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Diel movement and home range estimation of Walleye (*Sander vitreus*) within a no-take urban fishery

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ABSTRACT

Home range, movement, and habitat use of Walleye (*Sander vitreus*) in Onondaga Lake, New York, were determined using active and passive tracking of ultrasonic-tagged Walleye during the summer and fall of 2010 and 2011. Active tracking included bimonthly location surveys of all resident fish and bimonthly 24-h tracking surveys of individuals. Passive tracking was conducted using stationary receivers that were placed in the outlet and major inlets. Walleye in Onondaga Lake exhibit nomadic characteristics with large hourly and daily movements and extensive home and core ranges. Fish moved significantly farther distances per hour and were suspended over deeper water during the evening than during the day. Walleye core and home ranges were concentrated in the northeastern two-thirds of the lake, and there was substantial use of the outlet throughout the summer and fall by a majority of the tagged Walleye. Our findings support the hypothesis that there is a resident population of Walleye within Onondaga Lake during the summer and fall, but those fish exhibit extensive home ranges that include the Onondaga Lake outlet and likely the Seneca River. These results provide further evidence that distribution and movement of Walleye are determined by lake morphometry and forage base.

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Walleye; home range; diel movement; ultrasonic telemetry; habitat utilization

Introduction

Walleye (*Sander vitreus*) movement and distribution have been studied in rivers (Palmer et al. 2005; Haxton et al. 2015), shallow lakes/reservoirs (Forney 1963; Distefano and Hiebert 2000; McLellan and Scholz 2002; Foust and Haynes 2007), and the Laurentian Great Lakes (Brenden et al. 2015; Hayden et al. 2015). Understanding the movement and distribution of Walleye in different systems is important because they are one of the most sought after and managed species in North America. Walleye have been documented to migrate extensively to spawning areas (Eschmeyer and Crowe 1955; Crowe 1962, Forney 1963; Paragamian 1989; Distefano and Hiebert 2000; DePhilip et al. 2005; Palmer et al. 2005; Wang et al. 2007; Clark-Kolaks 2009), and then return to a defined summer home range (Forney 1963; McLellan and Scholz 2002; DePhilip et al. 2005; Palmer et al. 2005; Weeks and Hansen 2009). Post spawning, Walleye movement is determined by food availability (DePhilip et al. 2005; Foster and Drake 2013) and habitat characteristics such as light, water temperature (DePhilip et al. 2005), and oxygen levels (Tango and Ringler 1996).

Walleye often exhibit diurnal migrations with increased activity during low light irrespective of the system under study (DePhilip et al. 2005; Hanson 2006; Clark-Kolaks 2009; Bowlby and Hoyle 2011). However, post-spawning, summer distributions can vary substantially among systems. Walleye exhibit two types of summer distribution; the first is more nomadic, with large home ranges that can include large areas of rivers (DePhilip et al. 2005; Palmer et al. 2005) or lakes (Wang et al. 2007; Bowlby and Hoyle 2011). Other studies have found Walleye to occupy post-spawning home ranges of limited size (Williams 2001; Foust and Haynes 2007; Clark-Kolaks 2009).

Onondaga Lake was described as one of the most polluted lakes in the country because of industrial pollution and hypereutrophic conditions (Effler and Harnett 1996). A fishing ban was issued in 1970 that prohibited the consumption of all fish due to mercury and PCB contamination, and Onondaga Lake was designated a Superfund site in 1994 (Effler and Harnett 1996). As part of the Superfund remediation agreement, Honeywell International Inc. agreed to a \$451 million remediation project to remove contaminated soils from upland sites and to dredge and or cap 235 hectares (~20% of the total area) of the lake bottom (NYSDEC c2016a). Prior to remediation efforts, the fishing ban was lifted in 1999 (with restrictions), and revised in 2007, to limit consumption to four meals per month for brown bullhead, pumpkinseed, one meal per month for black bass less than 15 inches, but the restriction was maintained for Walleye and larger bass (New York State Department of Health c2014). Since remediation efforts have begun, mercury levels in Walleye filets have decreased from an average of 2.6 mg/kg wet weight in 2008 to 1.7 mg/kg wet weight in 2014; however, levels remain above the US EPA's water quality criterion of 0.3 mg/kg (United States Environmental Protection Agency 2015). The substantial investment in the remediation of municipal and industrial pollution has contributed to the development of a valuable recreational opportunity in and around Onondaga Lake. Currently, as the remediation project progresses and mercury is removed and/or isolated from the food web, there is the potential that Onondaga Lake could become a quality urban Walleye fishery.

State University of New York College of Environmental Science (ESF) has maintained a long-term data-set (2005–2012) of the pelagic fish community in Onondaga Lake. Walleye were the most common species caught, with an average gill net catch rate of 2.75 fish per hour from May to October (Siniscal 2009; SUNY ESF unpublished data) (Table 1). Comprehensive littoral and pelagic surveys of Onondaga Lake suggest that the Walleye population is predominantly comprised of old (>7 years) and large (>500 mm) individuals with very few juvenile Walleye (Parsons et al. 2011; Parsons 2013; Parsons and Anchor QEA 2013, 2014; SUNY ESF unpublished data), which in Oneida Lake is considered a fish under 4 years of age (Jackson et al. 2012). This population structure can be attributed to a lack of fishing pressure and absence of natural recruitment. Walleye are a primary sportfish in Central New York that are extensively managed in other lakes by the New York State Department of Environmental Conservation (NYSDEC). Approximately 150 million fry are stocked annually in Oneida Lake (Jackson et al. 2012), 8.7 million fry in Honeoye Lake (NYSDEC c2016b), and 45,000 fingerlings in Otisco Lake (NYSDEC c2016c). With the confidence that Onondaga Lake will become an urban Walleye fishery, this study was designed to (1) evaluate habitat use and estimate home ranges of Walleye within Onondaga Lake, and (2) to document the use of tributaries and the Onondaga Lake outlet post-spawning. We hypothesize that there is a resident population of Walleye within Onondaga Lake during the summer and fall, but those fish exhibit extensive home ranges that include the Onondaga Lake outlet and likely the Seneca River.

Table 1. Long-term gill net data for Walleye collected in Onondaga Lake (May–October, 2005–2012).

Year	2005	2006	2007	2008	2009	2010	2011	2012
Total hours fished	26.2	18.9	12	82	66	85	58	52.5
No. of Walleye captured	109	81	17	163	204	215	197	113
CPUE ¹ (fish per hour)	4.2	4.3	1.5	2.0	3.1	2.5	3.4	2.2
Mean length	578	616	624	564	565	548	550	557
Standard deviation	62	59	46	48	48	48	47	45
Min length (mm)	419	365	518	413	457	437	435	322
Max length (mm)	707	726	685	684	696	733	775	688

¹ CPUE, catch per unit effort.

Methods

Study site

Onondaga Lake is within the Oswego River drainage and is located north of the city of Syracuse (Figure 1). It is approximately 7.6 km long with a maximum width of 2 km, a surface area of approximately 1200 ha, and an average depth of 10.9 m. The north, east, and western boundaries of the lake have a narrow littoral area (~100 m) with a steep drop off from 3 m to 12 m, and then a gradual slope to the maximum depth of 19.5 m. The southern end has a more gradual slope towards the

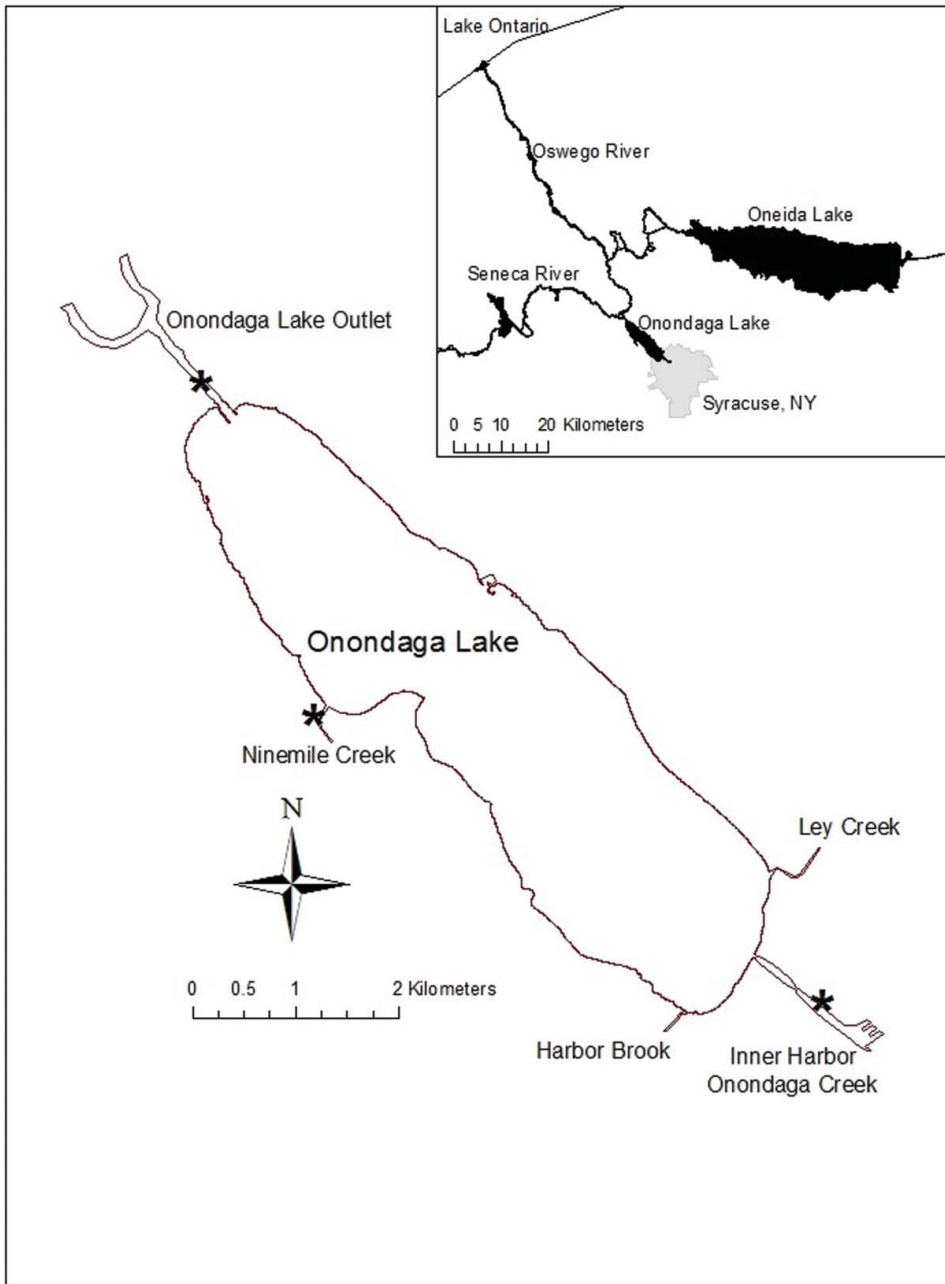


Figure 1. Map of Onondaga Lake, Syracuse, New York. * indicates passive receiver locations.

south basin. Onondaga Lake has three main inflows: (1) Nine Mile Creek, which flows from the outlet of Otisco Lake into the west side of Onondaga Lake; (2) Onondaga Creek, which flows into the southern end of Onondaga Lake and drains much of the Tully Valley and the city of Syracuse; and (3) The Metropolitan Syracuse Sewage treatment plant (METRO), which discharges effluent into the southern end of the lake. The lake has a single outlet at its northern end, which flows into the Seneca River (Figure 1).

Walleye telemetry tagging

Walleye were captured for sonic telemetry tagging using 30-min gill net sets at various locations in Onondaga Lake. The Walleye deemed suitable for tagging had to measure between 300 and 750 mm and exhibit minimal signs of stress (i.e. normal swimming and breathing behaviours) at the time of net retrieval. Individuals were then transferred to a 9.2 m² holding pen for a minimum of 12 h. The following day, the fish were removed from the pen and processed one at a time.

Walleye were individually anesthetized in approximately 60 mg/L clove oil (Peake 1998) and the fish were placed on their dorsal side in a V-shaped tagging trough made of soft foam. Surgical tools and internal tags were sterilized with rubbing alcohol and rinsed with deionized water. During the surgery, aerated water was continuously passed over the gills using a squeeze bottle. An incision (3–5 cm) was made to one side of the mid-ventral line at the deepest part of the body and the transmitter was inserted into the body cavity under the pectoral girdle. The muscle and skin were sutured together using 3/0-sized black nylon sutures. Fish were also externally tagged with a standard T-bar anchor tag that contained an identification code, phone number, and instructions to release fish upon capture. Fish were monitored in aerated live-wells until they resumed normal swimming behaviours, at which time they were released at the site of capture.

A total of 17 Walleye were tagged in 2010 and 12 were tagged in 2011, and the total length of tagged fish ranged from 465 mm to 705 mm, with a mean length of 548 mm (Table 2). The Walleye were tagged with Sonotronics, Inc. coded CTT transmitters that generated a unique auditory sequence at a certain frequency (70–83 kHz). The pulse interval time between pings indicated the temperature of the tag, and was used to approximate the location of the fish in the water column. The tags used were 63 mm in length, weighed 10 g, and had a battery life of 36 months.

Walleye active tracking

Walleye were actively tracked using a Sonotronics, Inc. DH-4 directional hydrophone and USR-96 receiver. Manual tracking was conducted weekly, alternating between two types of surveys: bi-weekly 24-h and location. During a 24-h survey, two fish were selected, located, and then located every hour for the 24-h period. We homed in on the fish's location by reducing the signal amplification as we moved closer to the fish. The position of each fish was determined when the signal amplification was turned down to the lowest setting, the signal strength was equal in all directions, and the receiver displayed the tag number and temperature. At that time, GPS coordinates were recorded and the second fish was tracked using the same methods. Twelve 24-h surveys were conducted in 2010 between 3 June 2010 and 2 November 2010, but on two dates (16 June 2010 and 2 November 2010) surveys were shortened to 12 hours because of hazardous weather conditions. In 2011, we conducted 10, 24-h surveys between 13 May 2011 and 17 October 2011 but surveys were shortened on four dates because of hazardous weather conditions.

The purpose of each location survey was to locate all of the tagged fish present in Onondaga Lake on a given day. A minimum of 15 locations spaced approximately equidistant throughout the lake were visited during each survey to scan individual frequencies at high signal amplification. Once a tag was detected, the signal was followed until the fish position could be determined. We then returned to our last search location and resumed the scanning of frequencies to locate the remaining fish. The survey ended when either all fish were located or all locations had been scanned. Twelve

Table 2. Tag information for Walleye collected in Onondaga Lake.

Fish ID	Length	Date of last location	Location surveys			24-h surveys		Passive receiver data			
			2010	2011	May 2012	2010	2011	2010 Outlet	2011 Outlet	2011 Inner Harbor	2011 Nine Mile Crk.
62	580	3 Aug. 2010 (dead)	2	–	–	1	–	–	–	–	–
63 ⁺⁺	465	31 May 2012	11	8	1	7	1	12	8	–	–
64 [*]	527	10 Nov. 2010	10	–	–	2	–	10	–	–	–
66 ⁺⁺	546	17 Oct. 2011	11	10	–	3	–	3	1	1	–
70 ⁺⁺	534	15 May 2012	10	10	1	1	1	6	–	–	–
78 [*]	540	5 Aug. 2011	6	2	–	–	–	19	14	–	–
65 [*]	501	20 July 2011	10	5	–	1	–	1	1	–	–
68 ⁺	507	26 Sept. 2011	5	6	–	1	1	–	–	–	–
69	644	27 May 2010	1	–	–	1	–	–	–	–	–
71 ⁺⁺	622	31 May 2012	9	7	1	1	1	–	–	–	–
77	523	1 Oct. 2010 (dead)	6	–	–	–	–	–	–	–	–
79	573	10 June 2010 (dead)	2	–	–	–	–	–	–	–	–
81 [*]	556	26 Sept. 2011	7	7	–	1	–	11	1	–	–
97	520	3 Aug. 2011	2	–	–	–	–	1	–	1	–
103	579	1 Sept. 2010	3	–	–	2	–	5	–	–	–
105	548	3 Aug. 2010 (dead)	1	–	–	–	–	1	–	–	–
119 ⁺	510	31 May 2012	2	7	1	1	2	8	–	–	–
124	525	17 Oct. 2011	–	5	1	–	–	–	3	–	–
125 ⁺	575	31 May 2012	–	11	1	–	2	–	1	–	4
126 ⁺	552	26 Sept. 2011	–	8	–	–	2	–	5	–	–
131 ⁺	515	26 Sept. 2011	–	6	–	–	–	–	12	6	–
142	548	31 May 2012	–	5	1	–	1	–	2	–	–
102	703	26 Sept. 2011	–	7	–	–	–	–	–	–	–
114 ⁺	528	31 May 2012	–	7	1	–	1	–	22	7	–
115 ⁺	531	31 May 2012	–	8	1	–	1	–	4	45	–
129 ⁺	516	6 Oct. 2011	–	9	–	–	–	–	–	–	–
109	556	17 Oct. 2011	–	8	–	–	–	–	–	–	–
111 ⁺	522	15 May 2012	–	7	1	–	–	–	7	–	–
112 ⁺	534	15 May 2012	–	6	1	–	1	–	3	–	–

Notes: Fish denoted with ^{*} had home ranges calculated in 2010 and those denoted with a ⁺⁺ had home ranges calculated in 2011.

The number of detection days observed for each fish according to survey type and sampling year are displayed.

location surveys were conducted between 22 May 2010 and 10 November 2010 and 12 surveys were conducted between 5 May 2011 and 17 October 2011.

Walleye passive tracking

Passive tracking was conducted using Sonotronics, Inc. SUR-1 submersible receivers to assess the utilization of two major tributaries and the lake outlet by tagged Walleye. In 2010, we installed three passive receivers; one in the outlet, 0.4 km downstream of Onondaga Lake outlet on 10 August; one in Nine Mile Creek, 0.2 km upstream of the lake on 10 September; and one in the Inner Harbor (Onondaga Creek), 0.8 km upstream of the lake on 24 August (Figure 1). The submersible receivers scan each programmed frequency once every 90 seconds, with a maximum detection range of 0.2 km. They were removed from all sites on 24 November. In 2011, passive receivers were deployed at all three locations on 6 June, and they remained active until 6 October.

Depth and distance moved

To determine if Walleye were using certain depths or moving greater distances during certain times of day, we used 24-h telemetry data. The depth of water at which a fish was located and the straight line distance between hourly locations were determined using ArcGIS 10.2. The 24-h telemetry data was projected over and joined with a digitized bathymetric map of Onondaga Lake. To test for significant differences in fish depth and distance travelled versus time of day, we divided the day into

four segments: 'day', 'sunset', 'night', and 'sunrise'. We categorized sunset and sunrise as the three hours around the hour of sunrise or sunset (e.g. if the official sunset time was 2035, we would classify sunset as the locations recorded during the 19:00, 20:00, and 21:00 h). We used SPSS software to perform one-way analysis of variance (ANOVA) with post hoc Tukey pairwise means testing to detect significant differences ($\alpha = 0.05$) in water depth, as well as, distance moved per hour during the four periods of day.

Inlets and outlet use

Passive telemetry data from the outlet and inlets were also used to determine whether utilization of these habitats by tagged fish was markedly different during certain times of day. Passive receiver data showed that the inlets were limitedly used by Walleye, so we only used the data from the outlet for time-of-day analysis. We divided the day into three hour blocks of time (0000–0300 hrs, etc.), and conducted an ANOVA with post hoc Tukey pairwise means testing ($\alpha = 0.05$), to determine whether tagged Walleye were using the outlet more during certain 3-h time blocks than others.

Walleye activity range analysis

The core ranges (50th percentile) and home ranges (90th percentile) of tagged Walleye were determined using kernel density estimation with defined boundaries in the ArcGIS add-on Fish-Tracker 10.1, as described by Laffan and Taylor (2013). This software uses telemetry data, as well as date and time to construct a most likely route of hourly probable points between known locations. Likely route was based on the shortest distance between two points and habitat friction. Open water habitat (≥ 3 m) was given a habitat friction value of 1 and shallow littoral area (< 3 m) was given a friction value of 2. Habitat friction values were assigned with the assumption that long distance movement would likely occur within open water habitat versus areas of dense vegetation. This program allowed us to use telemetry data from point locations, 24-h surveys, and passive receivers. We determined home and core ranges of fish that had location data for a minimum of 67% of attempts and either one 24-h tracking event or passive receiver data. We used SPSS software to perform Independent Student *t*-tests to detect significant differences ($\alpha = 0.05$) between years in core and home range.

Results

Fish survival and tracking

Of the 17 fish tagged with sonic telemetry tags in 2010, four fish evidently died because they were stationary for two weeks, at a temperature below thermocline, and were not detected by passive receivers. All of the fish were located at least once in the lake during location surveys with two fish being located 92% of the time. One fish (ID 69) was located and tracked for 24 h once after tagging, but was never located in the lake again; this fish likely left the lake before the passive receivers were deployed in August. Twelve fish were successfully located and tracked during at least one 24-h tracking event (Table 2). Four fish were tracked multiple times during the 2010 season. One fish (ID 63) was consistently found in the lake during surveys and was tracked every month from May to October. Nine of the 13 fish that were alive at the end of the 2010 sampling season were documented at least once in 2011; and 4 of those were also located during two surveys in May 2012 (Table 2). All fish tagged in 2011 were determined to have survived during the sampling season; and 7 of the 12 fish were documented in the lake in May of 2012.

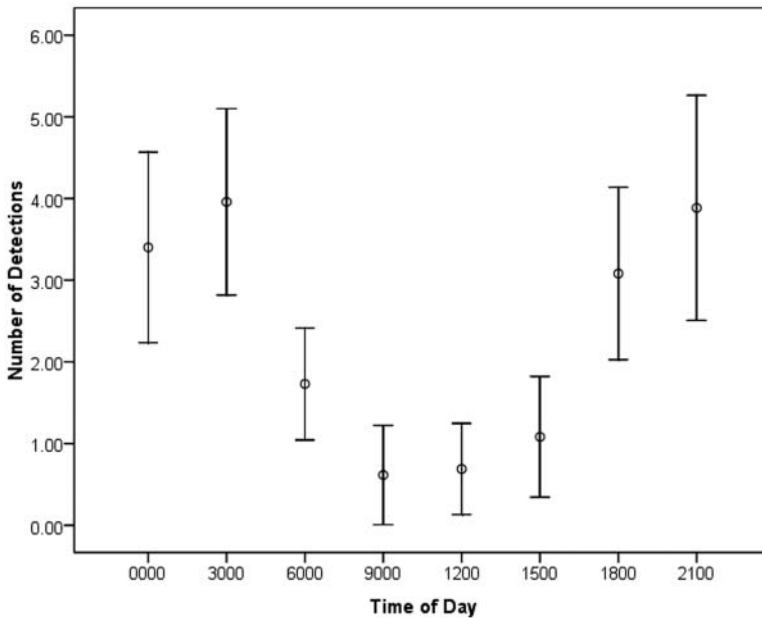


Figure 2. Passive receiver detections of tagged Walleye observed in the Onondaga Lake outlet (2010–2011). 95% confidence intervals are displayed.

Utilization of tributary inlets and Onondaga Lake outlet

Passive receiver data showed that the utilization of habitat in the inlets of Nine Mile Creek and Onondaga Creek (i.e. Inner Harbor) by tagged Walleye was comparatively less, in both the number of fish detected in each location and the duration of time spent there by individual fish, than in the outlet (Table 2). No fish were detected in the Inner Harbor or Nine Mile Creek during 2010. In 2011, only one fish (ID 125) was detected in Nine Mile Creek during four days in the summer. Five tagged Walleye were detected in 2011 in the Inner Harbor. The majority of the detections in the Inner Harbor were of one fish (ID 115) that was detected over 9000 times in a 45-day period from mid-July to early September.

The outlet of Onondaga Lake had considerably more tag detections than either of the inlets (Table 2); 11 of the 17 Walleye tagged in 2010 were detected in the outlet during the summer and/or fall. In 2011, 9 of the 12 fish that were tagged that year and 5 of the 9 fish that returned from 2010 were also detected in the outlet. We found significant differences in the number of detections among times of day (3-h blocks) (one-way ANOVA, $F_{7,968} = 8.7$, $p \leq 0.001$). There were three blocks of time during the day ((09:00 h, $\bar{x} = 0.6$, $SD = 3.4$); (12:00 h, $\bar{x} = 0.7$, $SD = 3.1$); (15:00 h, $\bar{x} = 1.1$, $SD = 4.1$)) that had significantly less detections than during four blocks of time during the afternoon and night ((18:00 h, $\bar{x} = 3.1$, $SD = 5.9$); (21:00 h, $\bar{x} = 3.9$, $SD = 7.7$); (00:00, $\bar{x} = 3.4$, $SD = 6.5$) (03:00 h, $\bar{x} = 4.0$, $SD = 6.4$) (Figure 2).

Distance travelled vs. time of day

Walleye in Onondaga Lake moved extensively according to 24-h surveys. In 2010, individual fish moved a total distance, based on hourly locations, between 1.90 km and 10.79 km, with 68% of them moving over 5.00 km in a 24-h period (Table 3). The straight line distance for individual fish estimated from start and end points was between 0.06 km and 3.89 km (Table 3). The fish moved shorter distances in 2011 with total distances between 1.06 km and 7.70 km, and straight line

Table 3. Total and straight-line distance measurements for Walleye tracked in Onondaga Lake in 2010.

Date	Search time (h)	Fish #1			Fish #2			Average distance travelled per hour
		ID	Total distance (m)	Straight-line distance (m)	ID	Total distance (m)	Straight-line distance (m)	
3 June 2010	24	63	4879	486	62	6652	1214	240
16 June 2010	12	78	5718	3652	81	3598	1535	388
1 July 2010	24	68	6323	3891	70	5007	324	236
13 July 2010	24	64	5426	1366	66	5413	933	226
28 July 2010	24	63	7819	589	103	1880	70	202
10 Aug. 2010	24	63	10790	1041	65	2183	55	270
24 Aug. 2010	24	63	6566	2614	103	3655	182	213
10 Sept. 2010	24	66	9172	617	71	7858	1918	355
22 Sept. 2010	24	63	4786	489				100
4 Oct. 2010	24	64	5364	3182	66	7714	1792	272
18 Oct. 2010	24	63	8532	2137	119	4795	640	278
2 Nov. 2010	12	63	2340	679				195

Note: Surveys under 24 h were shortened because of hazardous weather conditions.

distances between 0.04 km and 1.38 km (Table 4). In 2010, the average distance travelled per hour during 92% of the sampling events was >200 m (Table 3). In 2011, there was much more variability in the distance travelled per hour (Table 4). The average distances travelled by Walleye during the four designated times of day (day, sunset, night, sunrise) were significantly different among groups (one-way ANOVA, $F_{3,724} = 10.505$ m, $p < 0.001$). The post hoc Tukey HSD test showed that Walleye moved significantly less per hour ($p < 0.05$) during the day ($\bar{x} = 200.6$ m, $SD = 237.2$ m) than during night ($\bar{x} = 306.0$ m, $SD = 251.5$ m) and sunset ($\bar{x} = 316.5$ m, $SD = 302.1$ m) (Figure 4). The average distance moved each hour during sunrise ($\bar{x} = 282.8$ m, $SD = 256.3$ m) was not significantly different than any other time of day (Figure 3).

Depth of water vs. time of day

Daily shifts in the utilization of lake habitat were observed for Onondaga Lake Walleye. The depths of water in which fish were located were significantly different ($p < 0.05$) among the categorized time blocks (one-way ANOVA, $F_{3,805} = 10.5$, $p \leq 0.001$). The post hoc Tukey HSD test showed that Walleye occupied significantly ($p < 0.05$) shallower water during the day ($\bar{x} = 9.1$ m, $SD = 4.6$ m) than the night ($\bar{x} = 11.0$ m, $SD = 4.4$ m) and sunrise ($\bar{x} = 11.0$ m, $SD = 4.3$ m) (Figure 4). There was also a significant difference between sunset ($\bar{x} = 9.5$ m, $SD = 4.4$ m) and Walleye depths at night and at sunrise (Figure 4).

Table 4. Total and straight-line distance measurements for Walleye tracked in Onondaga Lake in 2011.

Date	Search time (h)	Fish #1			Fish #2			Average distance travelled per hour
		ID	Total distance (m)	Straight-line distance (m)	ID	Total distance (m)	Straight-line distance (m)	
20 May 2011	8	112	1799	138	126	1920	943	232
6 June 2011	24	112	5605	1081	129	7703	1252	277
20 June 2011	12	119	4682	1381				195
11 July 2011	24	115	1063	504				44
25 July 2011	9	119	2165	333				90
8 Aug. 2011	24	70	1607	175	142	6866	729	177
28 Aug. 2011	24	68	3373	435	114	6314	244	
28 Aug. 2011	24	126	3098	35				178
21 Sept. 2011	24	63	5929	914	125	3233	522	191
10 Oct. 2011	24	71	3069	1384	129	3089	125	128
24 Oct. 2011	6	125	1127	520	129	3184	1283	359

Note: Surveys under 24 h were shortened because of hazardous weather conditions.

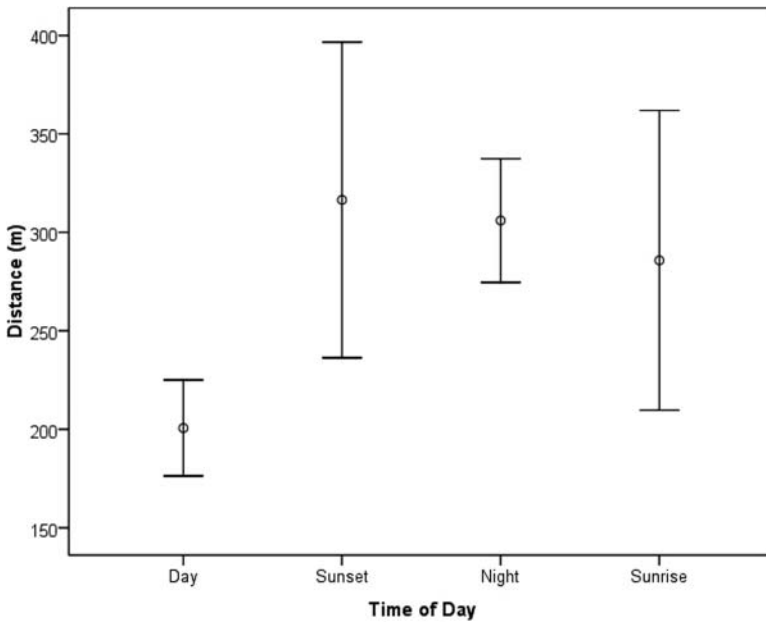


Figure 3. Mean distance travelled ($\text{m}\cdot\text{h}^{-1}$) by tagged Walleye in Onondaga Lake (May–November, 2010–2011) during daily time periods. 95% confidence intervals are displayed.

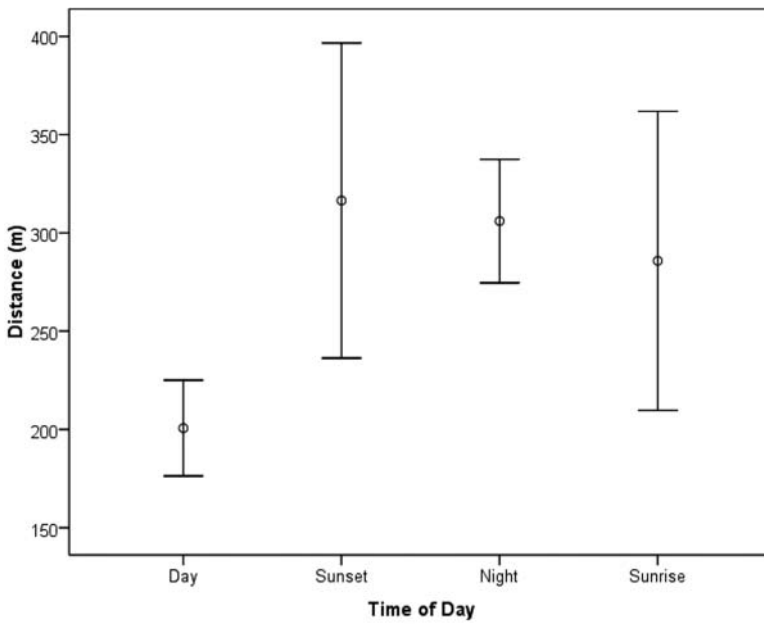


Figure 4. Mean depth (m) utilized by tagged Walleye in Onondaga Lake (May–November, 2010–2011) during daily time periods. 95% confidence intervals are displayed.

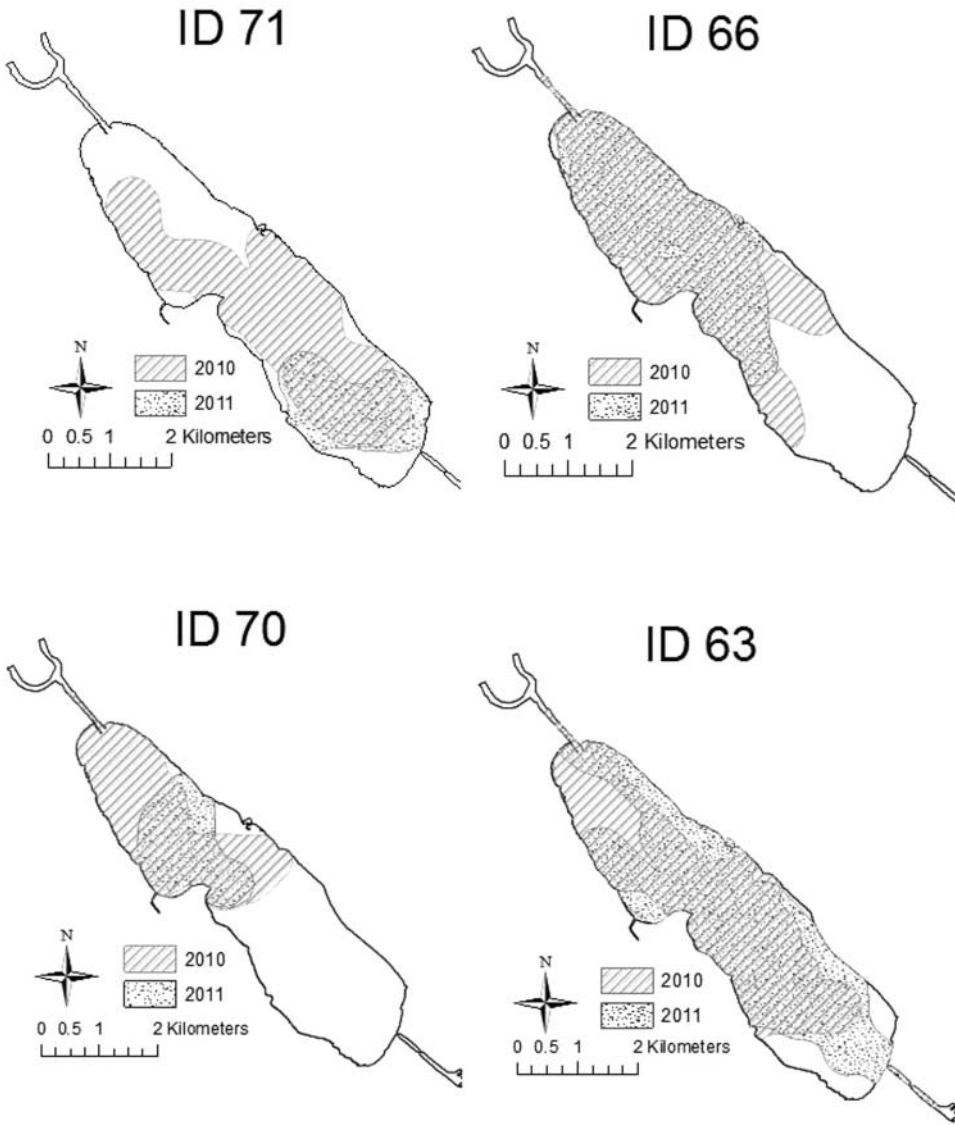


Figure 5. Home range maps for four Walleye, showing range overlap in Onondaga Lake between in 2010 and 2011.

Walleye home and core ranges

Core ranges (50th percentile) and home ranges (90th percentile) were determined for 8 Walleye in 2010 and for 14 Walleye in 2011. Four fish met the criteria for home range estimation in both years. Walleye 71's home ranges were primarily in the southern basin with a 25% overlap between years (Figure 3). Walleyes 70 and 63 had home ranges in the northern basin for both years with a 41% and 65% overlap, respectively (Figure 5). ID 66 had expansive home ranges that had a 75% overlap and encompassed approximately three-fourths of the lake; in both years the home ranges included the outlet, and in 2011, the home range also included the Inner Harbor (Figure 3). In general, Walleye core and home ranges were concentrated in the northern basin of the lake. During *T*-test analysis, the Levene's tests were significant ($p \leq 0.05$) for the core and home range data, and therefore, equal variance was not assumed. The mean core range of Walleye was not significantly different

($p > 0.05$) between 2010 ($\bar{x} = 433.8$ ha, $SD = 73.0$) and 2011 ($\bar{x} = 329.1$ ha, $SD = 167.8$). There also was no significant difference ($p > 0.05$) in the home ranges of Walleye between 2010 ($\bar{x} = 779.8$ ha, $SD = 131.8$) and 2011 ($\bar{x} = 584.8$ ha, $SD = 306.0$).

Discussion

Onondaga Lake supports a large and stable population of Walleye, which currently experience very little fishing pressure within the lake. The lake is currently mesotrophic (Effler and O'Donnell 2010; Murphy et al. 2015) with suitable water quality to support Walleye population's year-round, but there is no evidence that Walleye are utilizing lake habitat or the tributaries to spawn. There is also little evidence from this study that they are using the tributaries during the summer or fall for refuge. Walleye residing in the lake during the height of summer stratification and through fall turnover is a positive sign that the lake has recovered from its hypereutrophic past. In the early 1990s it was determined that Walleye and other large fish species would annually migrate into the Onondaga Lake outlet and the Seneca River during fall turnover, presumably avoiding, anoxic conditions (Ringler et al. 1996; Tango and Ringler 1996).

Movement and habitat use

Previous studies of Walleye movement and home range estimation, during the summer and fall, have documented populations using habitat differently depending on the system. In Onondaga Lake, Walleye exhibited similar diel movement patterns to other systems; with Walleye moving significantly shorter distances per hour during daylight hours (Williams 2001; DePhilip et al. 2005; Hanson 2006; Clark-Kolaks 2009) and were found in shallower water during the day than during the evening (Williams 2001; Clark-Kolaks 2009). In Onondaga Lake, Walleye were documented at significantly different depths during the day versus the night, but both the night-time depth of 11 m and daytime depth of 9 m are along the steep drop-off. The movement into deeper water was less pronounced in our study than the daily movement of Walleye, from 8.9 m in the daytime to 15.6 m night-time depths, found by Potter et al. (2009). Williams (2001) also found Walleye to occupy shallow flooded timber coves during the day and move into open water at night. Similar to Holt et al. (1977), our results suggest that Walleye in Onondaga Lake do not exhibit major diel movement between the deep and shallow water, but rather exhibit a parallel movement adjacent to shore and outside the macrophyte beds. We seldom tracked Walleye into the vegetated littoral area, more often locating them suspended in the open water. During the evening, there were several instances of extensive migrations (> 1.0 km), in 1 or 2 hours, from one side of the lake to the other. On these occasions, the Walleye would swim across the deepest sections of the lake and resume moving parallel to shore. Our results are contrary to Johnson and Hale (1977) and Ryder (1977), who found that Walleye populations moved inshore at night to feed.

Several studies have shown Walleye movement to generally increase during low-light conditions, such as DePhilip et al. (2005) that observed increased movement 1.5 hours before sunset and constant activity throughout the night. Similar results were found by Williams (2001) in Laurel River Lake Kentucky, where Walleye were more active during the night (119 m h^{-1}) than during the daytime (26 m h^{-1}). The periods of the greatest movement (evening and night) by Onondaga Lake Walleye were similar to other populations, but the distances that these fish travelled were markedly higher than in the aforementioned studies. Hourly movement of Onondaga Lake Walleye averaged between 200 and 300 m h^{-1} . During 24-h surveys, tracked Walleye routinely moved over 5 km, with one fish (ID 63) travelling as far as 10 km in a 24-h period. These extensive daily movement patterns of Walleye in Onondaga Lake are more comparable to what has been found in another Central NY lake with a similar morphology. Walleye in Otsego Lake travelled an average of 5.3 km in a 24-h period, based on hourly locations (Bryne et al. 2008). DePhilip et al. (2005) also observed some fish to move over 2 km in one night, but those fish returned to the same daytime resting

location. The extensive hourly movement, considerable detections in the outlet, and varied positions during location surveys contributed to the larger home and core ranges estimated in Onondaga Lake.

Home range

FishTracker 10.1 was a beneficial and user friendly add-on in ArcGIS for determining home and core ranges with boundaries, while incorporating multiple sources of telemetry data. One issue we found with the program was that we were unable to assign higher significance to the actual location points rather than the pseudo (between) location points that were determined by the program. We do not believe this invalidates the data because the estimated home and core ranges still encompassed the actual location points. When the telemetry data were incorporated into FishTracker 10.1, we found the home ranges of Walleye in Onondaga Lake were larger than have been described in other studies. In the lake, the average core range encompassed one-third of the lake area (~ 400 ha) and the average home range included half of the lake area (> 600 ha). The core and home ranges were predominantly concentrated in the northern two-thirds of the lake and a majority of the fish (77% in 2010 and 67% in 2011) were also detected by the outlet passive receiver. Even though it was a small sample size of four fish, we believe it should be noted that there was a high amount of overlap of home ranges between years. The fish utilized very similar areas of the lake, but there were differences in the size and shape of the home ranges. This finding does support site fidelity for summer home ranges, but more data would be needed to strengthen these findings.

Other studies in Central NY observed Walleye utilizing relatively small home ranges in the summer and fall. In Oneida Lake, Walleye have been documented to migrate long distances to spawn, but then move back to occupy a smaller summer territory (Forney 1963). Limited home range was also documented in Honeoye Lake, which like Oneida Lake, is a relatively shallow New York lake (Foust and Haynes 2007). Foust and Haynes (2007) documented the average home range of Walleye to be 67.9 ha and daily movements, based on consecutive day locations, of 37 m day^{-1} . These results are similar to Williams (2001), where he found 75% of Walleye in Laurel River Lake, Kentucky had a home range < 300 ha and average daily movements of 53 m day^{-1} . Clark-Kolaks (2009) did not determine home range area, but found the fish moved little between daily locations (103 m day^{-1} in summer and 117 m day^{-1} in fall); suggestive of a limited home range. The average straight line distance of Walleye in Otsego Lake at the beginning and end of a 24-h survey was 1050 m day^{-1} (Bryne et al. 2008), which was comparable to the 24-h survey straight line distance of Walleye in Onondaga Lake.

This study supports the hypothesis that lake morphometry and forage base have substantial impacts on the movement and habitat use of Walleye, which has been described in Otsego Lake Foster and Drake (2013). Onondaga Lake morphometry is more similar to Otsego Lake with steeper underwater slope and greater mean depth than Oneida Lake or Honeoye Lake. The relatively larger area of open water, in conjunction with an abundant pelagic food source, likely contributes to a less restricted home range. Foster and Drake (2013) observed Walleye in Otsego Lake moving significantly further during tracking studies, and utilizing deeper areas of the lake when alewife populations were high. The Walleye switched to shallower habitat and decreased movement when alewife populations dropped, presumably to feed on littoral zone baitfish (Foster and Drake 2013). The switch in habitat use and movement because of changes in prey availability would be predicted because of optimal forage theory (Breck 1993; Foster and Drake 2013). Walleye would not spend energy cruising for pelagic alewife, which disperse from schools at night (Janssen 1978, Dunning et al. 1992), if they were scarce relative to other prey. The alewife populations in Onondaga Lake have experienced boom and bust cycles during the past decade because of periodically strong year classes and occasional years with extensive winter mortality (EcoLogic LLC et al. 2012; Upstate Freshwater Institute et al. 2013). During this study the alewife population was moderately high (EcoLogic LLC et al. 2012; Upstate Freshwater Institute et al. 2013) and would have provided a large

pelagic forage base for Walleye (Murphy et al. 2015). In Honeoye Lake, where Walleye have restricted home ranges, the alewives were extirpated in 1996, and the primary forage fish are yellow perch (GFLRPC 2007). In Oneida Lake Adult Walleye are documented to forage heavily on young-of-the-year Yellow Perch and Walleye during spring and summer, but switch to gizzard shad in October (Jackson et al. 2015).

Management implications

There are several current and future management implications from this study.

At the moment, the recommendation from NY State Department of Health is to eat no Walleye from Onondaga Lake and adjacent sections of the Seneca River because of elevated levels of mercury and other toxins. Based on age, length, and contamination analysis for Walleye within this population (Parsons et al. 2011; Parsons 2013; Parsons and Anchor QEA 2014, 2013), the 29 fish marked and tracked during this study were likely between 5 and 20 years old and had mercury levels that were well above the New York Department of Health's water quality criterion. This study indicated that Walleye in Onondaga Lake maintain residency in the lake during the summer and fall, but they do periodically move into the outlet and likely into the Seneca River. This study also found that not all of the fish returned to Onondaga Lake in subsequent years, and we do not know if these fish died outside of Onondaga Lake or merely did not return. Our findings support the restrictions on not eating Walleye from the Onondaga Lake outlet or the Seneca River, but increased effort into public awareness may be warranted. From personal conversations with the public, it appears many of them do not realize the extent of the consumption advisory or mobility of this species, and that they should avoid eating large (fatty) individuals that are caught in the Seneca and Oneida River or Cross Lake.

As remediation of industrial contaminants nears completion, and mercury is removed from the food web, we believe Onondaga Lake will become a productive Walleye fishery. One of the goals of the restoration was to increase fishing access to an urban community that typically relies on shore fishing. The results of this study indicate that for the community to have access to the Walleye fishery they will need access to deep water because very few Walleye move into the shallow water to feed. Currently, there is access at the Outlet of Onondaga Lake along two jetties, but limited access elsewhere. Because Onondaga Lake has a relatively small littoral zone, and >80% of the shoreline is publicly owned there are substantial opportunities to increase deep water access with the construction of piers and docks. As Onondaga Lake continues to recover, and a take Walleye fishery is established, it will be important for future studies to estimate the population size of Walleye in the lake and determine the extent of migrations outside of the lake during the winter and during spawning season. If the lake becomes an active Walleye fishery it may be important to stock Walleye within the lake or tributaries so the fishery does not act as a sink population to the Oneida Lake and Seneca River populations.

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Disclosure statement

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