheehan. 2003. Responses of fishes, waterbirds, invertebrates, vegetation, and water quality to environmental pool management: Mississippi River Pool 25. U.S. Army Corps of Engineers, St. Louis District, Final Report.

Garvey, J. E., K. L. DeGrandchamp, and C. J. Williamson. 2006. Life history attributes of Asian carps in the Upper Mississippi River system.

Garvey, J., B. Ickes, and S. Zigler. 2010. Challenges in merging fisheries research and management: the Upper Mississippi River experience. Hydrobiologia 640(1):125–144.

George, A. E., and D. C. Chapman. 2013. Aspects of embryonic and larval development in Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*Hypophthalmichthys molitrix*). PLoS ONE 8(8):e73829.

Gido, K. B., and J. H. Brown. 1999. Invasion of North American drainages by alien fish species. Freshwater Biology 42(2):387–399.

Gozlan, R. E. 2008. Introduction of non-native freshwater fish: is it all bad? Fish and Fisheries 9(1):106–115.

Hayer C. A., J. J. Breeggemann, R. A. Klumb, B. D. S Graeb, and K. N. Bertrand. 2014. Population characteristics of Bighead and Silver Carp on the northwestern front of their North American invasion. Aquatic Invasions 9: 289–303.

Irons, K. 2012. Bighead Carp (*Hypophthalmichthys nobilis*). Nonindigenous Aquatic Species Database, Gainesville, FL. http://nas.er.usgs.gov/queries/SpecimenViewer.aspx?SpecimenID=543592, January 08, 2014..

Irons, K. S., G. G. Sass, M. A. McClelland, and T. M. O'Hara. 2011. Bigheaded Carp invasion of the La Grange Reach of the Illinois River: insights from the long term resource monitoring program. In *American Fisheries Society Symposium* (No. 74).

Irons, K. S., S. A. DeLain, E. Gittinger, B. S. Ickes, C. S. Kolar, D. Ostendorf, E. N. Ratcliff, and A. J. Benson. 2009. Nonnative fishes in the Upper Mississippi River system: U.S. Geological Survey Scientific Investigations Report 2009–5176, 68 p. http://pubs.usgs.gov/sir/2009/5176/.

Jennings, D. P. 1988. Bighead Carp (*Hypophthalmichthys nobilis*): a biological synopsis. U.S. Fish and Wildlife Service, Biological Report 88 (29).

Kolar, C., D. Chapman, W. Courtenay, C. Housel, J. Williams, and D. P. Jennings. 2007. Bigheaded Carps: a biological synopsis and environmental risk assessment Special Publication 33. American Fisheries Society, Bethesda, Maryland.

Krykhtin, M., and E. Gorbach. 1981. Reproductive ecology of the Grass Carp, *Ctenopharyngodon idella*, and the Silver Carp, *Hypophthalmichthys molitrix*, in the Amur Basin. Journal of Ichthyology 21(2):109–123.

Leuven, R. S. E. W., G. van der Velde, I. Baijens, J. Snijders, C. van der Zwart, H. J. R. Lenders, and A. bij de Vaate. 2009. The river Rhine: a global highway for dispersal of aquatic invasive species. Biological Invasions 11(9):1989–2008.

Lohmeyer, A. M., and J. E. Garvey. 2009. Placing the North American invasion of Asian carp in a spatially explicit context. Biological Invasions 11(4):905–916.

Macisaac, H. J. 1996. Potential abiotic and biotic impacts of Zebra Mussels on the inland waters of North America. American Zoologist 36(3):287–299.

Murphy, E. A., and P. R. Jackson. 2013. Hydraulic and water-quality data collection for the investigation of Great Lakes tributaries for Asian carp spawning and egg-transport suitability: USGS Scientific Investigations Report 2013–5106. Page 30.

Peters, L. M., M. A. Pegg, and U. G. Reinhardt. 2006. Movements of adult radio-tagged Bighead Carp in the Illinois River. Transactions of the American Fisheries Society 135(5):1205–1212.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. BioScience 50(1):53–65.

Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52(3):273–288.

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

Rasmussen, J. L. 2002. The Cal-Sag and Chicago Sanitary and Ship Canal: a perspective on the spread and control of selected aquatic nuisance fish species. US Fish and Wildlife Service, Region 3.

Sagoff, M. 2005. Do non-native species threaten the natural environment? Journal of Agricultural and Environmental Ethics 18(3):215–236.

Sass, G. G., T. R. Cook, K. S. Irons, M. A. McClelland, N. N. Michaels, T. M. O'Hara, and M. R. Stroub. 2010. A mark-recapture population estimate for invasive Silver Carp (*Hypophthalmichthys molitrix*) in the La Grange Reach, Illinois River. Biological Invasions 12(3):433–436.

Schrank, S. J., P. J. Braaten, and C. S. Guy. 2001. Spatiotemporal variation in density of larval Bighead Carp in the Lower Missouri River. Transactions of the American Fisheries Society 130(5):809–814.

Stohlgren, T. J., and J. L. Schnase. 2006. Risk analysis for biological hazards: what we need to know about invasive species. Risk Analysis 26(1):163–173.

Sullivan, C. J. 2016. Asian carp population characteristics and dynamics in the Mississippi River watershed. Masters thesis, Iowa State University, Ames, Iowa.

Sullivan, C. J., C. A. Camacho, M. J. Weber, and C. L. Pierce. 2017. Intra-annual variability of Silver Carp populations in the Des Moines River, USA. North American Journal of Fisheries Management 37:836-849.

U.S. Geological Survey. 2013. USGS water resources of the United States: boundary descriptions and names of regions, subregions, accounting units and cataloging units. http://water.usgs.gov/GIS/huc_name.html#Region07.

United Press International. 2011. Bighead Carp (*Hypophthalmichthys nobilis*). Nonindigenous Aquatic Species Database, Gainesville, FL. http://nas.er.usgs.gov/queries/SpecimenViewer.aspx?SpecimenID=275101, January 08, 2014.

United States Army Corps of Engineers (USACE). 2011. Waterborne commerce of the United States, Part 2–Waterways and Harbors Gulf Coast, Mississippi River System and Antilles. U.S. Army Corps of Engineers, IWR-WCUS-11-2.

United States Army Corps of Engineers (USACE). 2014. The GLMRIS report: Great Lakes and Mississippi River interbasin study.

Weber, M. J., and M. L. Brown. 2009. Effects of Common Carp on aquatic ecosystems 80 years after "Carp as a dominant": ecological insights for fisheries management. Reviews in Fisheries Science 17(4):524–537.

Wilcox, D., E. Stefanik, D. Kelner, M. Cornish, D. Johnson, I. Hodgins, S. Zigler, and B. Johnson. 2004. Improving fish passage through navigation dams on the Upper Mississippi River System. US Army Corps of Engineers, ENV Report 54.

Yi, B., Z. Yu, Z. Liang, S. Sujuan, Y. Xu, J. Chen, M. He, Y. Liu, Y. Hu, Z. Deng, S. Huang, J. Sun, R. Liu, and Y. Xiang. 1988. The distribution, natural conditions, and breeding production of the spawning ground on main stream of Yangtze River. In: Yi B, Yu Z, Liang Z (eds) Gezhouba water control project and four famous fishes in the Yangtze River. Hubrei Science and Technology Press, Wuhan: 1–46.

Zigler, S. J., M. R. Dewey, B. C. Knights, A. L. Runstrom, and M. T. Steingraeber. 2004. Hydrologic and hydraulic factors affecting passage of Paddlefish through dams in the Upper Mississippi River. Transactions of the American Fisheries Society 133(1):160–172.

Table 1. Sampling site codes for 2017-2018 sampling seasons. See Figure 1 for sampling locations.

Year Sampled	Site Codes	Site Names
2017-2018	UMR-UPW	Upper Mississippi River, Upstream of the Wapsipinicon River
	UMR-DNW	Upper Mississippi River, Downstream of the Wapsipinicon River
	WAP-MTH	Mouth of the Wapsipinicon River
	UMR-P15	Upper Mississippi River, Pool 15
	UMR-UPR	Upper Mississippi River, Upstream of the Rock River
	UMR-DNR	Upper Mississippi River, Downstream of the Rock River
	ROC-MTH	Mouth of the Rock River
	UMR-P17	Upper Mississippi River, Pool 17
	UMR-UPI	Upper Mississippi River, Upstream of the Iowa River
	UMR-DNI	Upper Mississippi River, Downstream of the Iowa River
	IAR-MTH	Mouth of the Iowa River
	UMR-UPS	Upper Mississippi River, Upstream of the Skunk River
	UMR-DNS	Upper Mississippi River, Downstream of the Skunk River
	SKK-MTH	Mouth of the Skunk River
	UMR-UPD	Upper Mississippi River, Upstream of the Des Moines River
	UMR-DND	Upper Mississippi River, Downstream of the Des Moines River
	DSM-MTH	Mouth of the Des Moines River
	DSM-KQA	Des Moines River at Keosauqua

Table 2. Electrofishing catch per unit effort (CPUE, fish/hr, mean ± 1 SE) of Asian carp in the UMR in 2017 and 2018. No Bighead Carp were captured and flows at Keosauqua were too low to safely sample in 2017.

Year	Site Code	Transects	Total Effort (hr)	Silver Carp Catch	Silver Carp CPUE ± SE	Bighead Carp Catch	Bighead Carp CPUE ± SE	Grass Carp Catch	Grass Carp CPUE ± SE
2017	WAP-MTH	1	0.57	0	0	0	0	0	0
	UMR-P15	1	0.661	0	0	0	0	0	0
	ROC-MTH	3	1.809	0	0	0	0	2	0.92 ± 0.92
	UMR-P17	3	1.045	0	0	0	0	1	0.85 ± 0.85
	IAR-MTH	4	0.894	4	3.14 ± 3.14	0	0	2	2.11 ± 2.11
	SKK-MTH	7	1.299	0	0	0	0	0	0
	DSM-MTH	3	0.752	150	228.77 ± 117.48	0	0	2	2.74 ± 2.74
2018	WAP-MTH	3	1.131	0	0	0	0	0	0
	UMR-P15	3	0.785	0	0	0	0	0	0
	ROC-MTH	3	1.101	0	0	0	0	0	0
	UMR-P17	3	0.703	0	0	0	0	0	0
	IAR-MTH	3	0.887	3	2.61 ± 2.61	0	0	1	0.87 ± 0.87
	SKK-MTH	4	1.152	7	7.17 ± 2.67	0	0	0	0
	DSM-MTH	3	0.698	188	494.40 ± 338.48	0	0	0	0
	DSM-KQA	5	0.902	16	18.22 ± 6.62	3	3.51 ± 1.88	7	5.15 ± 3.53

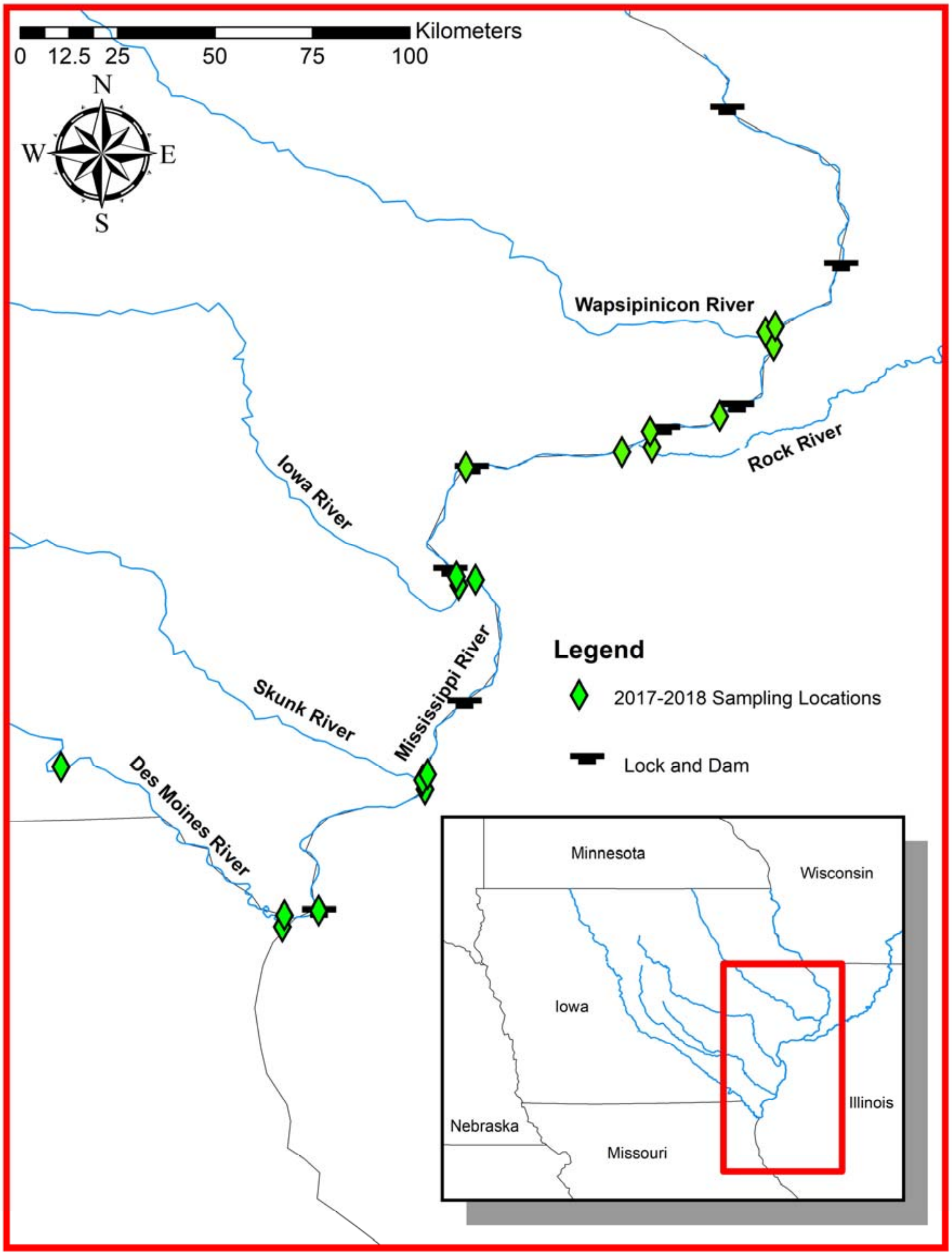

Figure 1. Map of study area on the southeast border of Iowa with the 18 sampling sites of larval fish and adult Asian Carp indicated by green diamonds. Mississippi River lock and dams within the sampling reach in black.

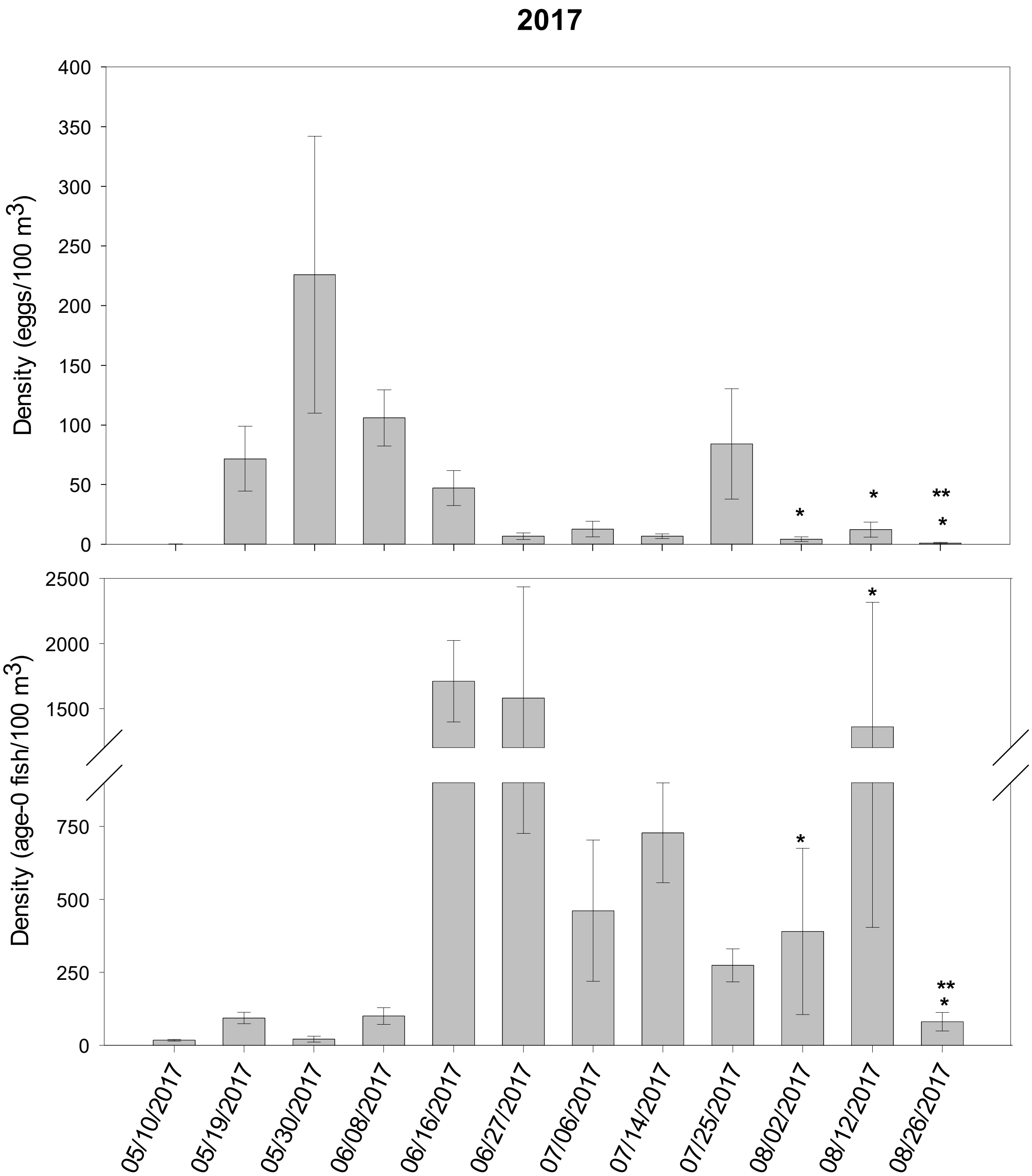

Figure 2. Density (mean ± 1 SE) of fish eggs (top) and age-0 fish (bottom) collected between May 10 and August 26, 2017.

* The Des Moines River at Keosauqua (DSM-KQA) was not sampled due to low flows.

**The Mississippi River upstream and downstream the Des Moines River (UMR-UPD, and UMR-DND) were not sampled due to unsafe weather conditions.

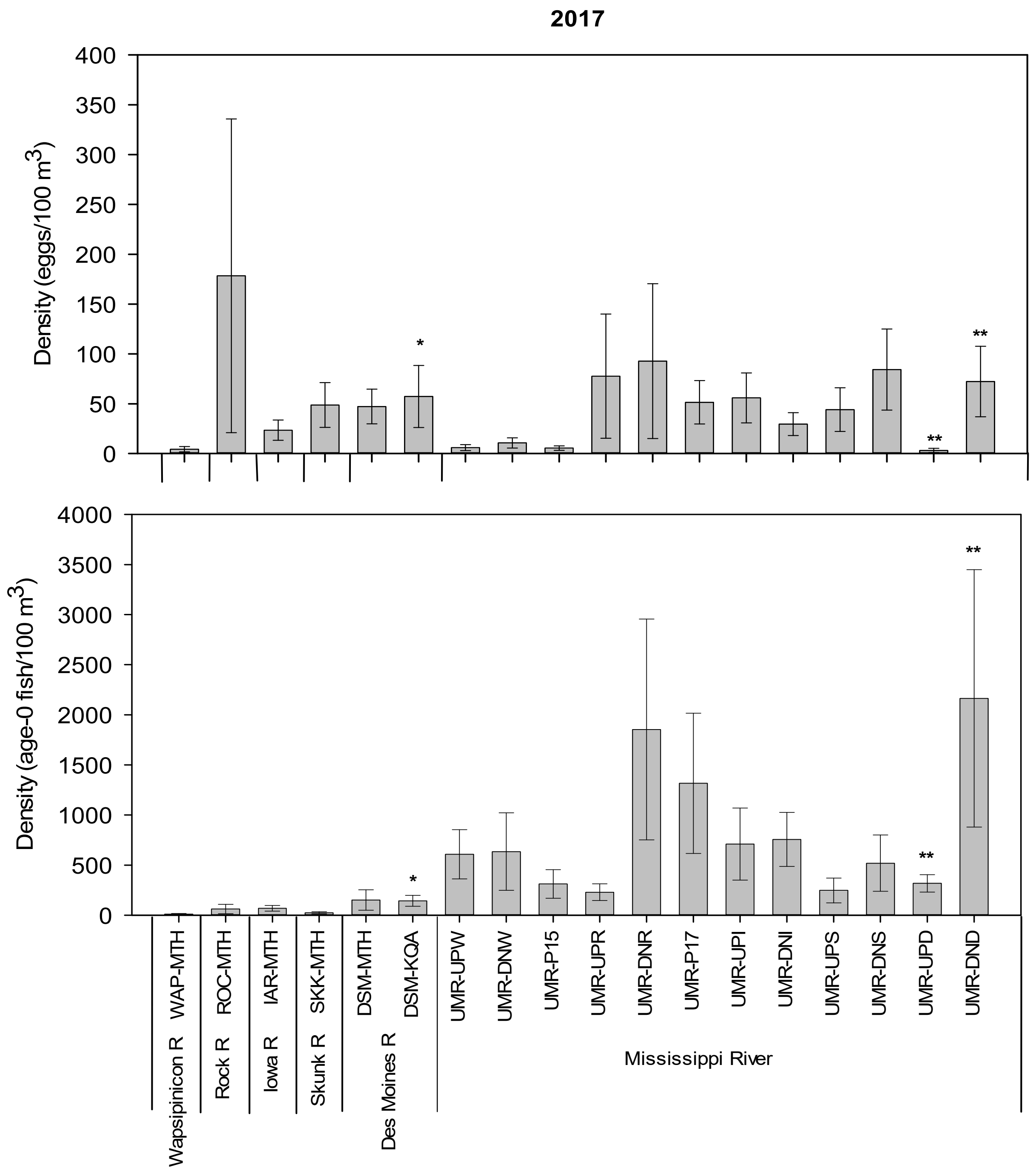

Figure 3. Density (mean ± 1 SE) of fish eggs (top) and age-0 fish (bottom) collected from each site during 2017. Site codes are defined in Table 1.

* The Des Moines River at Keosauqua (DSM-KQA) was unable to be sampled due to low flows.

** The Mississippi River upstream (UMR-UPD) and downstream (UMR-DND) of the Des Moines River were unable to be sampled due to severe weather.

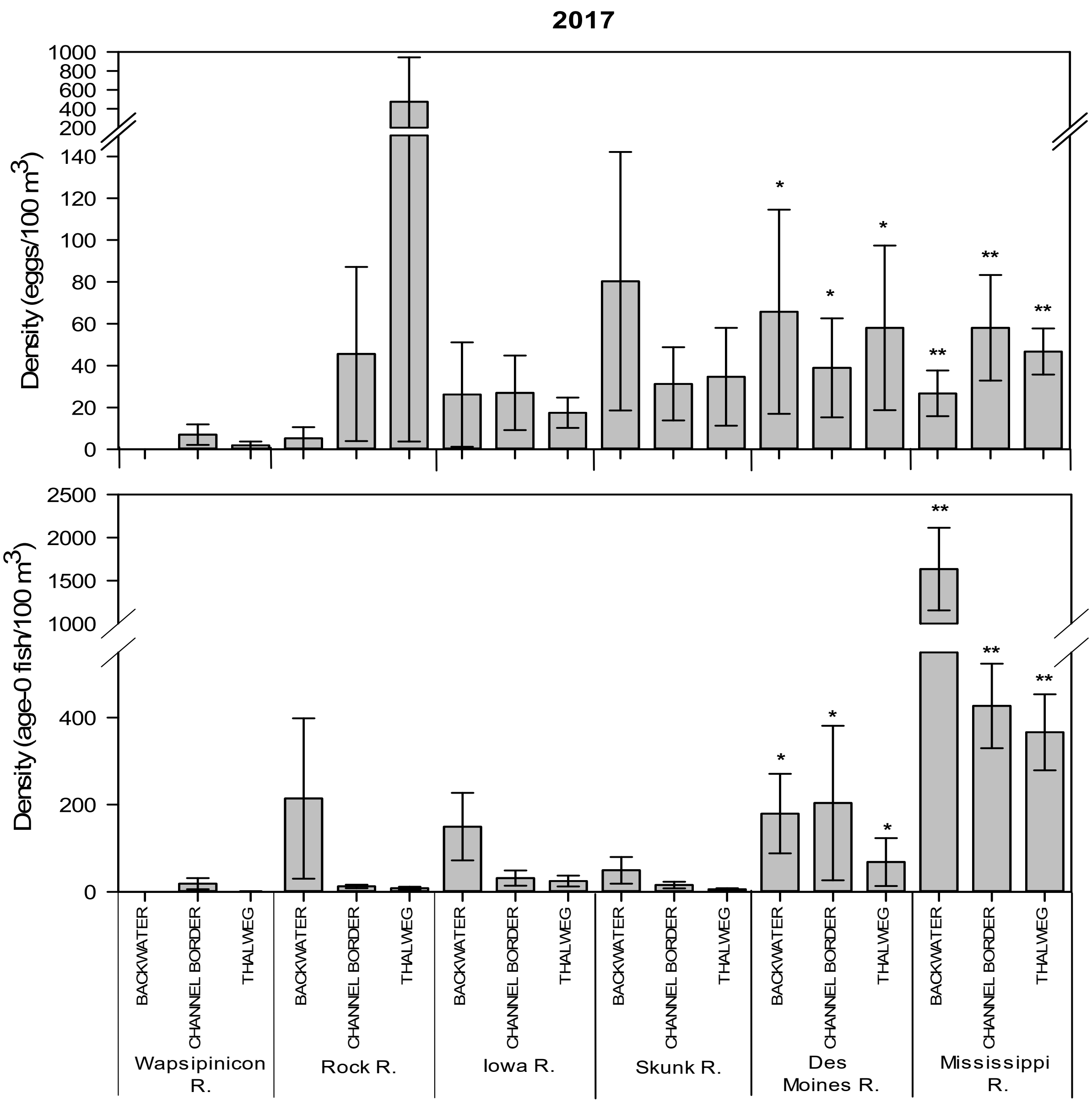

Figure 4. Density (mean ± 1 SE) of fish eggs (top) and age-0 fish (bottom) by habitat from the Wapsipinicon (WAP-MTH), Rock (ROC-MTH), Iowa (IAR-MTH), Skunk, Des Moines river (DSM-MTH) and (DSM-KQA), and all sites sampled within the Mississippi river from UMR-UPR down to UMR-DND during 2017. A list of sites can be found on Table 1.

* The Des Moines River, Keosauqua (DSM-KQA) was unable to be sampled during sampling sessions from August 2 to August 26 due to low flows.

** The Mississippi River upstream (UMR-UPD) and downstream (UMR-DND) of the Des Moines River were unable to be sampled due to severe weather during the sampling session August 26.

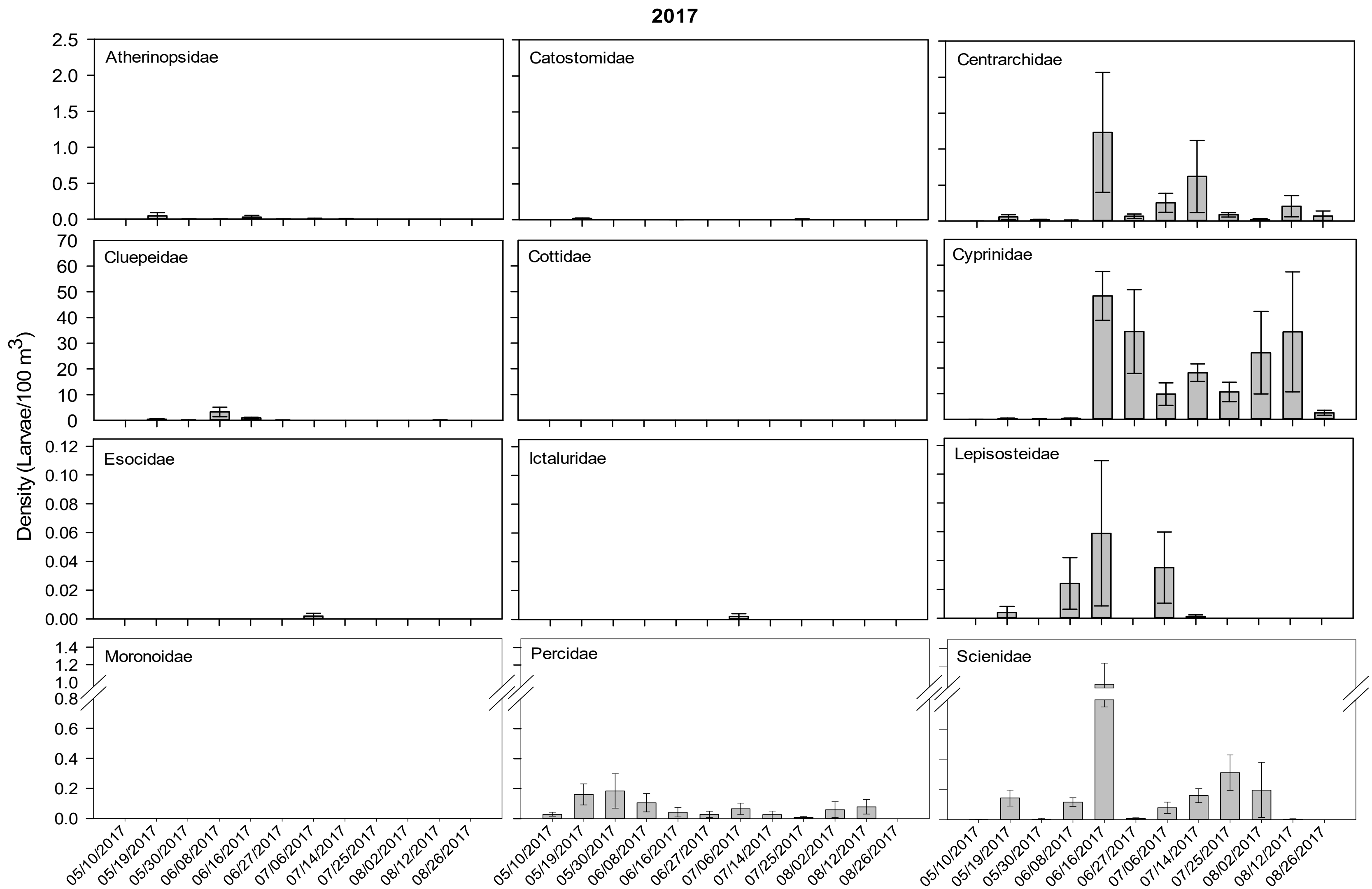

Figure 5. Density (mean ± 1 SE) of larvae by family from each sampling session in 2017.

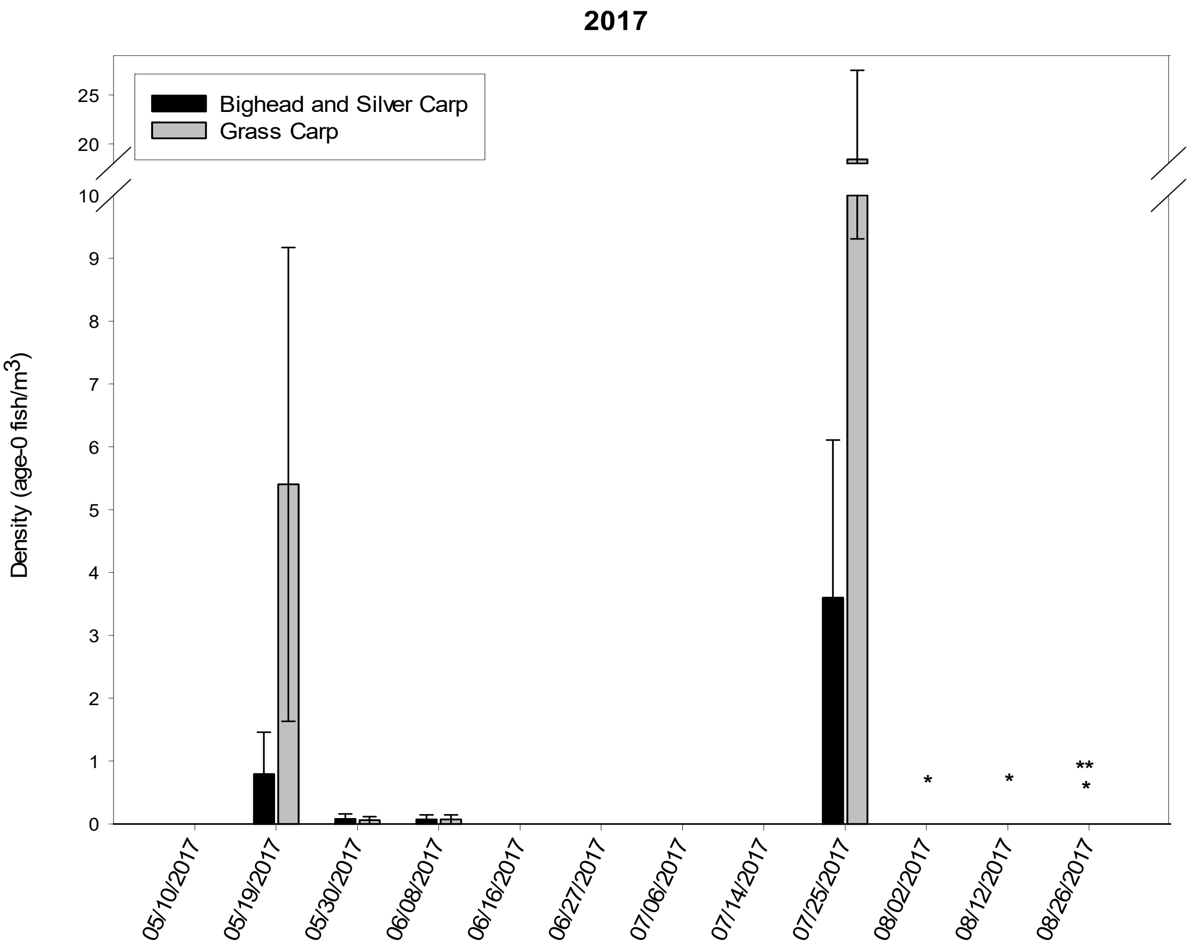

Figure 6. Density (mean ± 1 SE) of age-0 Bighead and Silver Carp (black bar) and Grass Carp (grey bar) by sampling session.

* The Des Moines River at Keosauqua (DSM-KQA) was unable to be sampled due to low flows.

** The Mississippi River upstream (UMR-UPD) and downstream (UMR-DND) of the Des Moines River were unable to be sampled due to severe weather.

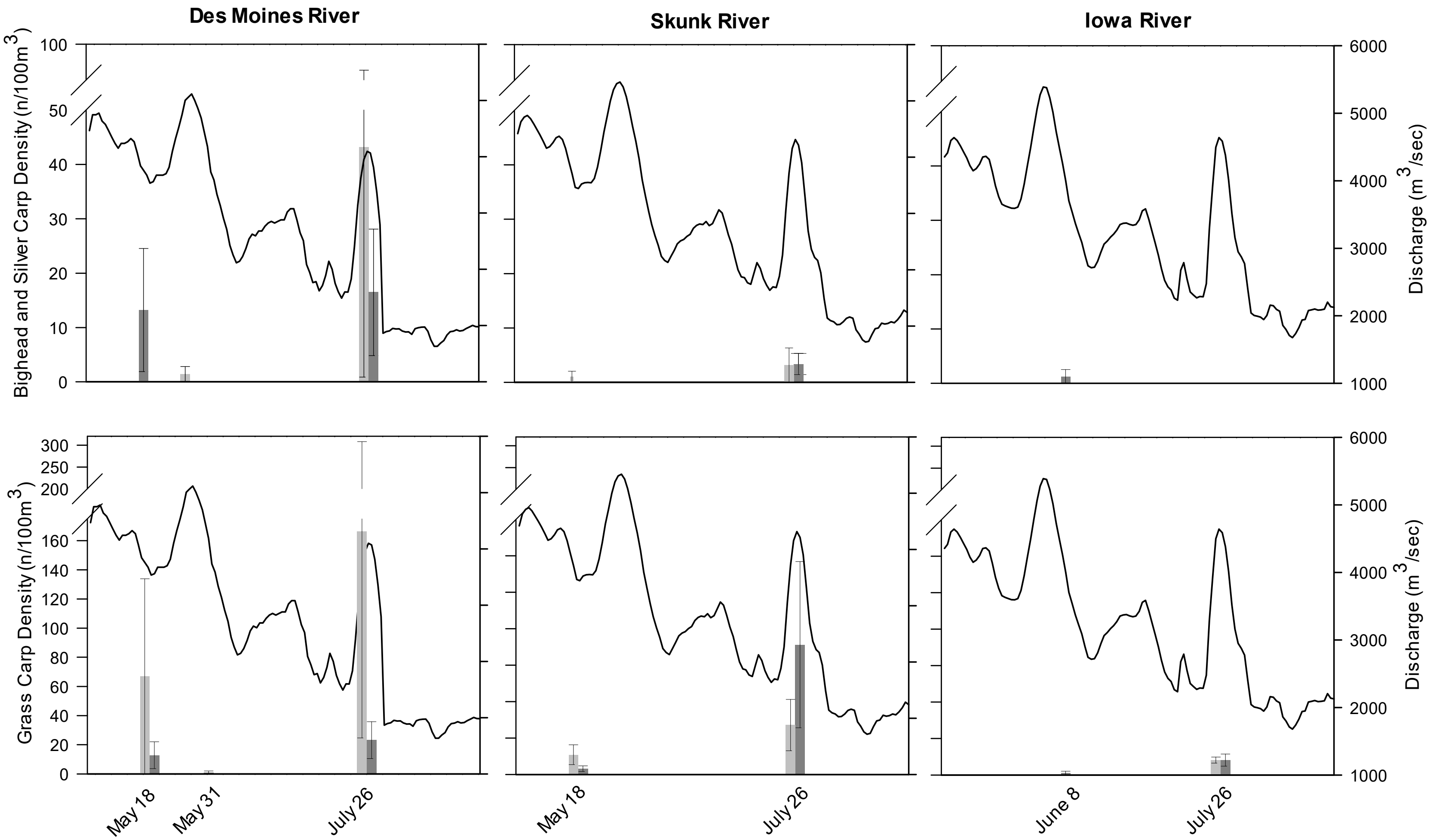

Figure 7. Age-0 Bighead and Silver Carp (top) and Grass Carp (bottom) density (vertical bars; mean 100 $m^3 \pm$ SE) across habitats from sites upstream (light gray) and downstream (dark gray) of the tributaries of the Des Moines (left), Skunk (middle) and Iowa (right) rivers. Mean daily discharge from the first day of sampling (May 8) to the last day (August 27) in 2017 were plotted with the solid line.

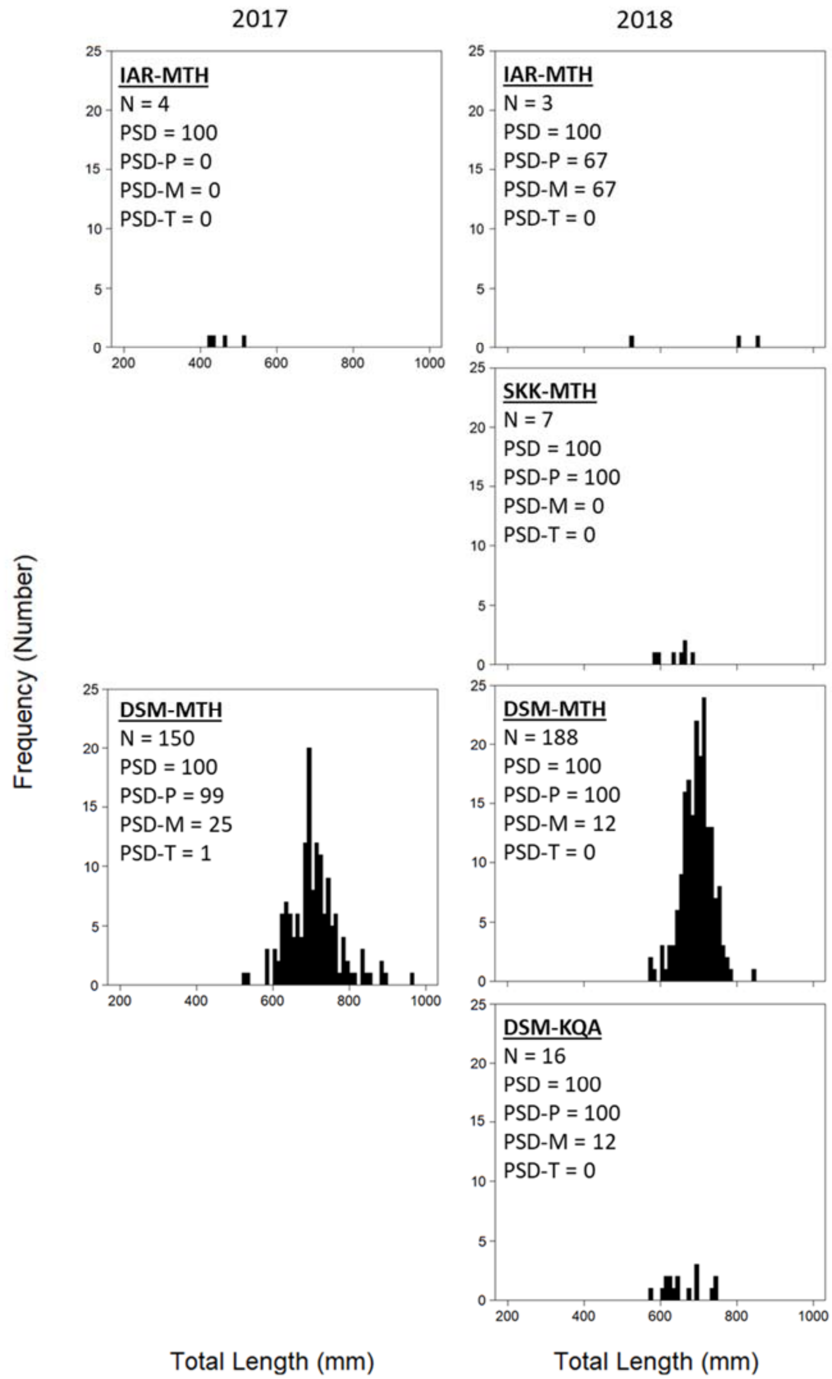

Figure 8. Length-frequency and proportional size distribution (PSD; P-Preferred, M-Memorable, T-Trophy) indices of Silver Carp captured during 2017 and 2018 in the mouths of the Iowa (IAR), Skunk (SKK), and Des Moines (DSM) Rivers as well as Keosauqua (KQA) within the Des Moines River. N = number of Silver Carp captured at each site.

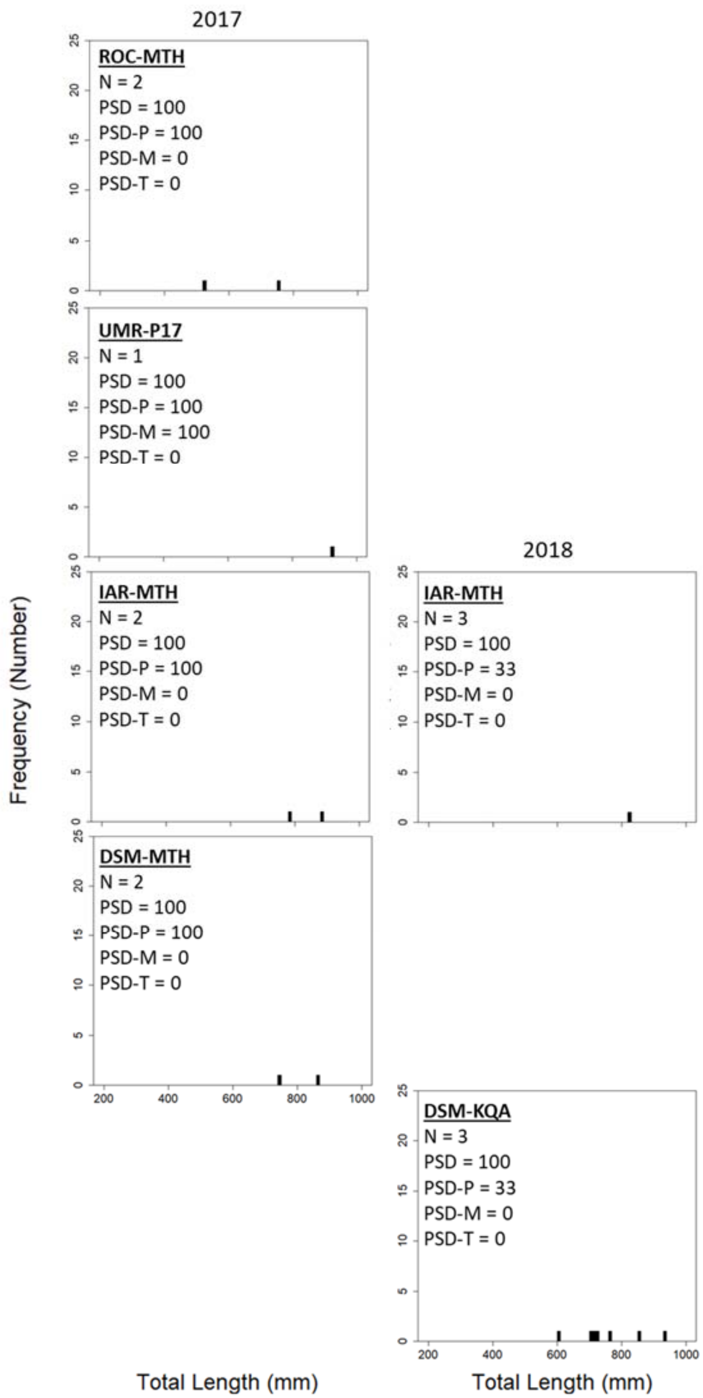

Figure 9. Length-frequency and proportional size distribution (PSD; P-Preferred, M-Memorable, T-Trophy) indices of Grass Carp captured during 2017 and 2018 in the mouths of the Rock (ROC), Iowa (IAR), and Des Moines (DSM) rivers as well as Keosauqua (KQA) within the Des Moines River and Pool 17 (P17) of the Mississippi River. N = number of Grass Carp captured at each site.

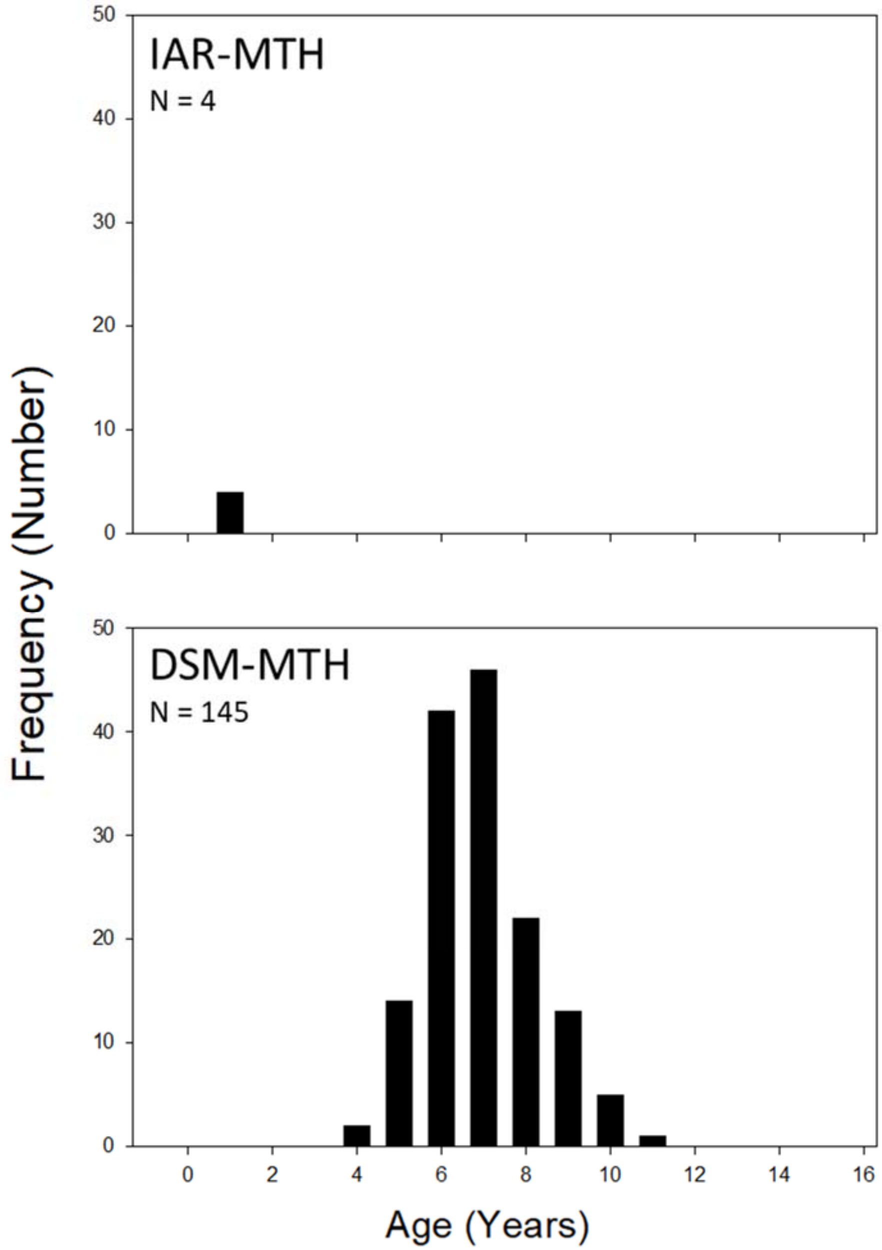

Figure 10. Silver Carp age-frequency histograms of fish collected in 2017 from the mouths of the Des Moines River (DSM-MTH) and the Iowa River (IAR-MTH). No Silver Carp were captured at the mouths of the Skunk, Rock, or Wapsipinicon Rivers, or from Pools 17 or 15 of the Upper Mississippi River.

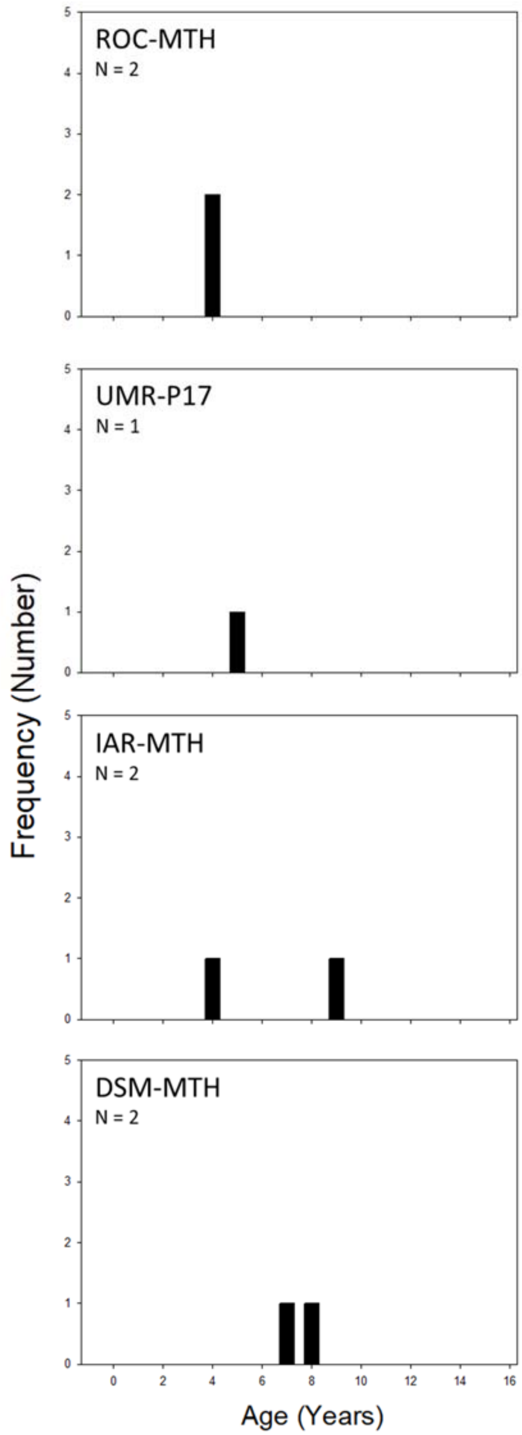

Figure 11. Grass Carp age-frequency histograms in 2017 from the mouths of the Des Moines River (DSM-MTH), Iowa River (IAR-MTH), and Rock River (ROC-MTH), as well as Pool 17 of the Upper Mississippi River (UMR-P17). No Grass Carp were captured at the mouths of the Skunk or Wapsipinicon Rivers, or from Pool 15 of the UMR.

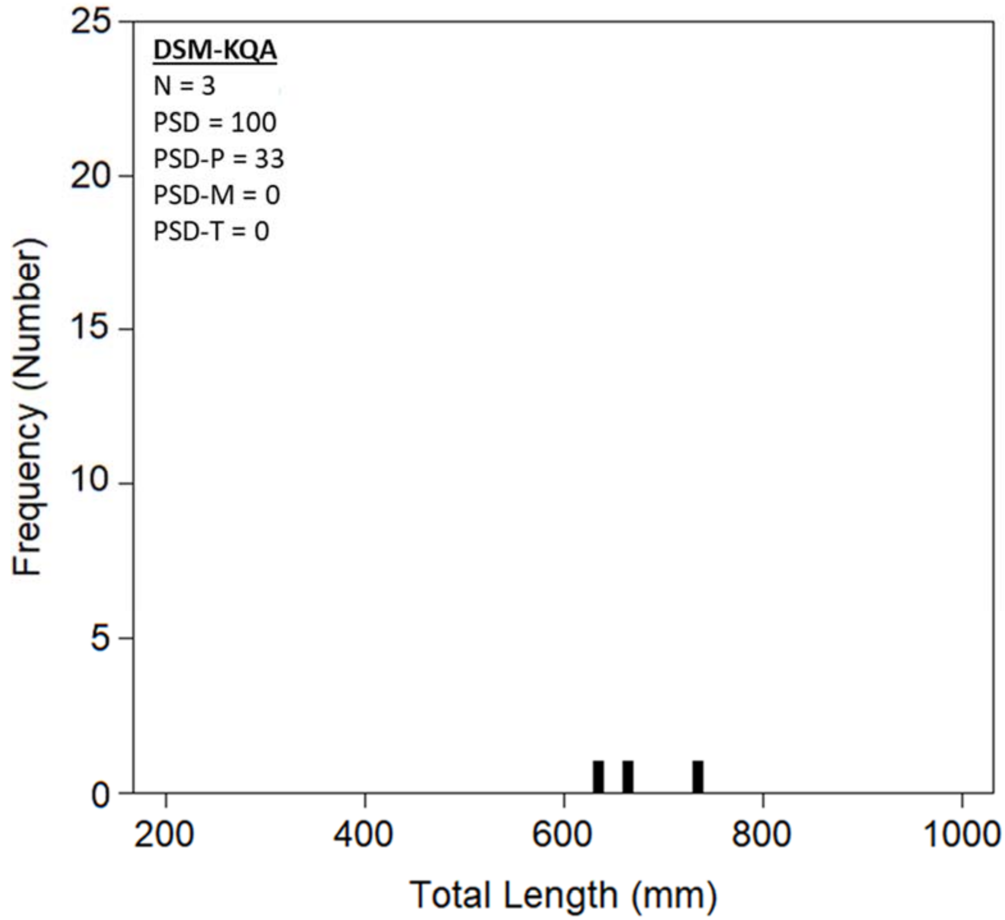

Figure 12. Length frequency and proportional size distribution (PSD; P-Preferred, M-Memorable, T-Trophy) indices of Bighead Carp captured during 2018 in the Des Moines (DSM) River at Keosauqua (KQA). N = number of Bighead Carp captured.