J. Aquat. Plant Manage. 39: 40-44

Effects of Hypoxia on Fish Assemblages in a Vegetated Waterbody

K. JACK KILLGORE[1] AND JAN JEFFREY HOOVER[1]

ABSTRACT

We evaluated fish species composition relative to dissolved oxygen concentrations in Mercer Bayou, a vegetated impoundment in southwest Arkansas. Sampling stations were distributed among three reaches that varied in dissolved oxygen concentrations ranging from 0.2 to7.5 mg/l. Hypoxia was pronounced at the downstream reach of the bayou because of stagnant water and nearly complete shading of the water's surface by floating plants. Fishes were sampled in each reach by seining and gill netting. Forty-five fish species were collected and the assemblage was dominated by phytophilic taxa. In upper and middle reaches, species richness was relatively high (>13 species per sample). In the lower hypoxic reach, species richness was low (<8 species per sample). Polynomial regression indicated a significant positive relation ($R^2 = 0.67$) between species richness (y) and dissolved oxygen (x): $y = 8.03 + 7.19x - 0.72x^2$. Species richness, abundance, and size of fish were substantially reduced at dissolved oxygen concentrations below 0.5 mg/l, suggesting a threshold response level of assemblage composition. Gars, topminnows, and small backwater sunfishes (29% of all species documented) persisted at low dissolved oxygen concentrations, but other sunfishes, darters, and larger benthic fishes avoided hypoxic waters, probably due to physiological limitations. Species adapted for aerial and surface film respiration dominated the fish assemblage in hypoxic waters. Our model suggests that dissolved oxygen can be used to predict fish species composition and quantify habitat quality in vegetated areas.

Key words: dissolved oxygen, fish species richness, fish size, fish abundance, respiration, aquatic plants, littoral zone.

INTRODUCTION

Submersed macrophytes influence dissolved oxygen levels through photorespiration, shading, and stagnation (Carpenter and Lodge 1986, Carter et al. 1988, Carter et al. 1991). Hypoxia, usually defined as dissolved oxygen concentrations less than 5 mg/l, typically occurs in dense vegetation and affects many physiological, biochemical, and behavioral processes in fish (Davis 1975, Kramer 1987). Hypoxia can change fish assemblage composition and may lead to mortality if fish cannot escape to more oxygenated waters (Smale and Rabeni 1995). As aquatic macrophytes increase in coverage and density, widespread hypoxia can occur that can lead to major fish kills. Hypoxic water, however, can be inhabited by various fish species tolerant of low dissolved oxygen concentrations.

Managing aquatic plants requires an understanding of the physiochemical changes associated with a control program. Reduction of plant density may minimize hypoxia, and therefore provide a benefit to aquatic organisms that are sensitive to low dissolved oxygen. Hypoxia tolerance studies indicate that fish species composition can be predicted over a range of dissolved oxygen concentrations, although we are not aware of this type of study being conducted in vegetated waterbodies. Our objectives in this study were to document fish species composition in vegetated locations differing in dissolved oxygen concentrations, and to develop a predictive model that can be used to evaluate impacts or benefits of aquatic plant management programs for fishes relative to dissolved oxygen concentrations.

MATERIALS AND METHODS

This study was conducted in Mercer Bayou, an impounded tributary of the Sulphur River in the Red River drainage system. Mercer Bayou is a 405-ha bottomland hardwood wetland approximately 14.5 km long, and is part of the Sulphur River Wildlife Management Area in southwest Arkansas. Upstream and downstream culverts with flap gates were constructed in the mid-1950s and control discharge through the bayou. Sampling stations were distributed among upper, middle, and lower reaches so that a range of habitat conditions, including dissolved oxygen, could be evaluated. Six stations were sampled in May and August 1999.

Juvenile and adult fishes were sampled during the day in littoral areas by seining (3 by 2.4 m, 5 mm mesh); ten seine hauls were taken at each station and pooled into one sample. Pelagic fishes were sampled with experimental mesh gill nets (27 m by 1.8 m, six mesh panels ranging from 2 to 9 cm); two nets were set overnight at each station. Concurrent with seining, physical habitat was characterized at each station using bathymetry data (cross-sectional transects of depth, channel width), and water quality parameters (dissolved oxygen, pH, conductivity, turbidity). Water quality was measured at the surface and bottom with a Hydrolab multi-parameter water quality probe. Aquatic plant coverage was estimated based on percentage of surface area obscured by floating and emergent species observed for a minimum distance of 100 m and areas free of submersed aquatic vegetation encountered while seining. Aquatic plants were identified in the field and listed. Dominant species and distribution of plants within the channel were noted.

---

[1] U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. Received for publication October 12, 2000 and in revised form October 15, 2001.

A Pearson's correlation coefficient was calculated for percent plant coverage and dissolved oxygen concentration (SAS 1989). Relationships between species richness and dissolved oxygen concentration were evaluated using linear and polynomial regression. Fish abundance and total length were $\log_{10}$ transformed and compared among stations with different dissolved oxygen concentrations using ANOVA. Means that were significantly different ($p < 0.05$) were compared using the Student-Neuman-Keuls (SNK) multiple range test.

RESULTS AND DISCUSSION

Water temperatures ranged from 21-34 C during the sampling period. The mean (±SD, n = 12) water depth of the main stem Mercer Bayou during summer and fall was 0.8 ± 0.3 meters; maximum depth was 2.1 meters immediately behind the downstream water control structure. There was no flow in the bayou during sampling. Substrates consisted of mud and detritus, primarily due to the annual senescence of aquatic vegetation. Water quality was typical of vegetated habitats during summer and fall: mean turbidity was low (11 ± 5.4 NTU's) and dissolved oxygen ranged from 0.2-7.5 mg/l. Vertical stratification of temperature and dissolved oxygen occurred in deeper waters (>1.5 m). Hypoxia was pronounced at the downstream reach during May and August because of deep, stagnant water and nearly complete shading of the water's surface by floating plants. Dissolved oxygen concentration was negatively correlated (Pearson's coefficient = -0.78, n = 12, p = 0.003) with surface coverage of aquatic plants. Conductivity and pH were similar among stations, with means of 150 ± 47 µmhos/cm and 6.9 ± 0.4, respectively.

Cypress trees (*Taxodium distichium* (L.) Rich.) and submersed woody structure occurred at all sites. Willows (*Salix* sp.) and oaks (*Quercus* sp.) occurred at most sites. Aquatic vegetation was moderately diverse, abundant, and varied in composition along the length of the bayou. Dominant taxa (in decreasing order of frequency observed) were: duckweed (*Lemna minor* L.), American lotus (*Nelumbo lutea*) (Willd.) Pers., coontail (*Ceratophyllum demersum* L.), emergent forbs and buttonbush (*Cephalanthus occidentalis*), water pennywort (*Hydrocotyle umbellata* L.), clumps of unidentified filamentous algae, alligator weed (*Alternanthera philoxeroides*) (Mart.), azolla (*Azolla caroliniana* Willd.), and water hyacinth (*Eichhornia crassipes*) (Mart.) Solms. In May, coverage ranged from 20-50% of the surface area in the upper and middle reaches with most vegetation occurring near the shoreline or in patches throughout the channel. In August, coverage increased to 50-100%. Dominant taxa were American lotus, which occurred at all sites on both dates, and duckweed and alligator weed. In the lower reach, coverage was 100% in May and in August. Dominant taxa were duckweed and water pennywort. American lotus did not occur.

A total of 45 species of fishes were collected (Table 1). Sunfishes and black bass were the most common group of fishes collected with seines. Other common taxa, typically found in aquatic vegetation, included golden topminnow (*Fundulus chrysotus* (Günther)), western mosquitofish, (*Gambusia affinis* (Baird and Girard)), brook silverside (*Labidesthes sicculus* (Cope)), pugnose minnow (*Opsopoeodus emiliae* (Hay)), pirate perch (*Aphredoderus sayanus* (Gilliams)), bluntnose darter (*Etheostoma chlorosomum* (Hay)), slough darter (*Etheostoma gracile* (Girard)), and grass pickerel (*Esox americanus* Gmelin). Gill nets caught larger fishes including spotted gar (*Lepisosteus oculatus* (Winchell)), bowfin (*Amia calva* Linnaeus), buffalo (*Ictiobus* sp.), channel catfish (*Ictalurus punctatus* (Rafinesque)), brown bullhead (*Ameiurus nebulosus* (Lesueur), yellow bass (*Morone mississippiensis* Jordan and Eigenmann), white bass (*Morone chrysops* (Rafinesque)), and freshwater drum (*Aplodinotus grunniens* Rafinesque). Shad (*Dorosoma* sp.) were commonly collected with seines and gill nets. In the upper and middle reaches, species richness was relatively high (>13 species per sample) and fish were abundant (>200 individuals) at each sampling station. In the lower reach, species richness (<8 species per sample) and abundance was low, particularly at the lowermost station (<100 individuals).

Eleven species were collected in dissolved oxygen concentrations less than 1.0 mg/l (Table 1), although not exclusively. A bivariate plot of species richness and mean dissolved oxygen concentrations showed a curvilinear relationship and water temperature did not affect the distribution (Figure 1). Consequently, polynomial regression using May and August samples was used to develop the following model to predict species richness (y) as a function of dissolved oxygen concentration (x): $y = 8.03 + 7.19x - 0.72x^2$. Species richness was the total number of species collected at an individual station (using seines and gillnets) and dissolved oxygen (mg/l) was the mean of surface and bottom values measured at the point and time of fish collections.

Topwater species were commonly collected in waters less than 0.5 mg/l, particularly golden topminnow and mosquitofish. Both species have dorsally-oriented mouths and dorso-ventrally flattened heads that facilitate surface film respiration, or "piping" (Lewis 1970, Meffe and Snelson 1989). These species skim the oxygen-rich surface layer and can therefore occupy hypoxic and even anoxic waters.

Other species collected in hypoxic waters exhibit specific behavioral and morphological adaptations to hypoxia. Banded pygmy sunfish (*Elassoma zonatum* Jordan) and pirate perch are solitary species exhibiting low levels of activity (Robison and Buchanan 1988), which should reduce respiration rates. Sunfishes, such as bluegill (*Lepomis macrochirus* Rafinesque) and warmouth (*Lepomis gulosus* (Cuvier)), are tolerant of hypoxia <1 mg/l (Moore 1942, Matthews 1987). These sunfishes have a well-developed accessory organ for respiration, the pseudobranch (Odum and Caldwell 1955), which may facilitate hypoxia tolerance. Gars and bowfin tolerate hypoxia by breathing atmospheric air into their physostomous swim bladder, which functions as a lung (Moyle and Cech 1988). By contrast, groups such as darters and species such as freshwater drum, which exhibit no behavioral or morphological adaptations to hypoxia (Ultsch et al. 1978, Bodensteiner and Lewis 1992), were not abundant in the system. Regionally abundant and widespread species known to be intolerant of hypoxia, such as the blacktail shiner (*Cyprinella venusta* (Girard)) (Matthews 1987), were conspicuously absent.

Several different laboratory measures of hypoxia tolerance indicate that dissolved oxygen concentrations ranging from 0.5 to 1.0 mg/l approximate lethal threshold levels for many fishes, and that fish must utilize some form of alterna-

Table 1. Fishes collected at 6 stations in Mercer Bayou, Arkansas during May and August 1999. Species with asterisk were collected in dissolved oxygen concentrations less than 1.0 mg/l.

	Seine	Gill nets
Number of samples	12	21
Number of individuals	2149	217
Lepisosteidae		
Spotted gar, *Lepisosteus oculatus* (Winchell)	2	29
Longnose gar, *L. osseus* (Linnaeus)*	4	
Amiidae		
Bowfin, *Amia calva* Linnaeus		8
Clupeidae		
Gizzard shad, *Dorosoma cepedianum* (Lesueur)	39	39
Threadfin shad, *D. petenense* (Günther)	123	
Esocidae		
Grass pickerel, *Esox americanus* Gmelin	33	
Cyprinidae		
Common carp, *Cyprinus carpio* Linnaeus		5
Golden shiner, *Notemigonus crysoleucas* (Mitchill)	55	
Taillight shiner, *Notropis maculatus* (Hay)	10	
Pugnose minnow, *Opsopoeodus emiliae* (Hay)	75	
Bullhead minnow, *Pimephales vigilax* (Baird and Girard)	4	
Catostomidae		
River carpsucker, *Carpiodes carpio* (Rafinesque)		7
Smallmouth buffalo, *Ictiobus bubalus* (Rafinesque)		2
Bigmouth buffalo, *I. cyprinellus* (Valenciennes)		22
Black buffalo, *I. niger* (Rafinesque)		3
Spotted sucker, *Minytrema melanops* (Rafinesque)		1
Ictaluridae		
Channel catfish, *Ictalurus punctatus* (Rafinesque)		9
Brown bullhead, *Ameiurus nebulosus* (Lesueur)		5
Black bullhead, *A. melas* (Rafinesque)	9	2
Yellow bullhead, *A. natalis* (Lesueur)*	3	3
Aphredoderidae		
Pirate perch, *Aphredoderus sayanus* (Gilliams)*	59	
Cyprinodontidae		
Starhead topminnow, *Fundulus blairae* Wiley and Hall	7	
Golden topminnow, *F. chrysotus* (Günther)*	234	
Blackstripe topminnow, *F. notatus* (Rafinesque)	1	
Poeciliidae		
Western mosquitofish, *Gambusia affinis* (Baird and Girard)*	122	
Atherinidae		
Brook silverside, *Labidesthes sicculus* (Cope)	140	
Percichthyidae		
White bass, *Morone chrysops* (Rafinesque)		1
Yellow bass, *M. mississippiensis* (Jordan and Eigenmann)		4
Centrarchidae		
Banded pygmy sunfish, *Elassoma zonatum* Jordan*	37	
Warmouth, *Lepomis gulosus* (Cuvier)*	66	4
Orangespotted sunfish, *L. humilis* (Girard)	18	
Bluegill, *L. macrochirus* Rafinesque*	296	15
Dollar sunfish, *L. marginatus* (Holbrook)	7	
Redear sunfish, *L. microlophus* (Günther)*	140	6
Redspotted sunfish, *L. miniatus* (Valenciennes)*	38	
Bantam sunfish, *L. symmetricus* Forbes*	198	
Largemouth bass, *Micropterus salmoides* (Lacépède)	222	16
White crappie, *Pomoxis annularis* Rafinesque	59	4
Black crappie, *P. nigromaculatus* (Lesueur)	63	29

TABLE 1. (CONTINUED) FISHES COLLECTED AT 6 STATIONS IN MERCER BAYOU, ARKANSAS DURING MAY AND AUGUST 1999. SPECIES WITH ASTERISK WERE COLLECTED IN DISSOLVED OXYGEN CONCENTRATIONS LESS THAN 1.0 MG/L.

	Seine	Gill nets
Number of samples	12	21
Number of individuals	2149	217
Percidae		
Mud darter, *Etheostoma asprigene* (Forbes)	4	
Bluntnose darter, *E. chlorosomum* (Hay)	42	
Slough darter, *E. gracile* (Girard)	31	
Cypress darter, *E. proeliare* (Hay)	6	
Logperch, *Percina caprodes* (Rafinesque)	2	
Sciaenidae		
Freshwater drum, *Aplodinotus grunniens* Rafinesque		3
Total Number of Species	33	22

tive respiration (aerial or anaerobic), exhibit avoidance behaviors, or die (Davis 1975, Smale and Rabeni 1995). Our study, however, suggests that some fish species commonly found in vegetated habitats can tolerate dissolved oxygen concentrations less than 0.5 mg/l, albeit their abundance's are considerably lower compared to normoxic waters.

We compared abundance of all fish species collectively among sampling stations with extreme hypoxic (<0.5 mg/l), hypoxic (0.5 to 5.0 mg/l), and normoxic (>5.0 mg/l) waters. Dissolved oxygen concentrations greater than 5.0 mg/l were considered normal because this value is widely accepted as a standard for the protection of fish, although it is not necessarily based on factual information (Doudoroff and Shumway 1970). A significant (df = 11, F = 6.60, p = 0.02) difference in fish abundance existed among these stations. Based on the SNK test, fish abundance (mean ± SD) at stations with extreme hypoxia was significantly lower (86 ± 77, n = 4) than stations with moderate hypoxia (289 ± 143, n = 4) and normal dissolved oxygen concentrations (216 ± 69, n = 4). A higher standard deviation of abundance at stations with slight to moderate hypoxia may suggest that these dissolved oxygen concentrations are approaching threshold levels that result in greater shifts in habitat use to avoid physiological impairment.

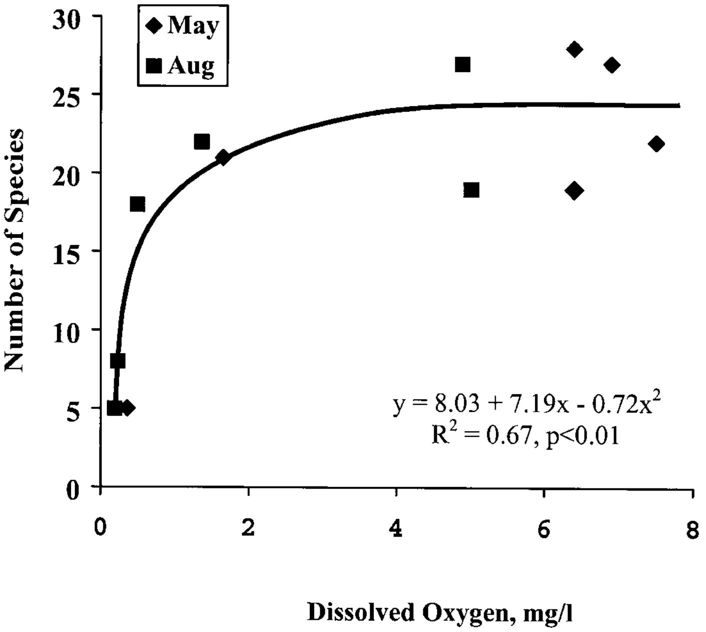

Figure 1. Bivariate plot of dissolved oxygen concentration and fish species richness from seining and gill net data collected at Mercer Bayou, Arkansas in May and August, 1999. May samples were collected in water temperatures ranging from 21.4 to 28.1 C; August in temperatures ranging from 26.1 to 34.5 C.

Total lengths (mean ± SD in mm) of all species combined were evaluated similarly. Fish species that inhabited hypoxic water were significantly (df = 11, F = 5.03, p = 0.03) smaller (80 ± 35), primarily due to the prevalence of topminnows and juvenile sunfishes, than at stations with moderate hypoxia (171 ± 69) and normal oxygen concentrations (180 ± 108). Three species accounted for 50% of all individuals collected in water less than 0.5 mg/l: golden topminnow, warmouth, and bantam sunfish (*Lepomis symmetricus* Forbes). In moderately hypoxic water, bluegill, bantam sunfish, redear sunfish (*Lepomis microlophus* (Gunther)), and golden topminnow comprised approximately 50% of all individuals collected. Largemouth bass, bluegill, pugnose minnow, and golden shiner accounted for 50% of all individuals collected in normoxic water.

Hypoxia eliminates those species maladapted for aerial and surface film respiration. Studies have concluded that low dissolved oxygen concentrations will contribute to a decline in fish species richness and abundance in riverine backwaters (Knights et al. 1995), river channels (Pihl et al. 1992), and lakes (Castleberry and Cech 1993). In Mercer Bayou, which is dominated by phytophilic species (Dibble et al. 1996), hypoxia results in a decline from 18-28 species per station to less than 8 species, and abundance and size of fish are reduced by a factor of 2 to 3 times.

Dense plant beds reduce hydraulic circulation and increase biological oxygen demand, both of which lower dissolved oxygen concentrations. However, the structural component of aquatic plants may offset some of the negative effects of slight to moderate hypoxia by providing numerous food items and refugia for younger and smaller fishes. The relatively high tolerances of phytophilic fishes collected at Mercer Bayou, and the inherent habitat value of aquatic plants, suggest that dissolved oxygen concentrations will have to decline below 1.0 mg/l to severely impact assemblage composition in vegetated areas. The relationship between species richness and dissolved oxygen developed in this study can be used to evaluate the relative habitat value of vegetated areas, and demonstrate that slight increases in dissolved oxygen can result in major gains in species richness and abundance. Thus, aquatic plant management can promote fish species diversity by minimizing dissolved oxygen concentrations below 1.0 mg/l through the reduction of dense plant beds.

ACKNOWLEDGMENTS

Assistance with field work was provided by Steven George, Bradley Lewis, and Dr. Neil Douglas. Dr. Neil Douglas identified fishes, catalogued, and deposited specimens into the Museum of Zoology, University of Louisiana at Monroe. Our appreciation goes to Mike Harris, Sulphur River Wildlife Management Area, for his logistical assistance in the field. Funding for this project was provided by the U.S. Army Corps of Engineers Aquatic Plant Control Research Program and the U.S. Army Engineer District, Vicksburg. Comments were provided by three anonymous reviewers. Permission was granted by the Chief of Engineers to publish this document.

LITERATURE CITED

Bodensteiner, L. R. and W. M. Lewis. 1992. Role of temperature, dissolved oxygen, and backwaters in the winter survival of freshwater drum (*Aplodinotus grunniens*) in the Mississippi River. Can. J. Fish. Aquat. Sci. 49: 173-184.

Carpenter, S. R. and D. M. Lodge. 1986. Effects of submersed macrophytes on ecosystem processes. Aquat. Bot. 26: 341-370.

Carter, V., J. W. Barko, G. L. Godshalk, and N. B. Rybicki. 1988. Effects of submersed macrophytes on water quality in the tidal Potomac River, Maryland. J. Freshw. Ecol. 4: 493-501.

Carter, V., N. B. Rybicki, and R. Hammerschlag. 1991. Effects of submersed macrophytes on dissolved oxygen, pH, and temperature under different conditions of wind, tide, and bed structure. J. Freshw. Ecol. 6: 121-133.

Castleberry, D. T. and J. J. Cech. 1993. Critical thermal maxima and oxygen minima of five fishes from the upper Klamath basin. Calif. Fish Game 78: 145-152.

Davis, J. C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Bd. Can. 32: 2295-2332.

Dibble, E. D., K. J. Killgore and S. L. Harrel. 1996. Assessment of Fish-Plant Interactions. *In:* L. E. Miranda and D. R. DeVries (eds.), Multidimensional Approaches to Reservoir Fisheries Management, Am. Fish. Soc. Symposium 16, Bethesda, Maryland, pp. 357-372

Doudoroff, P. and D. L. Shumway. 1970. Dissolved oxygen requirements of freshwater fishes. FAO Fisheries Technical Paper 86: 291 pp.

Knights, B. C., B. L. Johnson, and M. B. Sandheinrich. 1995. Responses of bluegills and black crappies to dissolved oxygen, temperature, and current in backwater lakes of the upper Mississippi River during winter. N. Am. J. Fish. Manage. 15: 390-399.

Kramer, D. L. 1987. Dissolved oxygen and fish behavior. Env. Biol. Fish. 18: 81-92.

Lewis, W. M., Jr. 1970. Morphological adaptations of cyprinodontoids for inhabiting oxygen-deficient waters. Copeia 1970: 319-326.

Matthews, W. J. 1987. Physicochemical tolerance and selectivity of stream fishes as related to their geographic ranges and local distributions. *In:* W. J. Matthews and D. C. Heins (eds.), Community and Evolutionary Ecology of North American Stream Fishes. University of Oklahoma Press, Norman. pp. 111-120.

Meffe, G. K. and F. F. Snelson. 1989. An ecological overview of peociliid fishes. *In:* G. K. Meffe and F. F. Snelson (eds.), Ecology and evolution of livebearing fishes (Poeciliidae). Prentice Hall, Englewood Cliffs, NJ. pp. 13-31.

Moore, W. G. 1942. Field studies on the oxygen requirements of certain fresh-water fishes. Ecology 23: 319-329.

Moyle, P. B. and J. J. Cech. 1988. Fishes: An introduction to ichthyology. Prentice Hall, Englewood Cliffs, NJ. 559 pp.

Odum, H. T. and D. K. Caldwell. 1955. Fish respiration in the natural oxygen gradient of an anaerobic spring in Florida. Copeia 1955: 104-106.

Pihl, L., S. P. Baden, R. J. Diaz and L. C. Schaffner. 1992. Hypoxia-induced structural changes in the diet of bottom-feeding fish and crustacea. Mar. Biol. 112: 349-361.

Robison, H. W. and T. M. Buchanan. 1988. Fishes of Arkansas. University of Arkansas Press, Fayetteville, 536 pp.

SAS. 1989. Statistical analysis system, Version 6. SAS Institute, Cary, NC.

Smale, M. A. and C. F. Rabeni. 1995. Hypoxia and hyperthermia tolerances of headwater stream fishes. Trans. Am. Fish. Soc. 124: 698-710.

Ultsch, G. R., H. Boschung, and M. J. Ross. 1978. Metabolism, critical oxygen tension, and habitat selection in darters (*Etheostoma*). Ecology 59: 99-107.

Very few fish species can survive in this hypoxic condition. The only other notable fish that affect E. zonatum are live-bearers (Poeciliidae), the grass pickerel (Esox americanus), and bowfins (Amia calva).[9] The bowfins are known to be occasional predators on the pygmy sunfish family. Occasionally, the grass pickerel and live-bearers are competitors for food with the pygmy sunfish.Â Effects of Hypoxia on Fish Assemblages in a Vegetated Waterbody. Aquatic Plant Management 39:40-44. ^ Mettee, M. F., and Scharpf, Christopher 1998. Although aquatic macrophytes are thought to contribute to fish species richness, our results suggest that excessive vegetation growth can have a negative impact on fish assemblages. While fish are considered to have a major effect in lentic ecosystems, dredging operations, which are widely used to maintain the function of lakes and ponds, can significantly change the structure of pond-dwelling fish by altering the dissolved oxygen level. Acknowledgements We are grateful to the staff of the city government of Oshu for their constant support that made this study possible.Â Effects of hypoxia on fish assemblages in a vegetated waterbody. J. Aquat. Plant Manag. The fish assemblage in the hypolimnion also changed in association with hypoxia. Overall fish abundance, number of species, and maximum length all de-creased in catch as a function of bottom DO con-centrations. The link between hypoxia and wind events appears to serve as a positive feedback loop by continuing internal loading and cyanobacterial blooms in the lake, while simultaneously eroding habitat quality for benthic fish.Â An intensely studied consequence of hypoxia is the effect it has on fish due to their economic and food importance. At the cellular level, hypoxia has been shown to be an endocrine disruptor, impair-ing the ability for fish to reproduce, as well as a teratogen, leading to malformed embryos (Wu and others 2003; Shang and Wu 2004).