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Evaluation of the physiology, behaviour, and survival of adult muskellunge (*Esox masquinongy*) captured and released by specialized anglers

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Angling for muskellunge (*Esox masquinongy*) is a specialized endeavor involving species-specific equipment and handling procedures. The latter were developed by anglers with little influence from fisheries managers or the scientific community. Today, release rates approach 100% for specialized anglers; therefore, a formal evaluation of these procedures was warranted. Using two handling treatments – one to mimic current handling procedures with a period of air exposure and another gentler alternative without a period of air exposure – we assessed the physiological and behavioural disturbances as well as mortality associated with the catch-and-release process. Seventy-seven muskellunge were angled and blood sampled during the 2009 and 2010 muskellunge angling seasons. An additional 18 muskellunge were electrofished and immediately blood sampled to obtain baseline physiology data. A subsample ($N = 30$, 15 per treatment) of the 77 angled individuals was fitted with external radio transmitters to assess behaviour and survival. Glucose and lactate concentrations were found to be significantly lower for controls, and glucose and potassium concentrations increased significantly with increasing surface water temperatures. No differences in physiology were noted between angling treatments. Muskellunge treated with normal and alternative handling procedures exhibited similar post-release behaviour, and no angling related mortalities were observed across a range of water temperatures (17.5–26.0 °C) This study demonstrates the effectiveness of current handling procedures at minimizing physiological and behavioural disturbances, particularly when compared with a gentler alternative. A fishery in which no angling mortality exists is not possible, but our study provides support for the notion that angling related mortality for muskellunge captured and released by specialized anglers using handling procedures evaluated in this study may indeed be negligible.

1. Introduction

The muskellunge *Esox masquinongy* is one of the most prized sport fishes in North America. Within the past 50 years, muskellunge angling has undergone dramatic paradigm shifts away from catch-and-kill to that of catch-and-release (C&R) angling. Today, release rates among specialized muskellunge anglers exceed 97% in both the United States and Canada (Fayram, 2003; Margenau and Petchenik, 2004; Kerr, 2007a). Specialized angler groups commonly release more of their catches and urge more stringent C&R regulations (e.g., increased minimum length limits) to improve the quality of a fishery (Chipman and Helfrich, 1988; Quinn, 1996). Fisheries management agencies often manage populations to produce trophy-size individuals through high minimum length and low bag limits (Hanson et al., 1986; Wingate, 1986; Quinn, 1996), which can be hampered by poor survival rates of released fishes (Brousseau and Armstrong, 1987). Nevertheless, C&R represents an important management tool for conserving muskellunge populations because individuals can live upwards of 30 years (Casselman and Crossman, 1986), population densities are relatively low (Jennings et al., 2010), and populations have suffered from historical overfishing (Crossman, 1986). The attitudes and actions by both anglers and managers, however, suggest both parties rely on the assumption that released fishes will survive, a concept fundamental to C&R angling (Wydoski, 1977).

Survival assessments can be complicated and mortalities may not be immediately apparent (Muoneke and Childress, 1994). Duration of air exposure, handling time, water temperature, and hooking

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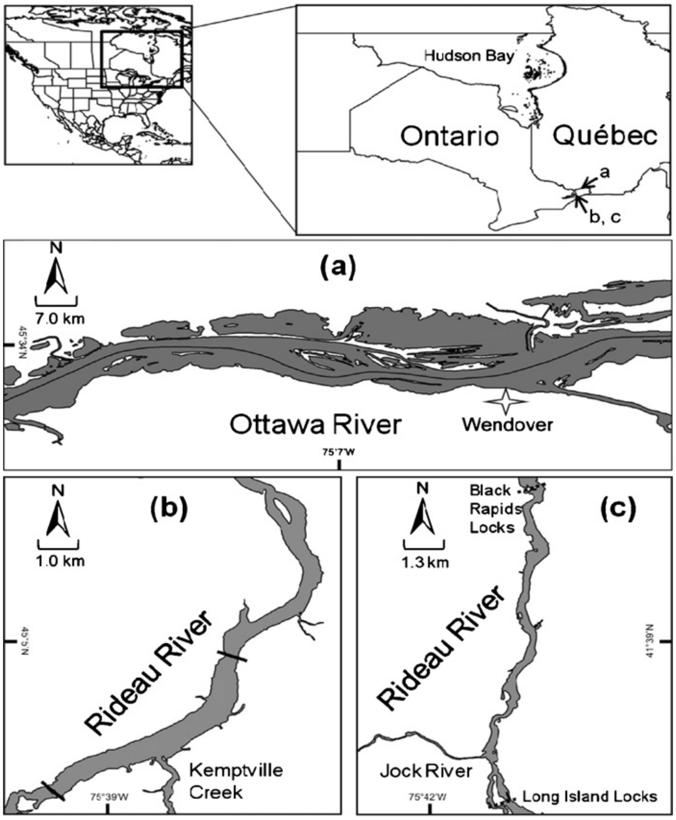

Fig. 1. Map of the Ottawa River study site (a) east of the city of Ottawa, Ontario and two stretches of the Rideau River south of Ottawa near Kemptville, Ontario (b) and between the Black Rapids and Long Island Locks (c). The thin black line splitting the Ottawa River separates the provinces of Ontario and Québec. For the Rideau River, solid lines indicate bridges and dashed lines indicate dam and lock systems.

location can significantly affect the survival of released fishes (see Bartholomew and Bohnsack, 2005; Cooke and Suski, 2005). Sublethal effects of angling (e.g., behaviour, physiology) can also affect overall welfare of angled fishes (e.g., Suski et al., 2003a,b, 2007; Klefoth et al., 2008), including potential fitness-related consequences ranging from mortality to reduced reproductive output (reviewed in Arlinghaus et al., 2007). Although anglers may not be able to control such factors as hooking location, particularly when using active angling methods, strategies to minimize the accumulation of sublethal endpoints could reduce delayed mortality.

Evaluating handling procedures used by angler groups offers the potential to increase survival among angled fishes (Cooke and Suski, 2005). However, species often differ in their responsiveness to various stressors, and where one set of handling procedures may be appropriate for a particular species a wholly different set may be needed for another (Cooke and Suski, 2005). Muskellunge anglers have made considerable efforts to develop and refine handling procedures as the sport's popularity increased (Gasbarino, 1986; Saric and Heiting, 1999; Kerr, 2007b; Landsman, 2008). Thus far, no scientific input has been used to create these handling procedures. Nevertheless, even a slight increase in annual harvest rates of muskellunge would necessitate large increases in recruitment rates to maintain trophy fisheries (Casselman and Crossman, 1995). Improved C&R practices would curb harvest and greatly benefit the fishery (Casselman and Crossman, 1995). Therefore, validating the appropriateness of current handling procedures used by specialized anglers is of interest for anglers, managers, and researchers alike.

The objectives of this study were to (1) quantify the post-release mortality rates of C&R muskellunge, (2) quantify the physiological and behavioural consequences associated with the C&R process for muskellunge, and (3) determine if alternative handling techniques (designed to minimize handling disturbances) would ameliorate physiological or behavioural disturbances and reduce mortality rates. This study was conducted in a natural, field setting, using a combination of radio telemetry and blood-based physiological analyses.

Fig. 2. A selection of muskellunge-specific artificial lures with up to nine barbed hook points.

2. Methods

2.1. Study sites

Angling took place in eastern Ontario, Canada on the Ottawa River (45°34′27.35″N, 75°7′42.01″W; Fig. 1a) and two reaches of the Rideau River: the "Long Reach" (45°4′23.84″N, 75°38′34.53″W; Fig. 1b) and the "Eccolands Reach" (45°18′53.38″N, 75°41′50.11″W; Fig. 1c). When and where angling occurred depended on regulations (e.g., closed angling seasons), local angler information, and weather. All research activities were conducted in accordance with guidelines from the Canadian Council on Animal Care as administered by Carleton University and under a scientific collection permit obtained from the Ontario Ministry of Natural Resources.

2.2. Angling

Volunteer specialized muskellunge anglers aided in capturing fish throughout the study. Although the vast majority of muskellunge were captured from one primary research boat (equipped for muskellunge angling), multiple boats were occasionally used to aid in fish collection. Additional boats remained either within eyesight or radio contact of the primary research boat, which would motor to a group of volunteers that had successfully captured a muskellunge to finish the sampling protocol described below. Anglers employed conventional muskellunge angling methods including the use of muskellunge-specific rods, reels, and terminal tackle (e.g., 36–45 kg braided line, fluorocarbon or steel leaders). A variety of artificial lures were used at the anglers' discretion, ranging in size from 15.2 to 45.7 cm with 1–9 barbed hook points (Fig. 2), and presented using both casting and trolling methods. All muskellunge were angled from less than 5 m of water. Lastly, live-bait was not used in this study because of its use during the months of fall, which were not included during the study period, are typically when anglers employ live-bait (Margenau, 2007). Furthermore, its use over artificial lures is also generally not preferred by anglers, specialized or generalist (Margenau and Petchenik, 2004).

Unedited online video footage, personal observation, and informal angler surveys were used to determine typical handling procedures used by specialized muskellunge anglers to develop handling protocols; these handling procedures were combined to define the "normal" handling treatment used in this study. This treatment group consisted of the following: muskellunge were angled as quickly as possible; large, knotless nets were used to restrain fish that were left submerged in the water; de-hooking with pliers began with fish still submerged, and continued for no more than 2 min, with hook cutters employed if de-hooking took longer than 2 min; fish were removed from the water for an admiration period (e.g., photos, measurements) of no more than 90 s and immediately returned to the water for release. As an alternative, a gentler handling procedure was compared to the procedures currently used by specialized anglers. In an effort to reduce handling time, the alternative treatment used hook-cutters only. In addition, the admiration period was removed from the alternative handling procedure to eliminate the consequences associated with air exposing angled fishes (Ferguson and Tufts, 1992; reviewed in Cooke and Suski, 2005). For both treatments, at least one angler used a stopwatch to time the duration of the angling events. At the onset of the study a dice was rolled to randomly assign the first angled muskellunge a particular handling treatment, after which treatments were alternated with each consecutive individual. Following the capture of each muskellunge, surface water temperature was recorded using a hand-held thermometer.

2.3. Sampling protocol

Following capture and de-hooking according to the treatment described above, muskellunge were transferred to a flow-through holding trough (300 L) where a non-lethal blood sample was collected for quantification of physiological disturbances. Approximately 1.5 mL of blood was extracted from the caudle vasculature using a 3 mL lithium-heparinized vacutainer and 21 gauge, 30 mm needle (Cooke et al., 2005). Whole blood was used to analyze glucose and lactate concentrations in the field with portable glucose (ACCU-CHEK glucose meter; Roche Diagnostics, Basel, Switzerland) and lactate (Lactate Pro LT-1710 portable lactate analyzer; Arkray Inc., Kyoto, Japan) meters. These field diagnostic tools have been previously verified for use on fish (Venn Beecham et al., 2006; Cooke et al., 2008). After using a centrifuge to separate the plasma and red blood cells, a ruler was used to assess hematocrit levels by measuring the volume of plasma to whole blood. Transfer pipettes were used to separate plasma from red blood cells, and samples were flash-frozen in liquid nitrogen for laboratory analysis. In the laboratory, cortisol concentrations were quantified using an enzyme linked, immunosorbent assay (Kit # 900-071; Assay Designs, Ann Arbor, MI, USA). This specific kit and procedure was demonstrated to produce acceptable results when compared to radioimmunoassay methods (Sink et al., 2008). Plasma sodium and potassium concentrations were determined using a flame photometer (model 2655-00; Cole-Parmer Instrument Company, Chicago, IL, USA); whereas plasma chloride concentrations were quantified using a digital chloridometer (Labconco, model 4425000, Kansas City, MO, USA).

To obtain baseline physiological data, the same physiological sampling procedures described above were applied to electrofished (2.5 Generator Powered Pulser; Smith-Root, Inc., Vancouver, WA, USA) muskellunge (Schreck, 1976). This method of fish capture is preferred over other methods, such as netting, because of the short period of time following capture that fish can be blood sampled resulting in more accurate measurements of baseline physiology (Harrell and Moline, 1992). Electrofishing efforts were conducted at discrete time periods coinciding with water temperatures similar in range to that of the angling period (i.e., 6.5–25.5 °C). All electrofishing took place on the Rideau River at both the Eccolands Reach and the Long Reach. Pulsed direct-current (rate: 60 pulses per second) was used to reduce the risk of injuring captured muskellunge (Snyder, 2003). The electrical current was set at 7–8 A and maximum output voltage was 500 V. Fish were sampled within 1 min of netting. Physiological measurements, therefore, were regarded as baseline values.

In 2009, a sub-sample (N_{total} = 30, N = 15 per handling treatment) of muskellunge used for our physiological analyses were externally affixed with individually coded, external radio transmitters (Holohil Systems, Ltd.; Carp, ON, Canada) that weighed 3.2 g in air (138–235 MHz, pulse rate 40 p/min, pulse width 22 ms). Two needles were pushed through the dorsal musculature near the soft dorsal fin and stainless steel wires were passed through the lumen of the needles. A small rubber backing plate made from gasket material served to secure the tag on the opposite side of the fish (see Fig. 1 of Bridger and Booth, 2003). Though weights were not recorded for tagged muskellunge, length–weight relationships of muskellunge reported by Casselman and Crossman (1986) indicated that radio-tagged adult muskellunge in this study weighed far more than the in-air weight of the transmitter (i.e., 3.2 g), thereby avoiding issues associated with a fish's ability to carry the transmitter. A 3-element yagi antenna (AF Antronics, Urbana, IL) and receiver (Biotracker; Lotek Engineering, Inc.; Newmarket, ON, Canada) were used to manually track individuals and assess survival as well as behavioural alterations immediately post-release (i.e., 10 min, 30 min, 1 h, 2 h), at 24 h post-release, 48 h, once every third day for 1 week, and weekly or bi-weekly thereafter. Global positioning system (GPS; Garmin E-Trex; Garmin International, Inc.; Olathe, KS, USA) coordinates were taken at each location.

Hightower et al. (2001) outlined methods for determining mortality of radio tagged fish and suggested that repeatedly tracking an individual at the same location indicated mortality. This criterion was used for the current study, though particular attention was paid to upstream movements since dead or moribund muskellunge cannot swim upstream. Furthermore, because most post-angling mortality occurs in less than 48 h (Muoneke and Childress, 1994) survival was determined if fish exhibited continued movements, both upstream and downstream, for at least 48 h. Locations could not be ascertained if muskellunge moved into water deeper than 10 m. Local weather conditions, boat traffic, and macrophyte cover may also have impaired our abilities to locate fish. Repeated attempts – multiple times per day or daily visits – to contact fish were made until contact was reestablished. Finally, recaptures were also used to assess survival, though local anglers were often able to supply only a photograph and unable to supply individual tag numbers. Identifications were made based on size, location, and individual markings.

Reflex impairment was also quantified for angled muskellunge in an attempt to correlate loss of reflex(es) with mortality. At the site of release, each fish's ability to (1) maintain equilibrium, (2) burst away, and (3) swim downward was observed and recorded. The absence and presence of these reflexes were scored on a 0–1 scale (0 = absent, 1 = present) and a composite score was created for each muskellunge. This method, also known as "reflex action mortality predictor" (RAMP), has been shown to be correlated with mortality (Davis and Ottmar, 2006; Davis, 2009).

2.4. Statistical analyses

Water temperatures were grouped into low (6.5–13.5 °C), moderate (14–21 °C), and high (21.5–28 °C) to account for temperature induced differences in baseline and post-angling physiological disturbances (Gustaveson et al., 1991). Blood data were tested for

Table 1
Results of the rank-transformed two-way ANOVA examining the effects of treatment, temperature, and treatment × temperature on seven physiological parameters for control and angled muskellunge.

Parameter	N	Effect	df	SS	F	P	Power (1−β)	Least significant N
Sodium (Meq/L)	67	Whole model	8	227.79	0.58	0.79		
		Treatment	2	87.58	0.89	0.42	0.24	170
		Temperature	2	24.65	0.25	0.78	0.07	1924
		Treatment × temperature	4	105.87	0.54	0.71	0.16	314
		Error	53	2828.47				
Potassium (Meq/L)	67	Whole model	8	123.63	3.00	**0.0074**		
		Treatment	2	11.19	1.08	0.34	0.29	137
		Temperature	2	42.77	4.16	**0.021**	–	–
		Treatment × temperature	4	63.09	3.07	**0.024**	–	–
		Error	53	272.64				
Chloride[a] (Meq/L)	33	Whole model	3	9.87	1.50	0.24		
		Treatment	1	4.42	2.02	0.17	–	–
		Temperature	1	0.043	0.020	0.89	–	–
		Treatment × temperature	1	6.04	2.75	0.11	–	–
		Error	23					
Cortisol[a] (ng/mL)	33	Whole model	3	375.58	1.85	0.17		
		Treatment	1	83.77	1.24	0.28	–	–
		Temperature	1	244.18	3.62	0.070	–	–
		Treatment × temperature	1	33.27	0.49	0.49	–	–
		Error	23					
Glucose (mmol/L)	84	Whole model	8	969.96	8.51	**<0.0001**		
		Treatment	2	262.32	9.20	**0.0004**	–	–
		Temperature	2	424.65	14.90	**<0.0001**	–	–
		Treatment × temperature	4	77.85	1.37	0.26	0.54	112
		Error	53	755.39				
Lactate (mmol/L)	84	Whole model	8	6005.97	5.79	**<0.0001**		
		Treatment	2	3799.73	14.66	**<0.0001**	–	–
		Temperature	2	455.76	1.76	0.18	0.47	109
		Treatment × temperature	4	213.04	0.41	0.80	0.18	362
		Error	53	6866.50				
Hematocrit (% PCV)	70	Whole model	8	339.40	1.26	0.28		
		Treatment	2	178.80	2.67	0.079	0.56	73
		Temperature	2	23.95	0.36	0.70	0.11	523
		Treatment × temperature	4	181.95	1.36	0.26	0.45	112
		Error	53	1766.14				

Note: Least significant *N* represents a power of $\beta = 0.5$.
Significant effects are denoted by bolded *P*-values.
[a] Signifies parameters without control data and excluding 2010 data from angled muskellunge. Power analysis results are reported for non-significant effects.

normality and homogeneity of variance using Shapiro–Wilk and Levene's tests (Sokal and Rohlf, 1995) and were rank-transformed to meet these assumptions (Conover and Iman, 1981). A two-way ANOVA was then applied (Conover and Iman, 1981) to evaluate physiological differences between treatments (including controls), temperature, and treatment × temperature. Movement data were log-transformed (Zar, 1984) and post-release behaviour was evaluated using a two-way repeated measures ANOVA (main effects: time interval, treatment, time interval × treatment; individual fish number entered as a random effect) because the same individuals were sampled more than once, thus violating the assumption of independence (Girden, 1992). Behaviour was evaluated at 10 min, 30 min, 1 h, and 2 h post-release. Reflex impairment was evaluated between treatments using a *T*-test. When a main effect(s) or interaction term was significant, a Tukey–Kramer HSD *post hoc* test was used to compare the statistical significance of means. All statistical tests were carried out using JMP 7.0 (SAS Institute, Cary, NC), significance levels set at $\alpha \leq 0.05$, and means are reported as ±standard error (S.E.) where appropriate. Correction factors were not applied because while the probability of committing Type I errors decreases, the probability of increasing Type II errors increases and statistical power decreases (Zar, 1984; Nakagawa, 2004) (Table 1).

3. Results

3.1. Angling and electrofishing

Over the 2009 and 2010 angling seasons, 77 muskellunge were successfully angled. The total length (L_T) of fish that were blood sampled in our normal and alternative treatments averaged 102.0 ± 3.0 cm (*N* = 34, range 63.5–131.0) and 98.2 ± 2.8 cm L_T (*N* = 33, range 57.2–132.1), respectively. Blood sampling occurred over periods where surface water temperatures ranged from 6.5 to 27.5 °C. Radio-tagged muskellunge in our normal treatment group had a mean L_T of 110.5 ± 3.8 cm (range 80.8–131.0 cm L_T) and 103.9 ± 3.4 cm (range 81.3–132.1 cm L_T) for our alternative treatment group. Water temperatures ranged from 17.5 to 26.0 °C during radio tagging periods. Mean L_T of electrofished muskellunge was 88.5 ± 3.9 cm L_T (*N* = 18; range 62.2–124.5 cm L_T) and water temperatures during electrofishing ranged from 6.5 to 25.5 °C.

3.2. Mortality and recaptures

All 30 radio tagged muskellunge exhibited continued movements following release (Table 2). These movements included at least two upstream movements during the period they were

Table 2
Movement data for all radio tagged ($N = 30$) muskellunge. Recaptures, the sum of distances moved up to 48 h, and the number of upstream movements for the entire tracking period were used to assess survival. An asterisk (*) denotes individuals tracked after being recaptured.

Fish #	Capture location	Capture date	Final tracking date (2009)	Recapture (Y/N)	No. of locations	Sum of distance (m) moved up to 48 h	No. of upstream movements between sequential tracking points
151.981	Rideau R. (Long)	22-Jun	28-October	N	19	754	4
150.681	Rideau R. (Long)	25-Jun	28-October	Y	19	1019	9
150.920	Rideau R. (Long)	4-July	13-August	N	14	569	8
150.359	Ottawa R.	8-July	12-August	N	12	802	6
150.580	Ottawa R.	8-July	23-November	N	18	952	10
150.960	Rideau R. (Eccolands)	11-July	3-October	N	16	562	7
151.479	Rideau R. (Eccolands)	13-July	3-October	Y	16	1655	6
151.121	Ottawa R.	16-July	14-October	Y	17	412	9
150.380	Rideau R. (Eccolands)	23-July	3-October	N	15	455	8
150.722	Ottawa R.	24-July	23-November	N	16	383	8
150.561	Ottawa R.	24-July	23-November	Y	16	285	7
150.840	Rideau R. (Long)	29-July	28-October	Y	14	1072	6
151.401	Ottawa R.	3-August	23-November	N	15	354	7
150.541	Ottawa R.	4-August	14-October	Y	14	2702	7
150.421	Ottawa R.	6-August	23-November	N	14	266	5
150.341	Ottawa R.	7-August	23-November	N	15	191	8
150.821	Ottawa R.	10-August	23-November	N	13	483	4
150.300	Ottawa R.	10-August	15-September	N	10	1778	5
151.440	Ottawa R.	11-August	25-September	N	11	337	4
151.560	Ottawa R.	14-August	15-October	N	13	680	5
151.460	Ottawa R.	15-August	15-September	Y	9	514	4
151.579	Ottawa R.	7-September	1-October	N	10	641	5
151.980	Ottawa R.	7-September	15-September	N	9	564	3
151.059	Ottawa R.	12-September	15-October	N	10	1415	4
150.200	Ottawa R.	18-September	23-November	N	10	250	5
150.041	Ottawa R.	20-September	23-November	N	9	905	4
150.099	Ottawa R.	24-September	23-November	N	9	496	2
151.920	Ottawa R.	24-September	14-October	N	8	932	3
151.900	Ottawa R.	24-September	23-November	N	10	881	6
151.880	Ottawa R.	25-September	23-November	N	8	2300	4

tracked (Table 2). In the summer of 2009, six radio-tagged muskellunge were recaptured, including one individual that was recaptured twice within a 2 week period. The transmitter from fish # 151.460 was found on shore and assumed to be an unreported recapture given the state in which the transmitter was recovered. For the 2010 angling season, two radio-tagged muskellunge were recaptured as well as an additional non-radio tagged (Floy tag only) muskellunge that was originally captured for physiological analyses. At least 23% ($N = 7$) of radio-tagged individuals were recaptured and reported during the study.

3.3. Physiological disturbances

Treatment had a significant effect on blood glucose (two-way ANOVA, $F_{2,53} = 9.2$, $P = 0.00040$; Table 1; Fig. 3a) and lactate concentrations (two-way ANOVA, $F_{2,53} = 14.7$, $P < 0.0001$; Table 1; Fig. 3b) where angling caused the two parameters to increase relative to controls (Tukey–Kramer HSD, $P < 0.05$; Fig. 3a and b). More specifically for angled muskellunge, blood glucose and lactate concentrations increased over 1.3 and 1.8 times to maximums of 3.6 ± 0.2 mmol/L and 6.9 ± 0.6 mmol/L, respectively (Fig. 3a and b). Nevertheless, no differences were observed between the two handling treatments themselves for any parameter (Tukey–Kramer HSD, P's > 0.05; Figs. 3a–e and 4a–e). Plasma potassium had a significant treatment × temperature interaction term (two-way ANOVA, $F_{2,53} = 3.1$, $P = 0.02$; Fig. 4b). For normally treated muskellunge, an increase of more than two-fold between low and high temperatures was noted as well as an increase of more than 1.5 times between controls and normally handled muskellunge at high temperatures (Fig. 4b). Temperature also significantly affected blood glucose concentrations (two-way ANOVA, $F_{2,53} = 14.9$, $P < 0.0001$; Table 1). Mean glucose concentrations at high temperatures increased significantly by over 1.5 times relative to low temperatures (Tukey–Kramer HSD, $P < 0.05$; Fig. 3a). Temperature and treatment effects, however, were not shown for any other parameter (Table 1; Fig. 4a–e). For non-significant effects, statistical power was low (<0.5) for many parameters and the least significant number of samples needed to attain a power of at least 0.5 ranged from 73 to 1924 (Table 1). Finally, plasma chloride ions and cortisol were analyzed without control data due to technical difficulties associated with transportation and analyses.

3.4. Behaviour and reflex impairment

Angled muskellunge behaved similarly irrespective of treatment (two-way repeated measures ANOVA, $F_{1,26} = 0.5$, $P = 0.50$; Fig. 5) and traveled a maximum of 45 m at any given period up to 120 min post-release (Fig. 5). Mean distance traveled per time interval increased consecutively until 2 h post-release, but this trend was not significant (two-way repeated measures ANOVA, $F_{3,77} = 2.2$, $P = 0.10$; Fig. 5). More specifically, muskellunge handled gently moved almost twice as far between 10 and 60 min post-release, but decreased movement by more than half from 60 to 120 min post-release (Fig. 5). Similarly for muskellunge handled normally, movement increased over two-fold from 10 to 60 min post-release and also decreased by more than half between 60 and 120 min post-release (Fig. 5). Finally, the treatment × time interval interaction effect had no significant impact on muskellunge post-release behaviour (two-way repeated measures ANOVA, $F_{3,77} = 0.05$, $P = 1.0$).

Reflex impairment could not be correlated with mortality because all tagged fish survived. In general, tagged and non-tagged

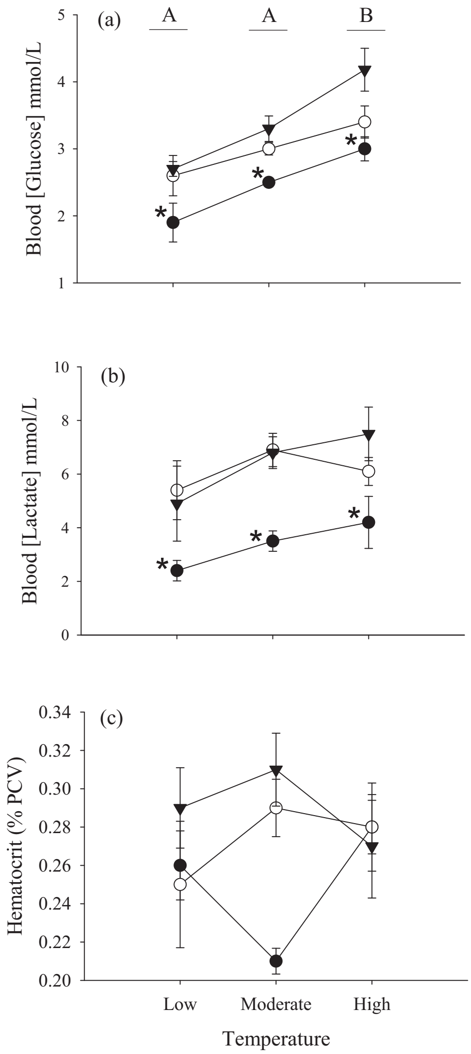

Fig. 3. Concentrations of blood glucose (a), lactate (b), and hematocrit (c; percent packed cell volume) for control (solid circle) and angled muskellunge subjected to alternative (hollow triangle) and normal (solid square) handling treatments. The sample sizes for glucose and lactate at low, moderate, and high temperatures for the three treatments were as follows: control (N = 8, 3, 7), alternative (N = 4, 11, 18), and normal (N = 4, 13, 15). Samples sizes for hematocrit at low, moderate, and high temperatures for the three treatments were: control (N = 8, 3, 6), alternative (N = 4, 10, 15), and normal (N = 4, 8, 10). An asterisk (*) denotes a significant difference between controls and angled muskellunge. Dissimilar upper case letters joined by horizontal lines denote significant differences between temperature groups.

fish from both treatments showed similar responses to reflex testing (T-test, F = 0.2, P = 0.6). The mean transformed proportion of reflexes present for muskellunge handled with alternative (N = 34) and normal (N = 34) procedures was 0.7 ± 0.04 and 0.7 ± 0.04, respectively. All but two muskellunge (i.e., N = 66; 97%) were able to maintain equilibrium. Upon release, 69% (N_{total} = 47) of angled muskellunge did not burst away from the handlers. In addition, 19% (N = 12) did not swim downward, but remained on the surface for upwards of approximately 5–10 min.

4. Discussion

We used radio telemetry to estimate mortality of caught-and-released muskellunge, an approach that has been identified as being particularly robust for generating field-relevant post-release mortality estimates (Donaldson et al., 2008). Based on radio tracking muskellunge in this study, none of the 30 radio-tagged muskellunge died as a result of the angling event. Our finding of a 0% mortality rate contradicts the 30% figure reported by Beggs et al. (1980). Their estimate, however, was made in a laboratory setting and may have introduced handling and confinement-related stressors resulting in an elevated mortality rate (Pollock and Pine, 2007; Donaldson et al., 2008). Moreover, Frohnauer et al. (2007) and Strand (1986) observed a 4.1% and 0% mortality rate of angled muskellunge from Shoepack Lake in Voyageurs National Park and Leech Lake, Minnesota, respectively. The C&R mortality rates reported in the present study Frohnauer et al. (2007) and Strand (1986) are markedly lower than those reported for other freshwater species (see Muoneke and Childress, 1994; Bartholomew and Bohnsack, 2005), but are consistent with mortality rates in specialized fisheries that are often less than 5% and sometimes below 0.1% (Policansky, 2002). Although no mortalities were observed in this study, it should be acknowledged that zero risk of angling mortality is never achievable in a fishery (Arlinghaus et al., 2007). Muskellunge angling mortality, therefore, may be negligible and management decisions should reflect this. For example, if creating trophy fisheries is a management agency's objective and employing high minimum length limits are used (Casselman, 2007), then angling mortality should be low to obtain the intended results (Brousseau and Armstrong, 1987). Indeed, the present study shows low angling mortality of muskellunge released by specialized anglers and provides support for increasing minimum length limits if the goal is to create trophy fisheries. However, it is uncertain what mortality rates are when non-specialized anglers handle muskellunge. We encourage future studies to address the possibility that muskellunge captured by non-specialized anglers (e.g., those using lighter gear and targeting smaller species) may exhibit higher levels of mortality (Gasbarino, 1986).

Angling inevitably causes some level of physiological disturbance for fish (Cooke and Sneddon, 2007). Indeed, the results of this study indicate that angling events cause significant physiological disturbances relative to control fish, though no significant differences between either handling treatments (i.e., normal vs. alternative) were noted. More specifically, blood glucose, blood lactate, and plasma potassium were the only parameters to display significant differences. Angling is a form of exhaustive exercise (Wood, 1991; Kieffer, 2000) that causes a cascade of physiological responses in fishes including the release of glucose into the bloodstream – providing fuel for tissues such as the heart, liver, and gills – and the production of lactate anions (Pagnotta and Milligan, 1991; Moyes and West, 1995; Wendelaar Bonga, 1997). A portion of the lactate produced leaks into the bloodstream, though evidence suggests the majority remains within white muscle tissue (Pagnotta and Milligan, 1991; Wood, 1991; Schwalme and Mackay, 1985). Previous work by Beggs et al. (1980) showed lactate levels of angled muskellunge reaching 4.0 mmol/L, but the present study indicates lactate levels exceeding 6.0 mmol/L. One potential explanation for this discrepancy could be related to size (Kieffer et al., 1996; Kieffer, 2000; Meka and McCormick, 2004) as the maximum size of fish used by Beggs et al. (1980) was 91.8 cm L_T compared to 132.1 cm L_T in this study. This relationship, however, was not explored in the present study because anglers cannot control for the size of fish that strike their lures. Though statistical power was low for many non-significant effects, this is likely explained by the short period of time from capture to blood sampling that may not have allowed some parameters to peak. For example, muskellunge lactic acid concentrations peaked 1 h into recovery (Beggs et al., 1980) and plasma cortisol concentrations for juvenile Chinook salmon (*Oncorhunchus tshawytscha*) also peaked 1 h after the final stressor (Barton et al., 1986). The large number of samples needed to obtain significant results indicates that many of the parameters tested are highly conserved between individuals immediately following capture. Regardless, the current study demonstrates that the angling

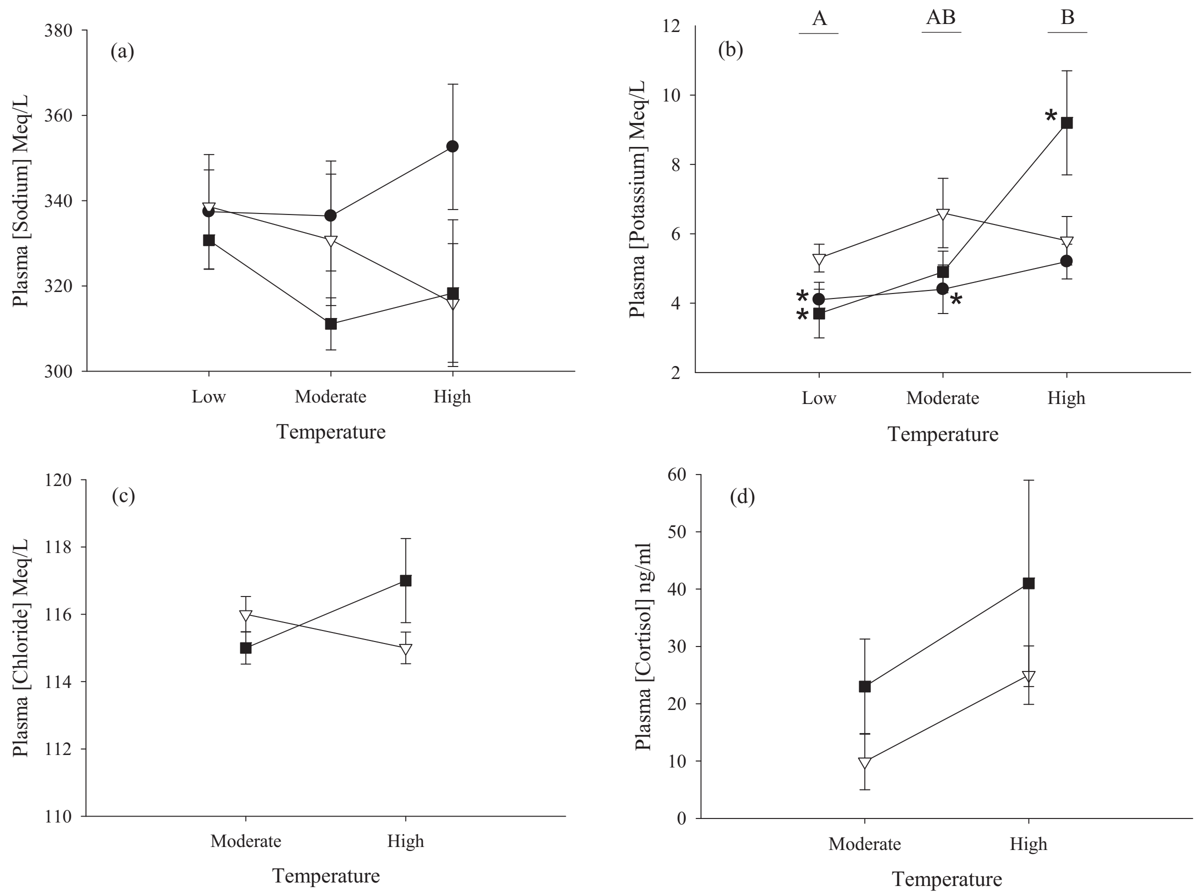

Fig. 4. Concentrations of plasma sodium (a), potassium (b), chloride (c), and cortisol (d) for control muskellunge (a–b, solid circle) and angled muskellunge subjected to gentle (hollow triangle) or normal (solid square) handling treatments. The samples sizes for plasma sodium and potassium ions at low, moderate, and high temperatures for the three treatments were as follows: control ($N = 8, 3, 6$), alternative ($N = 4, 10, 14$), normal ($N = 4, 9, 9$). Sample sizes for plasma chloride ions and cortisol were: alternative ($N = 7, 9$) and normal ($N = 7, 4$). Dissimilar upper case letters joined by horizontal lines denote significant differences between temperature groups, and asterisks (*) indicate treatment groups at given temperatures that are statistically different from each other (i.e., interaction effect).

event causes significant physiological disturbances relative to non-angled muskellunge.

Despite changes in muskellunge physiology following angling events, no significant differences in physiological status were noted between fish handled with and without 90 s of air exposure. Physiological disturbances resulting from air exposure can be large and result from collapsing gill lamellae which prevents gas exchange (Boutilier, 1990; Ferguson and Tufts, 1992). However, the severity and duration of a stressor may have profound effects on the stress response in fishes (Barton and Iwama, 1991; Schreck, 2000). This study demonstrates that 90 s of air exposure may not be long enough to cause significant physiological disturbances.

Suski et al. (2007) found that physiological differences among bonefish (*Albula vulpes*) were exacerbated as the duration of both angling time and air exposure increased to a maximum of 240 s of exercise and 180 s of air exposure. Additional studies on largemouth bass (*Micropterus salmoides*, Gustaveson et al., 1991), smallmouth bass (*Micropterus dolomieu*, Kieffer et al., 1995), and Atlantic salmon (*Salmo salar*, Thorstad et al., 2003) identify angling time as a significant stressor. The current study used handling procedures that minimized angling times in all cases, largely through the use of heavy lines and stout rods (i.e., standard muskellunge angling equipment). Extended angling durations often observed with long-line and down-rigger trolling (Beggs et al., 1980; Dedual, 1996; Bartholomew and Bohnsack, 2005) as well as inexperienced anglers (Storck and Newman, 1992) may cause greater physiological disturbances for muskellunge. This study demonstrates that muskellunge subject to normal handling procedures did not exhibit significantly different physiological responses compared to an alternative, suggesting current handling procedures are adequate for minimizing physiological disturbance. Anglers are, however,

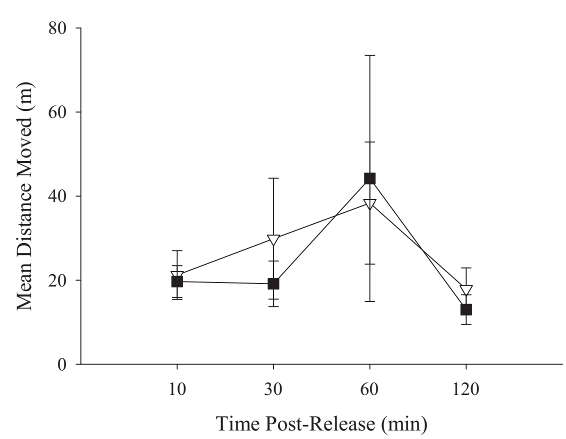

Fig. 5. Mean distance moved for angled muskellunge subject to normal handling procedures (solid squares) used by specialized anglers as well as an alternative handling procedure (hollow triangles). Sample sizes were $N = 15$ for both treatments except when one individual could not be located (i.e., $N = 14$) at 120 min post-release for the normal treatment and 10 and 30 min post-release for the alternative treatment.

advised to minimize air exposure as much as possible to ensure fish welfare. Moreover, no mortality was observed which suggests that these fish are indeed able to recover from the level of physiological disturbance incurred in the present study.

Muskellunge angling occurs across a broad range of temperatures, typically spanning late spring through late fall. This time period encompasses warm summer months, particularly in the muskellunge's northern portions of its range, where water temperatures may become excessively high which could increase physiological disturbances (Cooke and Suski, 2005). Anglers in latitudes extending into the southern portion of the specie's range (e.g., Illinois, Kentucky, Tennessee) typically cease angling for muskellunge when water temperatures rise above 27 °C (personal observation). The present study revealed that increases in water temperature caused significant increases in blood glucose and plasma potassium concentrations for muskellunge relative to angling at cooler temperatures, though temperatures rarely exceeded the optimal thermal preferenda (i.e., 25.6 °C; Scott and Crossman, 1973). Our findings agreed with several other studies demonstrating increased glucose concentrations at greater temperatures (Gustaveson et al., 1991; Meka and McCormick, 2004). The observed glucose concentration increases may be attributed to increased standard metabolic rates that rise as water temperatures warm (Dickson and Kramer, 1971; Cooke et al., 2001). In turn, production of liver glycogen rises resulting in an increase in glucose as glycogen is catabolized (Kieffer, 2000). Such energy demands are necessary for fish to recover following intense activity (Kieffer, 2000). Explanations for the observed increases in plasma potassium with water temperature are relatively unclear. However, potassium has been shown to enter plasma following exercise due to intercellular metabolic waste (Wang et al., 1994), red blood cell sodium-potassium pumps (Borgese et al., 1987), or intracellular gill uptake (Wood and Lemoigne, 1991), and elevated plasma potassium concentrations at higher water temperatures may result from increases in membrane fluidity (Cossins and Prosser, 1978; Gerner et al., 1980). This particular response is of interest because potassium cations influence nerve function (Hidaka and Toida, 1969; Abe and Oka, 1999) and elevated potassium levels (i.e., hyperkalemia) can contribute to cardiac failure in mammals (Guyton, 1981; Lindinger, 1995). Interestingly, Beggs et al. (1980) observed markedly higher plasma potassium concentrations in muskellunge that died compared to those fish that survived through the experimental period. Because most muskellunge angling occurs in the warm summer months (Kerr, 2007a), the potentially lethal effects of increased potassium concentrations and their relation to cardiac failure is of concern. Evidence from this study clearly indicates the propensity for physiological disturbance to increase with increasing water temperatures. Therefore, it is advisable to be cautious of the magnitude of stress imposed on muskellunge (e.g., severely limit air exposure and angling durations) when angling during periods of high water temperatures.

A failure of the different handling treatments to induce different physiological responses can likely be partially related to the immediate blood sampling procedure following angling. Serial sampling has revealed that physiological measures of stress may not peak until well after the onset of the initial stressor (e.g., Soivio and Oikari, 1976; Pickering et al., 1982; Barton et al., 1986; Young and Cech, 1993). Future studies should consider serial sampling to determine how much time elapses before concentrations of parameters such as blood glucose, blood lactate, and plasma cortisol peak and then return to basal levels. Another potential explanation for the minimal physiological differences across handling treatments in this study is the condition of angled muskellunge. Hematocrit can provide a measure of the overall condition for a fish (Barton, 2002) and the uniformity of hematocrit levels between treatments and controls suggests relatively good health for all fish in this study. Taken together, minimal responses for the physiological parameters tested may be attributed to the apparent good health of the muskellunge sampled and the immediate blood sampling procedures used to collect data.

As with the lack of physiological disturbances between handling treatments, this study further demonstrates that handling procedures with and without air exposure (within the limits used in this study) do not significantly affect post-release behaviour. Muskellunge moved an average of 45 m at 1 h post-release. Arlinghaus et al. (2009) found that total movement of northern pike (*Esox lucius*) post-release did not differ significantly with varying levels of air exposure. They also showed that with 60 and 180 s of air exposure, northern pike moved approximately 30 m in the first hour post-release which was similar with the distances noted in this study. Predation following angling is a concern for some species of fishes such as bonefish (Cooke and Philipp, 2004; Danylchuk et al., 2007) and red snapper (*Lutjanus campechanus*; Campbell et al., 2010), but predation of adult muskellunge is a non-issue because the size of adults preclude them as prey items for other species of fish. Behaviour of muskellunge pre-capture was not determined so it is unclear whether the patterns noted here conform to typical behaviour of non-angled muskellunge. Future studies on muskellunge should evaluate pre- and post-release behaviour and attempt to elucidate the duration necessary to fully recover from angling. It is unclear what affects, if any, the external tagging procedure had on muskellunge. However, because anesthetics were not used and muskellunge length-weight data suggests that even the smallest tagged individual (80.8 cm L_T) weighed several hundred times more than the transmitter weight (3.2 g in air; Casselman and Crossman, 1986) it is likely tagging effects were minimal (Ross and McCormick, 1981; Bridger and Booth, 2003). Nevertheless, we acknowledge the possibility that biofouling and tag abrasions could have caused behavioural disturbances, but these issues and others associated with external tagging are often manifest in juvenile or small sized fishes (see Bridger and Booth, 2003). Furthermore, some muskellunge may have tried to avoid the research boat as has been suggested for other fishes, particularly at distances less than 10 m away (Drašík and Kubečka, 2005). Regardless, the present study clearly demonstrates that angled muskellunge exhibit similar post-release behaviour despite air exposure in one handling method, but more fine-scale behavioural analyses could benefit our understanding of the recovery dynamics of muskellunge.

Another metric used to assess the affects of C&R angling on muskellunge was examining the degree of reflex impairment. Reflexes are tested as a rapid measure of fish condition and health (Davis and Ottmar, 2006). To date, reflex impairment has been used to predict mortality in several commercial species (Davis and Parker, 2004; Davis, 2005; Davis and Ottmar, 2006), but little has been done with recreationally important fishes. However, in the present study no mortality for angled fish was observed, therefore, no conclusions could be drawn for correlations between mortality and the absence of particular reflexes. Nevertheless, reflex impairment can still be used by anglers to assess the condition of their catch. For instance, we observed 19% of angled muskellunge remaining on the surface for a period of time and 69% that did not burst away following release. Anglers could potentially use these types of observations to adapt handling procedures accordingly, such as remaining in the vicinity of the catch to ensure no boats collide with released fish. Further validation of reflex impairment tests is needed to confirm its applicability in recreational fisheries.

5. Conclusions

Until now, formal evaluation of the handling procedures used by specialized muskellunge anglers has never been accomplished.

The creation of these procedures was done so with little science-based influence and as voluntary release rates approach 100%, the need to establish guidelines for proper handling procedures is necessary. The present study clearly demonstrates that current C&R handling procedures used by specialized muskellunge anglers maximize survival and minimize physiological and behavioural disturbances. The conscious decision to voluntarily release legal-sized muskellunge and employ methods that, as evidenced in this study, maximize survival is a testament to the conservation mind-set of many specialized muskellunge anglers. Rarely are these types of specialized fisheries seen in recreational angling. Analogous to North American muskellunge anglers are specialized carp (*Cyprinus carpio*) anglers in Europe. These anglers employ similar handling procedures, advocate voluntary C&R to conserve the resource, and continually refine handling procedures to include new developments in the angling industry (Arlinghaus et al., 2007). Although mortality is minimal in both European specialized carp (Raat, 1985) and muskellunge fisheries, species-specific impacts of handling should be evaluated in other specialized fisheries to ensure proper handling practices are employed (Cooke and Suski, 2005). The effectiveness of C&R and its value to fisheries management is only as good as the procedures used by anglers and promoted by managers. We advise managers to account for the low degree of angling-associated mortality evidenced in this study, particularly when developing management goals for muskellunge fisheries, and advocate promotion of these handling procedures to the general angling public.

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