MANAGEMENT BRIEF

Effects of Turbidity on Prey Selection and Foraging Rate of Hatchery-Reared Juvenile Tiger Muskellunge

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Abstract

Tiger muskellunge (Northern Pike *Esox lucius* × Muskellunge *E. masquinongy*) are stocked into aquatic systems across North America to control undesirable fish species or to create sportfishing opportunities. Because decreased water clarity can affect the post-stocking foraging ability of an ambush predator like the tiger muskellunge, we evaluated the effects of turbidity on the foraging success of tiger muskellunge in a laboratory setting. We tested prey selectivity and total prey consumption by juvenile tiger muskellunge at four turbidity levels (Secchi depths of >84, 53, 26, and 18 cm) using three prey species: Goldfish *Carassius auratus* (a surrogate for Common Carp *Cyprinus carpio*), Gizzard Shad *Dorosoma cepedianum*, and Green Sunfish *Lepomis cyanellus*. Tiger muskellunge consumed significantly less prey at Secchi depths of 26 and 18 cm than at a Secchi depth of >84 or 53 cm. Selectivity for or against all prey types decreased as turbidity level increased, such that all three prey types had similar neutral selectivity at the highest turbidity level even though Gizzard Shad were positively selected and Goldfish were negatively selected in clearer water. Green Sunfish were neutrally selected at all turbidity levels tested. These results suggest that increasing turbidity levels will negatively impact prey encounters and consumption rates, which likely will reduce growth rates of tiger muskellunge, ultimately reducing fish survival and stocking success.

Outcomes of predator–prey interactions are largely influenced by the ability of predators and prey to detect and respond to one another (Powers and Kittinger 2002; Chivers et al. 2013). Water clarity, particularly turbidity, affects interactions between predator and prey in aquatic environments and also influences interactions between and within species, thereby shaping fish communities (Carter et al. 2010; Lunt and Smee 2015; Figueiredo et al. 2016). Turbidity is typically produced by small particles of silt, clay, fine sand, or detritus that are suspended by wind action, rain events, or fish disturbing the substrate (Carter et al. 2010; Jonsson et al. 2013; Li et al. 2013) or by phytoplankton (Carlson 1977). Turbidity can affect the ability of fish to detect objects and discern their shape, color, size, and distance. As such, turbidity can alter predator–prey interactions by altering the size (Holzman and Genin 2005) or species (Shoup and Wahl 2009; Carter et al. 2010; Shoup and Lane 2015) selected by predators.

Increases in turbidity can also reduce the frequency of encounters between predator and prey (Gregory and Levings 1996; Shoup and Wahl 2009; Carter et al. 2010), leading to lower overall predator foraging return (Shoup

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and Lane 2015). However, some species appear unaffected by turbidity (juvenile Rainbow Trout *Oncorhynchus mykiss*: Rowe et al. 2003; age-0 Yellow Perch *Perca flavescens*: Wellington et al. 2010; juvenile Mandarin Fish *Siniperca chuatsi*: Li et al. 2013), and others even exhibit better foraging success in moderate turbidity levels (Koaro *Galaxias brevipinnis* and Redfin Bully *Gobiomorphus huttoni*: Rowe and Dean 1998; juvenile Atlantic Cod *Gadus morhua*: Meager and Batty 2007). As turbidity levels fluctuate, the ability of predators to recognize and consume prey constantly changes, as does the ability of prey to recognize and avoid predators (Huenemann et al. 2012; Shoup and Lane 2015), and such changes can alter prey selection (Shoup and Wahl 2009; Carter et al. 2010; Shoup and Lane 2015).

Few studies have investigated the effects of turbidity on ambush predator success, and these studies have produced conflicting results. Only one study has directly tested the effects of turbidity on esocid foraging success (Vanlandeghem et al. 2011); during that study, Muskellunge *Esox masquinongy* captured the same number of prey at low (0-NTU) and high (40-NTU) turbidity levels in controlled laboratory trials. Those results on foraging success were contrary to observations that Muskellunge growth was reduced from 1.2 mm/d at 30 NTU to 0.6 mm/d at a high turbidity level of 67 NTU (Weithman and Anderson 1977). Similarly, conflicting results have been reported for the effects of turbidity on Northern Pike *E. lucius*. Craig and Babaluk (1989) found that turbidity negatively affected Northern Pike condition, whereas Skov et al. (2002) found no impact of water clarity on the foraging success of Northern Pike.

Tiger muskellunge (Northern Pike × Muskellunge) are stocked into aquatic systems throughout North America (Crossman 1986; Wahl et al. 2012) to control overabundant or undesirable fish species (Lepak et al. 2014; Koenig et al. 2015; Sorel et al. 2016) or to create sport fisheries (Wahl et al. 2012; Sorel et al. 2016). Numerous studies have evaluated variables that may affect the survival of tiger muskellunge, including the use of artificial (pellet) versus natural (fish) diets administered prior to stocking (Gillen et al. 1981); predation (Stein et al. 1981; Wahl and Stein 1989); and predator acclimation (Wahl et al. 2012). However, no evaluations have been conducted to determine the effects of turbidity on tiger muskellunge foraging ability, which could affect fish survival and stocking success. Because turbidity is an environmental condition found in most aquatic systems (Vanlandeghem et al. 2011), it is important to understand how turbidity may affect continued stocking efforts to establish tiger muskellunge (Lepak et al. 2014; Koenig et al. 2015; Sorel et al. 2016). The purpose of this study was to test the effects of turbidity at four levels (Secchi depths of >84 [tap water], 53, 26, and 18 cm) on prey selectivity and foraging return

of juvenile tiger muskellunge by using three different prey species (Goldfish *Carassius auratus* [a surrogate for Common Carp *Cyprinus carpio*], Gizzard Shad *Dorosoma cepedianum*, and Green Sunfish *Lepomis cyanellus*) that are commonly found in southern U.S. reservoirs.

METHODS

Tiger muskellunge (mean TL = 238 mm; range = 213–313 mm) were transported from Speas Fish Hatchery (Casper, Wyoming) to the Bryon State Fish Hatchery (Burlington, Oklahoma), where they were placed into a 0.6-ha pond stocked with Bluegills *L. macrochirus* and Fathead Minnow *Pimephales promelas* as forage. Ten days later, the fish were seined from the pond and were transported to the Oklahoma Department of Wildlife Conservation (ODWC) Fishery Research Laboratory, Norman, where they were held in a 3,032-L raceway and were fed Fathead Minnow, Gizzard Shad, Green Sunfish, and Goldfish. Predators were acclimated in the laboratory for at least 7 d before their use in the experiment and were observed readily feeding on all three experimental prey types before being used in trials.

Gizzard Shad were collected via electrofishing from Lake Carl Etling, Oklahoma. Green Sunfish were obtained from Holdenville State Fish Hatchery (Holdenville, Oklahoma). Goldfish (gold/bronze in color) were raised in outdoor ponds with little human contact except to feed and harvest; they were originally donated by the Matt McBride fish farm (Wetumka, Oklahoma). All prey species were transported to the ODWC Fishery Research Laboratory, where they were placed into a 946-L, round tank with slow water exchange and aeration; prey fish were allowed to acclimate for at least 10 d prior to use in the experiment. Prey sizes were matched with predator sizes based on "optimal size" (optimum point of handling time divided by prey weight; Hoyle and Keast 1987). Optimal size for Gizzard Shad is 30–36% of tiger muskellunge mean TL (Carline et al. 1986). The optimal size of Green Sunfish for tiger muskellunge is unknown, so we used data from handling time trials for Bluegills as a proxy (optimal size of Bluegills is 25–30% of predator mean TL; Gillen et al. 1981). Similarly, the optimal size of Goldfish consumed by tiger muskellunge is unknown, so we used 15–21% of predator mean TL based on prey size information from Weithman and Anderson (1977).

Foraging trials were conducted indoors in eight round, fiberglass tanks (total volume = 0.49 m³; diameter = 1.22 m; depth = 0.42 m). Two full replicates (i.e., two trials of each of the four turbidity levels) of the experiment were run simultaneously on each trial date. On each date, tanks were assigned a turbidity level using a stratified random design (two replicates per turbidity level, but the assignment of turbidity levels to tanks was randomized

within each replicate). All tanks were equipped with aeration to keep the clay suspended, similar to the work of Shoup and Wahl (2009). Timers were installed on lights to produce a 12-h light : 12-h dark photoperiod. Tank temperatures averaged 19°C and dissolved oxygen averaged 7.9 mg/L throughout all trials.

Turbidity in each tank was produced using bentonite clay. Clay and water were first stirred together in a separate container until thoroughly mixed, and the mixture was then added to each round tank until the desired turbidity was achieved. Turbidity in each tank was measured using a Secchi tube (Myre and Shaw 2006). To maximize precision, the same observer always measured the Secchi depth. Secchi depth treatments used in this experiment were >84 (tap water), 53, 26, and 18 cm. Once the desired turbidity level was achieved in each tank, eight individuals of each prey species (24 prey total) were added to each tank. To isolate the predator from prey for a 24-h acclimation period, each tiger muskellunge was placed into a floating, clear container (42.4 × 30.4 × 33 cm) with 10-mm holes drilled haphazardly on every side. Turbidity was measured in each tank at the end of the 24-h period and was adjusted if the Secchi depth was not within 10% of the assigned level. The predator was then released and allowed to forage for 24 h before being removed. After the trials, tanks were drained, and the remaining prey were removed and counted. No predator was used in more than one trial.

The effects of turbidity on the number of prey consumed by tiger muskellunge was compared by using a generalized linear model (GLM; GLIMMIX procedure in SAS; SAS Institute 2013) that tested the number of prey items (all prey combined) consumed at each turbidity level. A Poisson probability distribution was specified for the number of prey consumed. A post hoc Tukey's honestly significant difference (HSD) test was used to conduct pairwise combinations of turbidity levels when the GLM was significant. Chesson's alpha values for each prey type were compared among turbidity levels by using a multivariate ANOVA (MANOVA; GLM procedure in SAS). This allowed the responses (i.e., Chesson's alpha values) from all three prey types to be tested in a single analysis that accounted for possible correlations between response variables. Significant differences were further evaluated with Tukey's HSD tests examining pairwise combinations of Chesson's alpha values (MIXED procedure in SAS) using the interaction of turbidity level and species (Kutner et al. 2005). All statistical analyses were conducted at a significance level of $P \leq 0.05$.

RESULTS

Overall, 43 replicates at each turbidity level were completed using 172 tiger muskellunge. The total prey consumed was highest (1.4 prey/d) in the tap water (>84-cm
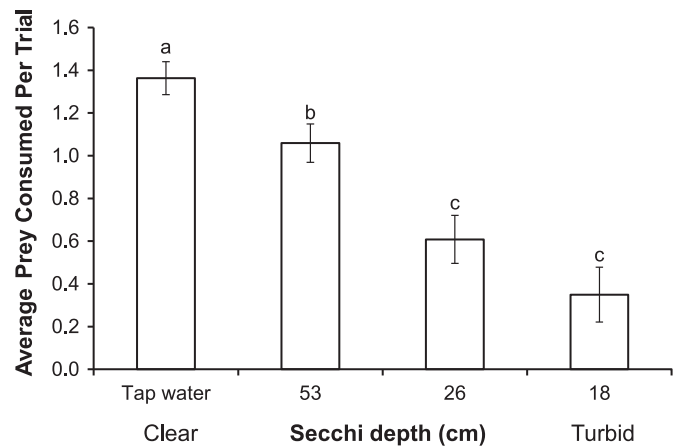

FIGURE 1. Mean (±SE) foraging rates of tiger muskellunge on Green Sunfish, Goldfish, and Gizzard Shad at four turbidity (Secchi depth) levels in laboratory tank experiments during a 24-h period. Means with different lowercase letters are significantly different.

Secchi depth) treatment and significantly declined at each higher turbidity level tested through 18-cm Secchi depth, at which less than half as many prey were consumed ($F_{3, 168} = 20.15$, $P < 0.01$; all Tukey's HSD comparisons: $P < 0.01$; Figure 1). Prey consumption was similarly low at the 26- and 18-cm Secchi depths (Tukey's HSD comparison: $P = 0.43$).

The pattern of prey selectivity also varied among turbidity levels (MANOVA: Wilks' $\lambda = 0.85$, $F_{6, 318} = 4.36$, $P < 0.01$). Selectivity became less pronounced at higher turbidity levels such that significant selection for prey types observed in low-turbidity treatments did not occur at higher turbidity levels: all prey were neutrally selected
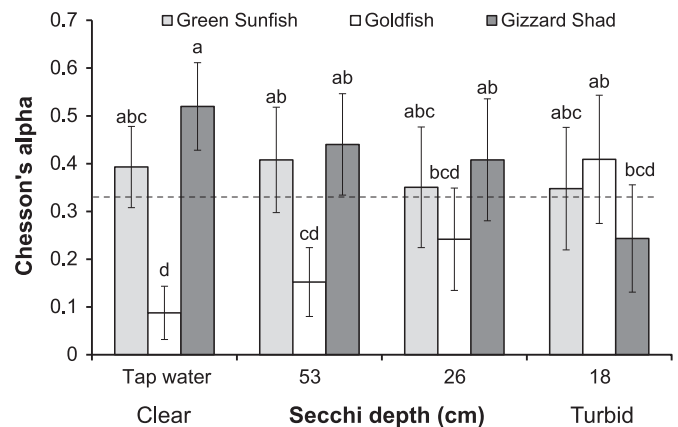

FIGURE 2. Selectivity (Chesson's alpha; mean ± 95% confidence interval) of Green Sunfish, Goldfish, and Gizzard Shad by tiger muskellunge at four turbidity (Secchi depth) treatments. The interaction among selection and turbidity levels was evaluated using multivariate ANOVA. Means with different lowercase letters are significantly different. The horizontal line at a Chesson's alpha value of 0.33 represents random (neutral) prey selection.

at higher turbidity (Figure 2). For example, tiger muskellunge exhibited positive selectivity for Gizzard Shad and negative selectivity for Goldfish at lower turbidity levels, but their selectivity for Gizzard Shad significantly declined and their selectivity for Goldfish significantly increased, such that all three prey types were neutrally selected at higher turbidity levels. Selectivity for Green Sunfish was neutral at all turbidity levels (all Tukey's HSD comparisons: $P > 0.99$).

DISCUSSION

Previous studies examining the effects of turbidity on ambush predators, such as esocids, are limited. Our results demonstrate that turbidity affects both prey selectivity and consumption rates of tiger muskellunge. Tiger muskellunge consumed less prey and were less selective of prey species as the turbidity level increased. At lower turbidity levels (≥53-cm Secchi depth), tiger muskellunge positively selected Gizzard Shad. In a laboratory experiment, Weithman and Anderson (1977) also found that tiger muskellunge preferred Gizzard Shad over centrarchids (Bluegills) and Goldfish at low turbidities. This may be due to the spines on centrarchids, which increase the handling time required to properly orient spiny-rayed fish for consumption (Gillen et al. 1981). Moody et al. (1983) reported that tiger muskellunge required four times as many strikes and took longer to capture Bluegills compared to Fathead Minnow. The length of time needed to capture *Lepomis* sp. might explain why Green Sunfish were not positively selected at any turbidity level.

Goldfish were also negatively selected at lower turbidity levels; however, as levels increased, so did selectivity for Goldfish. Goldfish, like Green Sunfish, have a dorsal and anal spine. Additionally, we observed that Goldfish frequently hovered just above the tank bottom and were not located in the upper water column with the other prey species at lower turbidity levels (we could not observe their location during the turbid treatments). This benthic behavior may have reduced their encounter rates with tiger muskellunge or may have produced a suboptimal vantage point for tiger muskellunge to strike and consume prey in clearer treatments. Goldfish exhibit the same benthic feeding strategy as Common Carp, which maintain benthic behaviors even at high turbidities (Bajer et al. 2010). New and Kang (2000) found that Muskellunge that were blinded sat motionless on the bottom of the tank awaiting prey to ambush. In our study, it is possible that tiger muskellunge implemented an ambush foraging approach on the bottom of the tanks as turbidity levels increased (a condition that may be analogous to being blinded), which would increase the selectivity of benthic-oriented Goldfish under these conditions. The lighter coloration of Goldfish could have also played a role in increasing selectivity at higher turbidity levels if this coloration increased the distance at which Goldfish could be detected by predators relative to other prey types in high-turbidity treatments. However, Coble (1973) documented no preference by Northern Pike for particular color morphs (gold, white, and natural) or tail form morphs (fan and regular tail) of Goldfish used in laboratory foraging experiments. Ultimately, tiger muskellunge were less selective at higher turbidity levels, either because they were less able to discriminate prey species or because decreased foraging return made it advantageous to be less selective when a feeding opportunity presented itself.

Increased turbidity significantly decreased the number of prey consumed by a tiger muskellunge in a 24-h period. Similar results have been found for numerous other predators (e.g., Rainbow Trout: Ginetz and Larkin 1976; juvenile Walleyes *Sander vitreus*: Vandenbyllaardt et al. 1991; Largemouth Bass *Micropterus salmoides*: Shoup and Wahl 2009; Shoup and Lane 2015; Smallmouth Bass *M. dolomieu*: Carter et al. 2010; juvenile Yellow Perch: Wellington et al. 2010). Low foraging return at high turbidity (i.e., ≤26-cm Secchi depth) could be problematic because it may prevent tiger muskellunge from capturing sufficient prey to meet caloric demands, thus negatively impacting recruitment.

Foraging return of ambush predators, such as esocids (Savino and Stein 1989), may not be as strongly affected by turbidity if the predator does not need to see prey from very large distances to be effective. In high-turbidity environments, the murky water could theoretically help ambush predators hide such that they are more effective. This idea is supported by the results of previous research demonstrating that ambush predators (Muskellunge) captured more prey than cruising predators (Largemouth Bass) at high turbidity levels, even though they had similar foraging returns at low turbidity levels (Vanlandeghem et al. 2011). It has been suggested that Muskellunge can rely on their highly developed lateral line when they cannot rely on vision (New et al. 2001; Vanlandeghem et al. 2011); this may be a mechanism that allows them to be successful at higher turbidity levels. However, Northern Pike become more active (i.e., abandon their ambush strategy) at higher turbidity in order to maintain their feeding rates (Andersen et al. 2008). Based on the results of our study, it is clear that increased turbidity reduces prey consumption and selectivity by tiger muskellunge. It is unknown whether tiger muskellunge transition to an active hunting strategy similar to Northern Pike at higher turbidity levels. Further research is needed to understand the mechanisms underlying changes in tiger muskellunge foraging return in highly turbid environments.

Results from this experiment indicate that turbidity could negatively impact the foraging success of and reduce selectivity by tiger muskellunge in turbid systems. Due to

their highly piscivorous nature and ability to control populations of undesirable fish species (e.g., White Sucker *Catostomus commersonii* and Black Crappie *Pomoxis nigromaculatus*: Siler and Beyerle 1986; Brook Trout *Salvelinus fontinalis*: Koenig et al. 2015), tiger muskellunge are used as a biological control agent, but based on our results, this strategy may be ineffective in lakes where Secchi depths average 26 cm or less. Furthermore, survival and recruitment of stocked tiger muskellunge may be affected, in part, by low food consumption when Secchi depths are 26 cm or less. Understanding how natural conditions affect the feeding ecology of stocked fishes will help fisheries managers to have a better grasp on the potential success of these stocking programs. Further research into the effects of turbidity on other life history characteristics (i.e., habitat use, growth, and movement) of tiger muskellunge will also have relevance to the development of management strategies for this species.

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