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Heat Death of Fish in Shrinking Stream Pools

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ABSTRACT: Responses of 14 species of fish were observed in two shallow (<20 cm), isolated pools of Indian Creek, Butler County, Ohio, when maximum water temperatures reached 38.3–39.5 C. Individuals of 12 species died from thermal stress in one pool. Despite occurrence of these high water temperatures on at least two separate dates, individuals of four (of 12) and 14 (of 14) species of fish survived in the two pools, respectively. Mean critical thermal maxima (CTM) of six species of fish (striped shiner *Notropis chrysocephalus*; silverjaw minnow *Ericymba buccata*; bluntnose minnow *Pimephales notatus*; central stoneroller *Campostoma anomalum*; quillback carpsucker *Carpiodes cyprinus*; fantail darter *Etheostoma flabellare*) collected from one of the pools after exposure to the high temperatures ranged from 36.2–38.8 C. Survival of fish in the pools was attributed to their elevated thermal tolerances (CTMs), and the use of shaded cooler refugia in each pool.

INTRODUCTION

Reports of heat death of fishes in nature are rare (Huntsman, 1942, 1946; Bailey, 1955; Matthews *et al.*, 1982), as water temperatures in temperate regions are generally below the tolerance levels of most fishes (*e.g.*, Matthews *et al.*, 1982; Hlohowskyj and Wissing, 1985; Matthews, 1987). However, under certain conditions including absence of water movement, high air temperatures and direct exposure to intense solar radiation, temperatures in shallow (<20 cm) waters may approach or exceed the upper thermal tolerances of fishes (Bailey, 1955; Matthews *et al.*, 1982). Under these conditions survival is enhanced physiologically by increases in thermal tolerances (*see* review by Spotila *et al.*, 1979; Matthews *et al.*, 1982), and/or behaviorally by occupying cooler habitats (Matthews *et al.*, 1982).

Hot, dry weather in southwestern Ohio during June to mid-July 1988 caused many streams to become intermittent, trapping fish in shallow, isolated pools. During a week of record-setting, high air temperatures, water temperatures >38 C occurred in pools with direct exposure to solar radiation. This study examined (1) the thermal tolerances of fish species inhabiting shrinking isolated pools in one stream; (2) the differential use of thermal microhabitats within these pools by fish in their attempts to ameliorate heat stress; and (3) the eventual heat death of individuals of 12 species of fish in the pools.

STUDY SITE

Indian Creek is a third-order stream in Butler Co., Ohio. The stream is 36.6 km long, drains 226 km^2 of rolling agricultural land and woodlots, and has an average gradient of 3 m km^{-1} (Ohio Department of Natural Resources, 1960). The study site (within Indian Creek Park adjacent to State Highway 732) is mostly wooded, but there is no canopy directly over most of the stream. Substrata consist primarily of fragmented limestone and shale bedrock, gravel, and coarse sand. These substrata are rearranged by periodic spates, often drastically altering stream habitats. More than 20 fish species representing five families (Cyprinidae, Catostomidae, Ictaluridae, Centrarchidae, Percidae) have been collected from the study site in recent years (T. Wissing and R. Kopp, pers. comm.).

During early July 1988, Indian Creek ceased flowing at the study site, forming a series

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TABLE 1.—Fishes collected from two isolated pools in Indian Creek on 14 July 1988

Family/common name	Scientific name	Pool
Cyprinidae		
Creek chub	*Semotilus atromaculatus*	1,[a] 2
Striped shiner	*Notropis chrysocephalus*	1,[a] 2[b]
Sand shiner	*Notropis stramineus*	1,[a] 2
Silverjaw minnow	*Ericymba buccata*	1,[b] 2
Bluntnose minnow	*Pimephales notatus*	1,[b] 2[b]
Central stoneroller	*Campostoma anomalum*	1,[b] 2[b]
Catostomidae		
Quillback carpsucker	*Carpiodes cyprinus*	2
Northern hog sucker	*Hypentelium nigricans*	1,[a] 2
Ictaluridae		
Black bullhead	*Ictalurus melas*	2
Centrarchidae		
Smallmouth bass	*Micropterus dolomieui*	1,[a] 2
Green sunfish	*Lepomis cyanellus*	1,[a] 2
Percidae		
Johnny darter	*Etheostoma nigrum*	1,[b] 2
Greenside darter	*Etheostoma blennioides*	1,[a] 2
Fantail darter	*Etheostoma flabellare*	1,[a] 2

[a] No survivors on 18 July; [b] death of some individuals observed during study, but survivors remained on 18 July

of isolated pools (<20 m long, <3 m wide, <20 cm deep). Subsequent collections indicated that similar fish species were trapped in each of two adjacent pools (Table 1); no large predatory fish were present in either pool. As water temperatures increased, these pools became the focus of heat tolerance and behavior studies.

When the study began on 14 July, both pools were relatively small (lengths of pools 1 and 2 were 9 and 15 m, respectively) and shallow (maximum depths of 13 and 18 cm). Each pool was exposed entirely to direct sunlight for approximately 4.5 h (0830–1300 h) each day during mid-July (excluding days with partial or complete cloud cover). By mid-afternoon (1330–1400 h) each pool was shaded partially (pool 1 approximately 20% shaded, pool 2 approximately 50% shaded) by shoreline vegetation. Large (30–50 cm diam, 5–8 cm thick) limestone slab rocks were scattered throughout the pools, and each pool had a submerged, overhanging rock shelf extending along the western shoreline.

METHODS

Field observations.—The fish species innhabiting two pools in Indian Creek were observed on 14, 15, 17 and 18 July. On each date all habitats in each pool were sampled intensively (hand-held dip net, 5-mm mesh), and species presence was recorded. Sampling continued in each pool until no additional species was collected for 10 min. Although no quantitative estimates of fish densities were attempted, casual observations on relative abundances were noted. Any dead or dying fish were recorded (but not removed), as was the behavior of dying individuals. Before sampling occurred in either pool, differential habitat use by the fish was documented. High water clarity and shallow pool depths facilitated direct observations.

Water temperatures (Casio Model 515TS-1200 digital thermometer or certified mercury thermometer to the nearest 0.1 C) were taken in as many microhabitats as possible: pool margins, center, surface, bottom, cavities beneath rocks, and in shaded and unshaded areas of both pools. Dissolved oxygen concentrations in the pools were measured (YSI Model 51B dissolved oxygen meter to the nerest 0.1 ppm) periodically throughout the study. Field studies terminated when heavy rainfall began late on 18 July and continued for 2 days, rewatering the stream and connecting the isolated pools.

Laboratory studies.—At 0700 h on 18 July (following the period of high water temperatures), surviving individuals of the six most abundant species (striped shiner, silverjaw minnow, bluntnose minnow, central stoneroller, quillback carpsucker and fantail darter, scientific names given in Table 1) were collected from pool 2 (water temperature = 24.0 C), and transported to the laboratory in aerated, insulated containers. The thermal tolerance of each fish was determined within 3 h of capture by use of the critical thermal maximum (CTM) procedure (Becker and Genoway, 1979). The CTM is that temperature at which the locomotory activity of an animal becomes impaired, preventing its escape from conditions that would lead promptly to heat death (Cox, 1974).

CTM tests were conducted by placing 5–10 fish (depending on size) of the same species in a 1-liter, flat-bottomed glass bowl containing 900 ml of stream water (24 C). Water in the bowl was aerated continuously to prevent thermal stratification and possible hypoxia (Rutledge and Beitinger, 1989). The bowl was wrapped with a rheostat-controlled heating tape which increased water temperature at a rate of 0.5 to 0.8 C min^{-1}. Water temperature was monitored to the nearest 0.1 C with a digital thermometer (Bailey Instruments Model BAT 8). The CTM of each fish was defined as that temperature at which first loss of equilibrium with failure of righting response occurred (Becker and Genoway, 1979; Rutledge and Beitinger, 1989). After reaching this endpoint, fish were measured (mm total length) and returned to 24 C water. All fish tested recovered within 30 min. Mean CTM values were compared among species by analysis of variance (ANOVA) and Duncan's new multiple range test (SAS Institute, Inc., 1982).

RESULTS AND DISCUSSION

On 14 July, fish occupied all areas of both pools, and striped shiners, silverjaw minnows, bluntnose minnows, central stonerollers and fantail darters appeared to be the most abundant species present. These species generally are the most common at the study site (T. Wissing, pers. comm.). Both pools were isothermal, with maximum water temperatures reaching 30.5 C at 1700 h under completely overcast skies. A few (<5) dead, mostly decomposed fish were present in or beside each pool.

On both 15 and 17 July, both pools were exposed to direct sunlight from midmorning through early afternoon, and water temperatures rose quickly. By midafternoon water temperatures in sunlit pool areas ranged from 37.5–39.5 C (Table 2). Temperatures (35.8–37.5 C) in shaded areas were lower, and coolest temperatures (32.5–34.5 C) were recorded in cavities beneath submerged or partially submerged rocks. Temperatures in pool 1 were approximately 1 C higher than those in pool 2.

As a result of the high water temperatures, dead fish representing 12 species were numerous in pool 1 on 15 July (Table 1), and many other fish swam sluggishly and frequently lost equilibrium in unshaded waters (behavior identical to fish at water temperatures at or near their CTM during laboratory tests). Only a few (<10) dead or dying striped shiners, bluntnose minnows and central stonerollers were observed in pool 2 on this date, and in

TABLE 2.—Ranges in measured water temperature (C) within two isolated pools of Indian Creek, 15 (1400 h) and 17 (1330 h) July 1988. Sample sizes for each habitat/date are 3 or 4

Habitat	Pool 1		Pool 2	
	15 July	17 July	15 July	17 July
Nonshaded areas	38.8–39.5	39.0–39.5	37.5–38.3	38.0–38.8
Shaded areas	36.0–37.5	36.0–37.5	35.8–37.0	36.0–37.3
Cavities beneath rocks	—	33.0–34.5	—	32.5–34.5

either pool on 17 July. This study represents only the second recent report of apparent natural heat death in stream-dwelling fishes trapped in isolated pools (Matthews *et al.*, 1982), and documents that at least some individuals of every species of fish occupying one pool perished (Table 1).

The mean CTM values for all six species tested (individuals that survived the high water temperatures in pool 2) were lower than the high water temperatures recorded on 15 and 17 July for unshaded sections of two pools in Indian Creek (Table 3). Mean species CTM values ranged from 36.2 C for the striped shiner to 38.8 C for the quillback carpsucker. Significant differences ($P < 0.05$) in thermal tolerance were present among the species (Table 3). Several investigators (Brett, 1944, 1956; Hart, 1952; Holland *et al.*, 1974; Cheetham *et al.*, 1976; Matthews *et al.*, 1982) have shown that fish exposed to water temperatures >30 C had elevated temperature tolerances (CTMs or upper incipient lethal temperatures) ranging from 36.0–43.4 C, similar to values determined for the six species in the present study. Stream fishes exposed to high water temperatures apparently can compensate partially (within genetic limits) by raising their thermal tolerances physiologically (0.1–0.5 C increase in mean CTM for each 1.0 C increase in water temperature; Hlohowskyj and Wissing, 1985), thereby increasing their chances of survival. It is not known whether small stream fishes compensate physiologically for diel temperature fluctuations.

Despite the apparently lethal water temperatures, live fish still were present in both pools on the afternoons of 15 and 17 July. Matthews *et al.* (1982) reported that water temperatures of 38–39 C eliminated the orangethroat darter *Etheostoma spectabile* from isolated pools in an Oklahoma stream, but made no mention of the fate of other species of fish. Bailey (1955) observed that at least 13 of 21 species of fish survived a water temperature of 38 C for 2 h in a shallow (<16 cm) Michigan pond. Survival was attributed to differences in heat tolerance among the species. In Indian Creek, live fish were concentrated in dense aggregations in cavities beneath rocks and in other shaded areas, suggesting rather intense competition for

TABLE 3.—Mean (±SD) critical thermal maxima (CTM) of six species of fish collected from Indian Creek (water temperature = 24.0 C), 18 July 1988. *N* is the sample size and TL is the range in total length of fish tested. CTM values not followed by a common letter are significantly different ($P < 0.05$) from one another (ANOVA, Duncan's new multiple range test)

Species	*N*	TL (mm)	CTM (C)
Quillback carpsucker, *Carpiodes cyprinus*	6	45–57	38.8 ± 0.8 a
Bluntnose minnow, *Pimephales notatus*	10	45–78	37.9 ± 0.5 b
Central stoneroller, *Campostoma anomalum*	6	43–87	37.7 ± 0.8 bc
Fantail darter, *Etheostoma flabellare*	10	41–55	37.7 ± 0.5 bc
Silverjaw minnow, *Ericymba buccata*	10	52–74	37.0 ± 0.9c
Striped shiner, *Notropis chrysocephalus*	6	77–97	36.2 ± 1.0 d

these sites. Fantail darters rested on shaded limestone slabs in 1–2 cm of water, whereas other species occupied slightly deeper areas nearby. Apparently, the survival of fish in pools of Indian Creek depended on the availability of thermal refugia and the abilities of fish to locate them. Water in shaded areas and cavities beneath rocks was as much as 6.5 C cooler than unshaded areas. The abundance of fish using these refugia, and their quick return after being driven away, suggests that the fish were very proficient at locating them. Several investigators (*e.g.,* Ingersoll and Claussen, 1984; Hlohowskyj and Wissing, 1987b; Matthews, 1987) have shown that many species of stream fishes are particularly adept at selectively avoiding high temperatures in laboratory thermal gradients, and may, in fact, compete with one another for habitats with preferred temperatures (Medvick *et al.,* 1981).

No fish in either pool were observed gulping air at the air-water interface, indicating that hypoxic conditions probably did not exist in either pool in Indian Creek (Tramer, 1977; Rutledge and Beitinger, 1989). Dissolved oxygen concentrations in the two pools were always >2.4 ppm during the study, generally higher than levels known to produce stress in most stream fishes (*e.g.,* Tramer, 1977; Ultsch *et al.,* 1978; Hlohowskyj and Wissing, 1987a).

Collections on 17 and 18 July indicated that all 14 species of fish found previously in pool 2 were still present, but only four (silverjaw minnow, bluntnose minnow, central stoneroller and one johnny darter) of the original 12 species remained in pool 1. This differential mortality between pools probably resulted from the interactions of several factors. The slightly cooler temperatures in pool 2 in midafternoon, resulting from its more extensive shading by shoreline vegetation at that time, was likely the most important factor in fish survival. Pool temperatures only differed by approximately 1 C, but when temperatures approach critical levels this small difference can mean the difference between life and death. Field studies by Matthews *et al.* (1982) demonstrated that only a 1 C increase in water temperature (from 37 to 38 C) resulted in an 82% decrease (from 93% to 11%) in short-term (10–22 min) survivorship in exposed orangethroat darters.

The more extensive shading and greater total number of submerged or partially submerged rocks in the larger pool 2 also provided a larger area of thermal refugia than that in pool 1. More fish could be accommodated in this greater area of slightly cooler water, increasing the likelihood that some individuals of the less abundant species might survive. Those species that were eliminated from pool 1 were, in general, the less abundant rather than the less thermally tolerant (CTM tests) forms. However, striped shiners and fantail darters were abundant initially in pool 1, but were eliminated along with the less abundant species. These apparent discrepancies may be explained, in part, by the much lower thermal tolerance of striped shiners compared to those of other stream fishes (Matthews, 1987; present study, the mean CTM of this species was lower than water temperatures in most of the thermal refugia in pool 1), and the dewatering (between 15 and 17 July) of the only thermal refugium apparently used by fantail darters in pool 1.

Predation by larger fishes, birds or snakes on the small fish in either pool was not observed. However, tracks left by raccoon (*Procyon lotor*) around the pool margins indicated that they probably were responsible for removing the dead and/or dying fish from the pools. Whether they also removed live fish, and thereby affected the number of species surviving in pool 1 at the end of the study, is not known.

This study has demonstrated that fish in isolated stream pools cope with high water temperatures in two ways: (1) by developing a high physiological tolerance to heat, and (2) by seeking out and occupying cooler thermal refugia. When water temperatures become unusually high (>36 C) and approach or exceed species' tolerance limits, fish survival may be greatly dependent upon the availability and abundance of these refugia. Oxygen concentrations also become increasingly important to fish survival under these conditions (Tramer, 1977; Rutledge and Beitinger, 1989).

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