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Gastric evacuation rate, index of fullness, and daily ration of Lake Michigan slimy (*Cottus cognatus*) and deepwater sculpin (*Myoxocephalus thompsonii*)

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ABSTRACT

Accurate estimates of fish consumption are required to understand trophic interactions and facilitate ecosystem-based fishery management. Despite their importance within the food-web, no method currently exists to estimate daily consumption for Great Lakes slimy (*Cottus cognatus*) and deepwater sculpin (*Myoxocephalus thompsonii*). We conducted experiments to estimate gastric evacuation (GEVAC) and collected field data from Lake Michigan to estimate index of fullness [(g prey/g fish weight)100%) to determine daily ration for water temperatures ranging 2–5 °C, coinciding with the winter and early spring season. Exponential GEVAC rates equaled 0.0115/h for slimy sculpin and 0.0147/h for deepwater sculpin, and did not vary between 2.7 °C and 5.1 °C for either species or between prey types (*Mysis relicta* and fish eggs) for slimy sculpin. Index of fullness varied with fish size, and averaged 1.93% and 1.85% for slimy and deepwater sculpins, respectively. Maximum index of fullness was generally higher (except for the smallest sizes) for both species in 2009–2010 than in 1976 despite reductions in a primary prey, *Diporeia* spp. Predictive daily ration equations were derived as a function of fish dry weight. Estimates of daily consumption ranged from 0.2 to 0.8% of their body weight, which was within the low range of estimates from other species at comparably low water temperatures. These results provide a tool to estimate the consumptive demand of sculpins which will improve our understanding of benthic offshore food webs and aid in management and restoration of these native species in the Great Lakes.

Introduction

Obtaining accurate estimates of consumption by fishes is a critical tool for fisheries managers and ecologists. When species-specific field-validated bioenergetics models are available, they are generally agreed to be the best tool to use (Madenjian, 2011; Ney, 1993), but because these models require extensive laboratory experimentation for multiple sizes of fishes and multiple temperatures, as well as additional field work to compare model-predicted and observed growth (Bajer et al., 2004; Hansen et al., 1993), bioenergetics models do not exist for many fish species. In this case, scientists have resorted to traditional daily ration models (e.g., Eggers, 1977; Elliott, 1972) that were used prior to development of bioenergetics models and which require estimates of fish stomach content weight (over different intervals) and gastric evacuation rates. These models can be simpler to parameterize than bioenergetics models, yet are subject to criticism given the diel and seasonal variability that can occur in fish feeding (Darbyson et al., 2003; Hayward, 1991) and the effects of different prey types (dos Santos and Jobling, 1988; Kitchell and Windell, 1968) and water temperatures (Persson, 1979; Ruggerone, 1989) on gastric evacuation rates. Nonetheless, daily ration estimates can still provide reasonable estimates of fish consumption (e.g., Hop et al., 1997; Rice and Cochran, 1984) and are commonly used when bioenergetics models are not available.

In the Laurentian Great Lakes, bioenergetics models exist for multiple planktivorous and benthivorous fishes (e.g., alewife *Alosa pseudoharengus*, bloater *Coregonus hoyi*, rainbow smelt, *Osmerus mordax*, lake whitefish *Coregonus clupeaformis*, round goby *Neogobius melanostomus*), yet no model exists for slimy (*Cottus cognatus*) or deepwater sculpin (*Myoxocephalus thompsonii*) despite their ability to reach relatively high biomass in some lakes. For example, deepwater sculpin biomass collected in bottom trawls averaged six times the biomass of rainbow smelt between 1973 and 2011 in Lake Michigan (D.B. Bunnell, unpublished data). Even slimy sculpin biomass collected in bottom trawls has exceeded the biomass of rainbow smelt in 10 out of 13 years since 1999. Although previous studies have speculated on the potential importance of these native benthivores as competitors with deepwater coregonids and age-0 lake trout for invertebrate prey (Hudson et al., 1995; Isaac, 2010) or as predators on the eggs and larvae of lake trout (Luecke et al., 1990; Savino and Henry, 1991), no method for estimating their consumption has yet been developed.

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Slimy and deepwater sculpin are key native species within offshore (>30 m depth) food webs in the Great Lakes (Madenjian et al., 2002, 2005; Zimmerman and Krueger, 2009) that are becoming increasingly infiltrated by nonindigenous invasive species. Diets of these sculpins have historically been dominated by native invertebrates *Diporeia* spp. and *Mysis* spp. (Sly and Christie, 1992; Wells, 1980), and sculpins have served as prey for native lake trout (*Salvelinus namayacush*, Van Oosten and Deason, 1938) and burbot (*Lota lota*, Fratt et al., 1997). As nonindigenous species proliferate, however, slimy and deepwater sculpin may be facing increasing competitive threats from round goby (*Neogobius melanostomus*) for benthic prey (Bergstrom and Mensinger, 2009; but see Mychek-Londer et al., 2013) and reduced densities of *Diporeia* spp. which appear to be related to the expansion of dreissenid mussels (Nalepa et al., 2009, 2010). These threats may help explain recent shifts in depth distributions (Madenjian et al., 2012), food habits (Mychek-Londer et al., 2013; O'Brien et al., 2009; Owens and Dittman, 2003) and energy densities (Hondorp et al., 2005; Pothoven et al., 2011) of slimy and deepwater sculpin in the Great Lakes. Improved understanding of consumption by native sculpins may improve our understanding of how they contribute to food web dynamics, and could aid in management of diminished deepwater sculpin populations in Lakes Ontario and Erie (Lantry et al., 2007; Owens and Dittman, 2003; Roseman et al., 1998).

Herein, our primary objective was to use established methods to develop daily ration models for slimy and deepwater sculpin. To that end, we estimated *i*) gastric evacuation rates from experiments conducted in the laboratory at different temperatures and with different prey types, and *ii*) index of fullness from field-collected samples taken from multiple sites in Lake Michigan. Our daily ration model estimated consumption for water temperatures that slimy and deepwater sculpin experience in late winter and early spring in Lake Michigan. For both species, we were able to compare the maximum index of fullness in 2009-2010 to that estimated in 1976 (Kraft and Kitchell, 1986) when *Diporeia* spp. were still an abundant prey resource. We hypothesized that the maximum index of fullness in the 2000s would be lower than in 1976, following observations by Pothoven et al. (2011) that stomach content dry weights for deepwater sculpin were positively related to densities of *Diporeia* spp.

Methods

Gastric Evacuation Experiments

Fish Collection

Slimy and deepwater sculpin used in gastric evacuation (g dry weight of food evacuated/hour) experiments were sampled in autumn 2009 and 2010 onboard the USGS Research Vessel Grayling with 13-m Yankee bottom trawls towed for 5–10 min at depths from 50 to 128 m in offshore Lake Michigan (Ludington, MI; 43 55.96 N, 086 40.36 W). Using the same vessel and gear, some additional deepwater sculpin were collected from Lake Huron (Hammond Bay, MI; 45 38.64 N, 083 54.72 W). Aboard the vessel, sculpins were transferred into sanitized, covered 170-liter coolers filled with offshore surface lake water that was cooled to 3–5 °C using frozen well water from the USGS Great Lakes Science Center (GLSC) laboratory. Every 15 min we used a digital thermometer (Omega™, HH11B, accuracy ±0.1%) to ensure that proper water temperatures were maintained. Dockside, we transferred fishes into a 1100-L, truck-mounted holding tank for transport to the GLSC. In coolers and holding tanks, we used aerators and added salt (0.5% NaCl, by mass) to reduce stress. Upon arrival to the GLSC laboratory, we transferred fishes into 19-L buckets and over the next hour gradually added water from laboratory acclimation aquaria. When differences in water temperatures between buckets and laboratory acclimation aquaria were <1 °C, sculpins were transferred into species-specific acclimation aquaria.

Fish Acclimation

Sculpins were held in acclimation aquaria for one to nine months prior to experimentation. Water quality was tested bi-monthly. About 75% of fishes acclimated in one of six aquaria (four were 114-L and made of fiberglass; two were 170-L and made of glass) that were included within a recirculating water system fed by a 1000-L holding reservoir that contained chillers to cool water down to as low as 2.5 °C. Water was cleaned through active carbon filtration, ultraviolet treatment, and multiple media based filtration. Mean temperatures in these aquaria during acclimation ranged from 2.2 °C to 5.8 °C. The remaining 25% of fishes acclimated in two 227-L, fiberglass aquaria that received flow-through well water that ranged from 7.0 °C to 9.0 °C. At least 30 days prior to any gastric evacuation experiments, these fish were transferred into one of the recirculating acclimation aquaria.

Each acclimation aquaria had an airstone, one to three shelters (8-cm long halved pieces of 5-cm diameter polyvinylchloride pipe), a water inlet with adjustable flows set to 2–5 L min^{-1}, and a screened standpipe to drain recirculated water. No bottom substrate was used and styrofoam was placed on the side and top of each aquaria to insulate, reduce light levels, and minimize disruption. Lights in the laboratory were programmed to simulate seasonal daylight patterns in Ann Arbor, MI. Water temperature was manually recorded once daily, and fishes were fed either *Mysis relicta* (from Piscine Energetics) or fertilized rainbow trout eggs (RBT, *Oncorhynchus mykiss*, from Ennis National Hatchery, Montana) ad libitum over 4 to 8 h, three times a week. After each feeding, uneaten prey and detritus were siphoned out and any water losses to the system were resupplied by adding GLSC well and reverse-osmosis (RO) treated water to the holding reservoir.

Experiments

Experimental gastric evacuation test chambers were online with the same recirculating system as the six acclimation aquaria. Three test chambers were created in each of two modified fiberglass acclimation aquaria by installing two partitions (0.6-cm thickness) that had ~20 holes (0.6-cm diameter) screened over with 0.16 cm mesh to permit water exchange, and which excluded prey transfer between chambers. Each chamber had its own airstone, water inlet with flows set from 1.5 to 3.5 L min^{-1}, one fish shelter, and a calibrated, bottom submerged, Hobo Pendant™ temperature logger (accuracy ±0.1 °C) that recorded hourly data.

Gastric evacuation experiments were designed to occur at two temperatures (approximately 2 °C and 5 °C) with one prey type (*Mysis relicta*) for both slimy and deepwater sculpin. At each temperature, we sought to estimate evacuation rate over at least seven different digestion periods (ranging from 1 to 240 h) and included two to four fish per digestion period. To evaluate the effect of prey type, we conducted an additional feeding experiment with slimy sculpin at 5 °C where we used fish eggs rather than *Mysis relicta*. The mean temperatures that occurred in each of the five experiments ranged from 2.73 °C to 2.81 °C for the 2 °C experiments and 4.48 °C to 5.14 °C for the 5 °C experiments (Table 2).

Experimental temperatures were set within the recirculation system at least three weeks before feeding experiments began. Individual fish were selected from one of the six acclimation aquaria and transferred into one of six test chambers. Food was withheld for 5 or 7 days for the 5 °C and 2 °C experiments, respectively, to maximize the likelihood of empty stomachs (Elliott, 1972; Hurst, 2004). Experimental prey was either a known quantity of *Mysis relicta* (N = 10–15 offered; mean total length (TL) head to telson = 3.8 mm, mean individual dry weight = 0.012 g) or fertilized RBT eggs (N = 10–15 offered; mean diameter = 2.6 mm, mean individual dry weight = 0.013 g). For two trials of slimy sculpin at 5 °C, we used unfertilized bloater eggs (N = 60 offered, mean diameter = 1.95 mm, mean individual dry weight = 0.001 g). Fishes were permitted to eat undisturbed for exactly 30 min (Amundsen and Klemetsen, 1988).