Hydrobiologia (2018) 813:223–235
https://doi.org/10.1007/s10750-018-3533-z

PRIMARY RESEARCH PAPER

# Assessing the potential for using low-frequency electric deterrent barriers to reduce lake sturgeon (*Acipenser fulvescens*) entrainment

**Lauren J. Stoot · Daniel P. Gibson · Steven J. Cooke · Michael Power**

Received: 8 September 2017 / Revised: 18 January 2018 / Accepted: 27 January 2018 / Published online: 8 February 2018


**Abstract** Given the limited evidence on utilizing low-frequency electrical fields as deterrents to fish, we studied lake sturgeon (*Acipenser fulvescens* Rafinesque, 1817) behavioural responses and short-term physiological reactions to low-frequency (0.1–50 Hz) low-voltage (0.024–0.3 v) electric fields. Fish from 2 year classes were used as a means of including size considerations in the study. Individuals from both year classes exhibited differing responses to the same electric fields, with smaller, younger fish being more reactive to the electric stimulation of the fields than / older, larger fish. The smaller, younger fish also had reduced weight gain 30 days post experiment compared with fish that were a year older. Short-term physiological effects were observed in the older, larger fish in the form of elevated blood glucose levels. Our results show that individuals can acclimatize to electric fields in a relatively short time period and that larger individuals tend to be less affected by low-frequency/low-voltage electric fields than smaller fish. Testing the utility of electric deterrents in a more realistic riverine setting using pulsating electric field is, therefore, highly recommended to ensure decisions regarding the implementation of low-frequency/low-voltage electric barrier systems to reduce entrainment adequately account for possible sublethal effects on lake sturgeon.

**Keywords** Entrainment · Hydro-electricity · Physiology · Lake sturgeon · Management

Handling editor: Ingeborg Palm Helland

L. J. Stoot · M. Power (✉)
Department of Biology, University of Waterloo, 1200 University Ave., Waterloo, ON N2L 3G1, Canada
e-mail: m3power@uwaterloo.ca

D. P. Gibson
Environment Services, Ontario Power Generation, 800 Kipling Avenue, Etobicoke, ON M8Z 5S4, Canada

S. J. Cooke
Fish Ecology and Conservation Physiology Laboratory, Department of Biology, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada

## Introduction

In recent years the maintenance, enhancement and restoration/recovery of native lake sturgeon (*Acipenser fulvescens* Rafinesque, 1817) populations has become a central focus for resource managers throughout North America (Haxton et al., 2014; Bruch et al., 2016). As the only member of the *Acipenseridae* family in North America that is found strictly in freshwater, lake sturgeon are endemic throughout much of the Great Lakes and Hudson Bay basins in Canada and are characterized as large, cartilaginous benthic fishes (Scott & Crossman, 1998). Lake sturgeon populations currently exist in low numbers throughout most of their range due in large part to commercial overfishing throughout the early 19th century (Harkness & Dymond, 1961; Pikitch et al., 2005; Golder Associates Ltd., 2011; Bruch et al., 2016). Furthermore, many North American rivers underwent extensive industrialization and hydroelectric development in order to meet the needs of rapidly increasing resource and urban developments. The resulting loss, degradation and fragmentation of habitat still affects lake sturgeon populations and in some cases limits the access to historic habitat used for key life history migration and spawning events (Baxter, 1977; Houston, 1987; Ferguson & Duckworth, 1997; Baker & Borgeson, 1999; Jager et al., 2001; Haxton & Cano, 2016). Among the threats facing lake sturgeon are concerns related to entrainment and impingement at hydroelectric facilities and other industrial or agricultural intakes (Billard & Lecointre, 2001; Bruch et al., 2016; Haxton & Cano, 2016), with studies indicating between 8 and 27% entrainment rates depending on life-stage, initial residency location with respect to the dam and river morphology (McDougall et al. 2013).

In response to legislative protection provided by their endangered/threatened status (COSEWIC, 2006), many facilities and dam owners have implemented improvements at hydro stations designed to enhance fish survival and minimize entrainment (Amaral, 2001). Various studies have assessed the potential for improved fish survival at turbines via improving the mechanics of the units (e.g. use of leading edge blades; minimum gap runner turbines) as well as minimizing fish interactions with the facility to reduce entrainment and impingement (Čada, 2001; Hogan et al., 2014). For lake sturgeon in particular, numerous studies have been conducted to better understand population status and interactions with hydroelectric dams (e.g. Sheehan & McKinley, 1992; McKinley et al., 1998; ESA Consulting, 2002; Welsh & McLeod, 2010; Hatch Energy Consulting, 2012; Thiem et al., 2013; reviewed in Haxton & Cano, 2016).

Mitigation methods to limit fish entrainment can be separated into two categories; (1) mechanical, or physical barriers that exclude fish, such as nets (Stober et al., 1983; Hutchison & Matousek, 1988), and intake screen configurations (Hanson et al., 1977; Davis et al., 1988; Matousek et al., 1988) or other physical structures that interrupt movement patterns (Noatch & Suski, 2012), and (2) behavioural barriers, such as sight (Enami, 1960; Bibko et al., 1973; Patrick et al., 1988a), sound (Haymes & Patrick, 1986; Patrick et al., 1988b), light (Fore, 1969; Wichahm, 1973), bubbles (Zielinski & Sorensen, 2015) and electrical fields (Seyler et al., 1996; Basov 1999, 2007). In recent years, interest in non-physical barriers has increased as a result of concerns about limiting the spread of invasive species or deterring fish from occupying habitats proximate to industrial infrastructure that can cause mortality, i.e. dams and water intakes (Noatch & Suski, 2012).

Use of non-physical electrical field barriers have a long history of use in fish sampling as a result of the transference to fish of a portion of any electrical current applied to water (Reynolds, 1996). The dissipation of electrical energy in water means that the effects of an electrical field will vary from taxis to immobilization depending on distance from the electrical source, fish size and species and water conductivity (Bullen & Carlson, 2003; Noatch & Suski, 2012). At appropriate intensities, electrical fields can prove effective deterrents to fish by eliciting a behavioural avoidance response (Katopodis et al., 1994). As a result the use of weak electrical fields has been viewed as having deterrent potential for sturgeon species (Seyler et al., 1996; Basov, 1999, 2007). For example, electrical fields have been noted for their ability to influence behavioural responses in Russian sturgeon (*Acipenser gueldenstaedtii*, Brandt & Ratzeburg, 1833; Basov, 1999, 2007) and Sterlet sturgeon (*Acipenser ruthenus,* Linnaeus, 1758; Basov 1999, 2007) and paddlefish (*Polyodon spathula,* Walbaum, 1792; Wilkens et al., 1997; Gurgens et al., 2000) species. Furthermore, electroreceptors used to detect low-frequency electric fields have been identified in *Chondrostei* that aid sturgeon in detecting prey (Jorgensen et al., 1972). Some studies have also explored the potential to manipulate electroreceptors using electropositive metals with endangered Atlantic sturgeon (*Acipenser oxyrhynchus* Mitchill) populations as a means of reducing interactions with fishing gears (Bouioucos et al., 2013).

Within the Great Lakes, electrical barriers have been used historically to prevent the spawning runs of invasive sea lamprey (*Petromyzon marinus,* Linneaus, 1758) and more recently as a means of controlling the entry of silver carp (*Hypophthalmichthys molitrix,* Valenciennes, 1844) and bighead carp

(*Hypophthalmichthys nobilis,* Richardson, 1845) into the Great Lakes (Katopodis et al., 1994; Noatch & Suski, 2012). Given the evidence to date on utilizing low-frequency electrical fields as deterrents for sturgeon and other fish species, the objective of our study was to assess the potential for the use of such fields to manipulate lake sturgeon behaviour, and to compare results to those obtained in previous low-frequency electric field (1.0–50 Hz) studies completed using Russian and Sterlet sturgeon (Basov, 1999). In addition, we also sought to assess the immediate physiological responses of lake sturgeon to low-frequency electric field exposure to assess potential acute physiological stress and latent growth effects. Specifically, we hypothesized that: [$H_1$] as the electric frequency increased we would see a change in behaviour, which at the higher frequencies and voltages would result in visible avoidance of the electric field, and, [$H_2$] electric field exposure would have no measurable physiological effect on experimental fish.

## Methods

Trials were conducted in April 2014 at Manitoba Hydro's Grand Rapids Fish Hatchery in Grand Rapids, Manitoba (53°12 N, 99°18 W). Lake sturgeon were acquired through the Nelson River Sturgeon Board, which monitors the lake sturgeon population in the upper Nelson River. Within the test group of fish there were four family groups from a 2 × 2 cross (2 females, 2 males) of lake sturgeon caught in the Nelson River, near the confluence of the Landing River (57°11 N, 99°25 W). Fish from 2 year classes (2012, 2013) were raised from fertilized eggs incubated at the Manitoba Hydro Grand Rapids Fish Hatchery. Fish were grown in large recirculation system troughs (495 cm × 66 cm × 27 cm; Progressive Yard Works, Saskatoon, SK) using surface water (pH 7.96–8.38; conductivity: 459–573 S $cm^{-1}$; alkalinity: 260–266 $mgl^{-1}$) drawn from the Cedar Lake (53.239° N, 100.098° W) with a flow-through, recirculation system. A total of 50 (2013 year class, age-1) and 51 (2012 year class, age-2) individuals, respectively, were randomly selected for use in the trials.

In March 2014, all fish were measured (fork length (mm), total length (mm) and weight (g)) and a PIT tag (8 mm FDX-B; Oregon RFID, Inc., Portland, OR) was inserted into their dorsal musculature. Prior to experimentation, fish were once again measured (Table 1) and moved from the rearing troughs to large, circular flow-through holding tanks (1135 l). Following hatchery protocol, fish were fed bloodworms to satiation twice daily (7:30 am and 12:30 pm) and their holding tanks were cleaned twice a day an hour after feeding throughout the experimental period.

### Trials

For experimental trials, individual fish were selected from their circular holding tanks and placed in a 1-m-long experimental arena which was created by sectioning off an area in the middle of the 5 m rearing troughs using plastic snow fence to prevent fish from escaping the arena. In the centre of the arena, two stainless steel electrodes (30 × 5–0.05 cm) were placed 60 cm from each other with 20 cm on either side of the electrode to the snow fence barriers, and centred both longitudinally and latitudinally in the experimental arena (Fig. 1). The electrodes were connected to a 7 MHz DDS function generator (Model 4007B, B&K Precision Corp., Yorba Linda, CA), which established an electric field within the experimental area. The electric field was monitored using an oscilloscope (Model 2530B, B&K Precision Corp., Yorba Linda, CA) which was connected to a voltage probe used to measure the electric field. Characterization of the electric field (mV/cm) with the voltage probe indicated it was strongest over the electrodes, varying with frequency, and declined significantly beyond 15 cm from the centre of each electrode (Fig. 2). Thus while there were no refuge areas per se, there were areas within the experimental tanks with weaker electric fields.

### Experimental procedure

To test the behavioural effects of electricity exposure hypothesis ($H_1$), fish were exposed to low-frequency electrical fields in four separate trials; low, medium, high and very high that varied the frequency of the electric field between 0.1 and 100 Hz depending on the experimental treatment (see Table 2). Frequency levels within each treatment were chosen for comparative purposes to replicate the range of frequency considered by (Basov, 1999) using Russian and Sterlet sturgeon. Within each treatment, three experimental

**Table 1** Mean lake sturgeon fork length (FL), total length (TL) and weight (WT) for the age-1 and age-2 fish before use in experiments

| Year class | *N* (control, experimental) | Mean ± SE FL (mm) | Mean ± SE TL (mm) | Mean ± SEWT (g) |
|---|---|---|---|---|
| Age-2 | 51 (26,25) | 296 ± 28.6 | 339 ± 35.7 | 139 ± 35.7 |
| Age-1 | 50 (25,25) | 202 ± 14.1 | 235 ± 14.1 | 48 ± 7.1 |

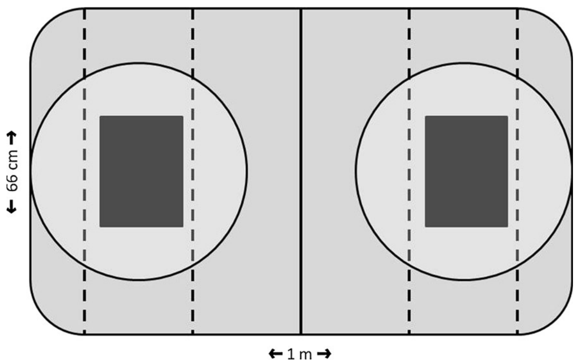


**Fig. 1** Set up of anodes in the experimental are of each rearing trough created by section at the end of a 5 m trough off with plastic fencing. The black solid line is at the middle of the experimental area and the dashed line represents the division of the area into observation zones. The large dark grey rectangles are the anodes, which supplied the experiment with the electric field. The light grey circles denote the measured areas where the electric field was > 2 mV/cm at all experimental frequencies

time periods were defined for observation purposes as described below.

For the low-level treatment, age-1 individuals were randomly selected from the circular holding tank and placed in the experimental area. Fish were acclimated for a 5-min period (before electricity), observed and behaviours and/or reactions were classified following Table 3. Consistent with Table 3, acclimation was determined on the basis of observed behaviours (e.g. sedentary, slowly exploring) and the absence of any of the listed avoidance reactions. After acclimation, a low level of electricity was applied at a frequency of 0.1 Hz and 0.024 V for a period of 5 min and fish reactive behaviour was recorded (after 1st electricity level). After 5 min, the amplitude was raised to 0.066 V, while the frequency remained at 0.1 Hz, and behaviour was again recorded (after 2nd electricity level). The electric field was turned off after 5 min and fish reactive behaviour post-electrical exposure

**Fig. 2** Calibration profile of all frequencies used at an intensity of field of 5.0 mV/cm in the experimental set-up

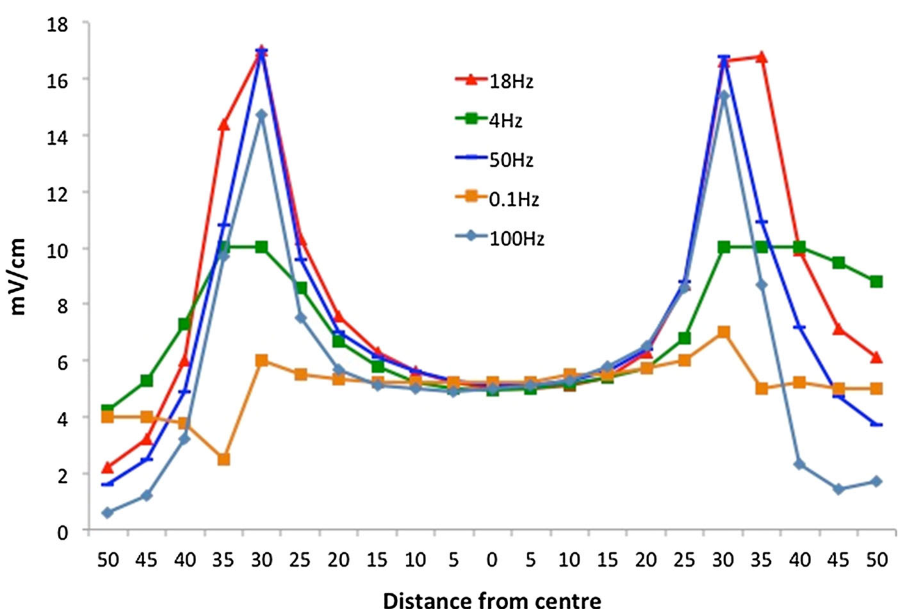

**Table 2** Overview of the four levels of low-frequency electric fields used in the deterrent experiments

| Experimental level | Frequency of field (Hz) | Intensity of field (mV/cm) | Volts (v) |
|---|---|---|---|
| Low | 0.1 | 0.4 | 0.024 |
| | 0.1 | 1.1 | 0.066 |
| Medium | 4 | 2.5 | 0.150 |
| | 18 | 2.75 | 0.165 |
| High | 50 | 1.2 | 0.072 |
| | 50 | 5.0 | 0.300 |
| Very high | 100 | 1.2 | 0.072 |
| | 100 | 5.0 | 0.300 |

**Table 3** Overview of the behaviours and reactions witnessed before and during the experiment. Behaviour is defined as any action taken by the fish prior to electrical exposure. A reaction is any observed action taken by the fish during the period of electrical exposure

| Behaviour or reaction | Type | Description |
|---|---|---|
| Sedentary | Behaviour | Fish was stationary and inactive during observation in the experimental area |
| Slowly exploring | Behaviour | Fish was moving throughout the experimental area at a slow pace |
| Actively exploring | Behaviour | Fish was moving through the experimental area at moderate pace |
| Hyperactive | Behaviour | Fish was frantically moving throughout the experimental area |
| Nothing | Reaction | No visible reaction when exposed to the electrical field |
| Gill flare | Reaction | Fish immediately flared gills when exposed to the electrical field |
| Avoidance behaviour movement | Reaction | Fish exhibited an avoidance behaviour (wiggle) after immediate exposure to the electrical field |
| Involuntary movement | Reaction | Fish exhibited an involuntary body movement (spasm) after immediate exposure to the electrical field |
| Relax | Reaction | Fish exhibited a muscle relaxation after immediate exposure to the electrical field |
| Tetany | Reaction | Fish exhibited a muscle and body freeze after immediate exposure to the electrical field |

was recorded for approximately 1 min. Fish were then transferred to a recovery trough and provided a minimum 48-h recovery period before being exposed to the next experimental level. For the medium, high and very high treatment levels the same experimental protocol was followed using the intensities (mV/cm) and voltages given in Table 2.

Control fish were randomly selected and placed in the experimental arena and monitored for 5 min. Fish were then removed and placed in the recovery trough and left to recover for a minimum of 48 h before being observed again (Table 3) to account for possible handling-related effects. After all fish had completed all four experimental levels, they were returned to the troughs and left untouched for 30 days, after which they were re-measured for fork length, total length and weight. The same experimental procedure was replicated with the age-2 fish.

## Blood physiology

To test the residual physiology of electricity exposure hypothesis (H2), the age-2 individuals were blood sampled at the low- and extra high-frequency tests 5 min post-trial. A similar sample was obtained from non-tested control fish. A 0.2 ml blood sample was obtained for both the control and experimental fish from the caudal vasculature using a 1 ml sodium heparin (10,000 USP units $ml^{-1}$; Sandoz Inc., Princeton, NJ)-coated syringe with a 21.5 gauge, 38 mm needle (Becton–Dickinson, Franklin Lakes, NJ). Blood lactate and blood glucose were measured immediately after collection (on whole blood) at ambient temperature, using a Lactate Plus™ (Nova Biomedical, Mississauga, ON) lactate metre and an Accu-Chek Compact Plus™ (Roche Diagnostics, Indianapolis, IN) glucose metre (see Stoot et al., 2014). As a precaution against injury, age-1 fish were not used for physiological blood sampling owing to their small size. Blood lactate is an indicator of anaerobic respiration and hypoxia (Sopinka et al., 2016) which can occur as a result of interaction with electricity (Burns & Lantz, 1978; Bracewell et al., 2004) and glucose is mobilized as part of the typical glucocorticoid stress response (Barton, 2002; Sopinka et al., 2016).

### Data analysis

To ensure that our control and experimental groups did not vary by size, we compared fork length, total length and weight prior to the experiments between control and experimental individuals using a two-sample *t* test for both year classes (Zar, 2010).

For hypothesis $H_1$, the proportions of fish in both year classes reacting to the electrical treatment were tested for significant differences among the electric treatments (low, medium, high, extra high) within each of the experimental time periods (before electricity, after 1st electricity level, after 2nd electricity level) using the Kruskal–Wallis H test to guard against possible violations of the ANOVA assumptions, with testing corrected for tied ranks as required (Zar, 2010). Data were also aggregated to time period groups and tested with the Kruskal–Wallis H test using time period as the independent factor. Pending the determination of significant differences among the time periods, a multiple comparisons of medians test following Levy (1979) was used to determine between which time periods significant differences existed (e.g. Zar, 2010).

For hypothesis $H_2$, we compared blood physiology, as represented by blood lactate and blood glucose, for age-2 fish at the low and extra high electric treatment levels. As blood lactate and glucose residuals did not violate the assumptions of normality and homogeneity of variance, we used a two-sample *t* test to test the mean difference between control and experimental groups at both electric treatments (Zar, 2010). Furthermore, for both year classes, we assessed whether control and experimental groups differed significantly in length and weight characteristics 30 days after completion of the experiments. As length and weight increment measures did not violate the assumptions of normality and homogeneity of variance, we similarly used a two-sample t-test to test the mean difference between the control and experimental groups.

Two-sample *t* tests were also used for all other incidental testing, with the form of the test used varyingly to ensure conformance with the required variance assumptions (Zar, 2010).

All statistical tests were performed using JMP (Version 9.0.1, SAS Institute, Cary, NC). Significance was accepted at $\alpha = 0.05$.

## Results

All of the 101 fish were able to complete the 4 levels of the experiment, and no individuals died or were observed to sustain experimental-related injuries. Prior to the experiment, the age-2 fish displayed no significant differences between the control and experimental groups in fork length ($t_{(49)} = 1.76, P = 0.09$), total length ($t_{(49)} = 1.64$, $P = 0.108$) or weight ($t_{(49)} = 1.78$, $P = 0.081$). Similarly, prior to the experiment, the age-1 fish showed no significant differences between the control and experimental groups in fork length ($t_{(40)} = 1.25, P = 0.217$), total length ($t_{(41)} = 1.13$, $P = 0.264$) or weight ($t_{(38)} = 1.00, P = 0.323$).

When observing the behaviour of individuals throughout the trials, two distinctive types of responses were associated with exposing lake sturgeon to weak electric fields (See Table 3). The first was an "acute" reaction, which was observed immediately following changes in current flow (i.e. on or off) and often associated with involuntary responses, such as an observable muscle contraction causing movement, gill flare or any other tetanic muscle contraction causing the body to "freeze" for periods of between 5 and 60 s. The second type of response to exposure to weak electrical fields was a behaviour that entailed an avoidance response (i.e. swim activity) associated with movement out of the strongest portions of the electric field and was observed over a period of 30–45 s following a change in the electric current (i.e. on or off).

For all ages, the majority of individuals began the trial exhibiting an "active exploration" behaviour regardless of the level of electric field to which they were exposed. As the electricity level changed, the age-1 individuals tended to decrease their activity levels and become more sedentary. The age-2 individuals showed only a slight decrease in activity levels, as approximately half of the individuals continued to actively explore. Both age classes tended to decrease their actively levels throughout the trial. The age-1 fish did exhibit displays of hyperactivity when electricity was emitted throughout the trough, while the age-2 fish only demonstrated hyperactivity when introduced to the trough.

Although both year classes were equally likely to react upon entry to the experimental arena (94% for both year classes), the age-2 fish exhibited reactions such as gill flaring (involuntary) or swim movement (avoidance behaviour) significantly more often than the age-1 fish in all other time periods. For example, two-sample *t* tests indicated significantly higher reactions among the age-2 individuals before electricity ($t = 2.776$, $df = 198$, $P = 0.006$), after 1st electricity level ($t = 4.704$, $df = 198$, $P < 0.001$) and after 2nd electricity level ($t = 4.754$, $df = 198$, $P < 0.001$).

Tests for significant differences in the proportion of age-2 fish reacting to the electrical stimulus among the different electric treatments (low, medium, high, extra high) within each of the experimental time periods (before electricity, after 1st electricity level, after 2nd electricity level) showed no significant differences (Fig. 3): before electricity, $H_{3,100} = 6.433$, $P = 0.092$; after 1st electricity level $H_{3,100} = 1.737$, $P = 0.629$; after 2nd electricity level $H_{3,100} = 2.642$, $P = 0.054$. As a consequence, electrical treatment data were aggregated to time period, where there were no significant differences among time periods with all Levy's multiple pairwise comparison of medians test $P > 0.131$ (Fig. 4).

Similar results were obtained for the age-1 fish, with there being no significant differences in the proportion of fish reacting among the different electric treatments (low, medium, high, extra high) within each of the experimental time periods (Fig. 5): before electricity, $H_{3,100} = 1.426$ $P = 0.700$; after 1st electricity level $H_{3,100} = 0.760$, $P = 0.859$; after 2nd electricity level $H_{3,100} = 6.049$, $P = 0.109$. Thus, electrical treatment data were aggregated to time period. There were significant differences among time periods, with Levy's multiple pairwise comparison of medians test indicating that the proportion of fish reacting during a given time period was significantly higher before the electricity period (Fig. 6) than after the 2nd electricity level ($P < 0.001$). All other time period comparisons were not significantly different (all $P = 0.059$).

Our test of the immediate physiological effects of exposure to low-level electrical fields (0.1 Hz; Figs. 7 and 8) on age-2 fish revealed a significant difference

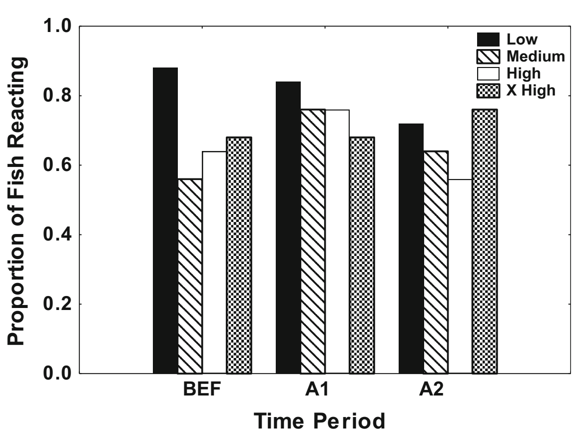


**Fig. 3** Proportion of age-2 experimental fish that showed a reaction to the electricity over various different intensities of electricity and over different time periods in the experiment. BEF = before electricity, A1 = after 1st electricity level, A2 = after 2nd electricity level

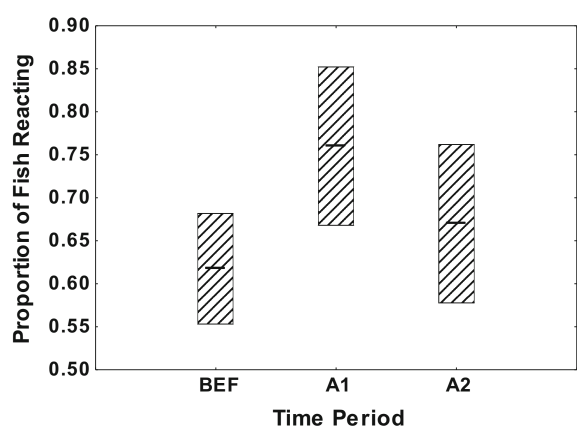


**Fig. 4** Proportion of the age-2 fish reacting in the experimental tank averaged across all electrical treatments: low, medium, high, extra high. Horizontal bars define the mean. Columns define the mean ± standard deviation. BEF = before electricity, A1 = after 1st electricity level, A2 = after 2nd electricity level. There were no significant differences among electric treatments within each time period ($P > 0.05$). Proportion of fish reacting was not significantly different among the periods E ($P > 0.05$)

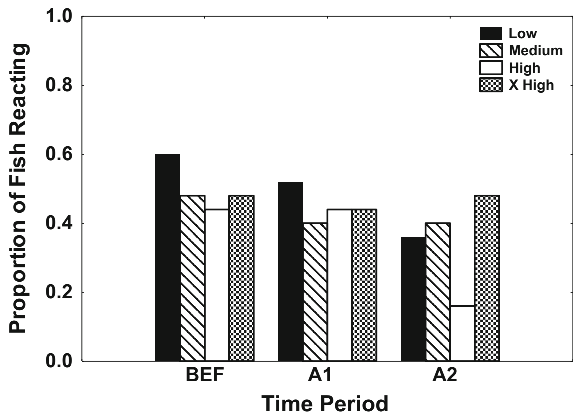


**Fig. 5** Proportion of age-1 experimental fish that showed a reaction to the electricity over various different intensities of electricity and over different time periods in the experiment. *BEF* before electricity, A1 = after 1st electricity level, A2 = after 2nd electricity level

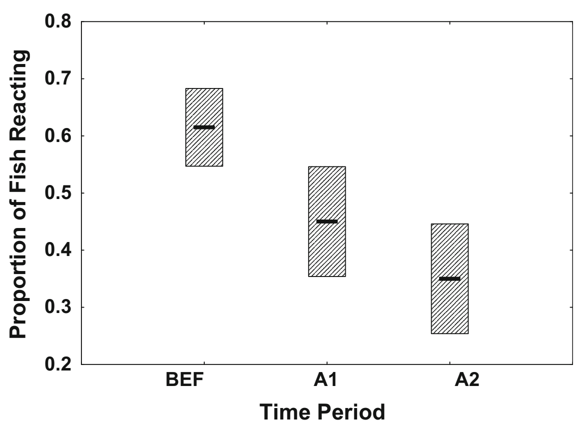


**Fig. 6** Proportion of the age-1 fish reacting in the experimental tank averaged across all electrical treatments: low, medium, high, extra high. Horizontal bars define the mean. Columns define the mean ± standard deviation. BEF = before electricity, A1 = after 1st electricity level, A2 = after 2nd electricity level. There were no significant differences among electric treatments within each time period ($P > 0.05$). Proportion of fish reacting was significantly greater in period BEF ($P < 0.05$) than in any period A2. A1 did not differ statistically from A2

between control and experimental groups for both blood lactate ($t = 2.87$, $df = 29$, $P = 0.008$) and blood glucose ($t = 2.13$, $df = 43$, $P = 0.039$). We did not find a significant difference between control and experimental individuals for blood lactate ($t = 1.33$, $df = 49$ $P = 0.191$) or blood glucose ($t = 0.93$, $df = 45$, $P = 0.360$) at the high electric field (100 Hz; Figs. 7 and 8).

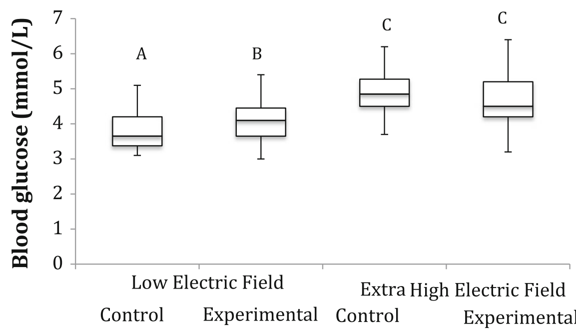


**Fig. 7** Blood glucose level box plots (median ± standard error) for the control and experimental age-2 groups for low and extra high electric field levels. Letters indicate homogenous groups within which there were no statistically significant differences

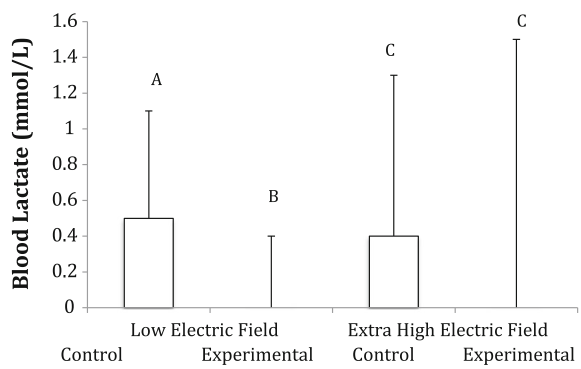


**Fig. 8** Blood lactate levels (median ± standard error) for the control and experimental groups for low and extra high electric field levels. Letters indicate homogenous groups within which there were no statistically significant differences

We also assessed whether exposure to low-frequency electric fields had effects on growth rates over the 30-day period following the experiments. We did not find significant differences in growth based on fork length ($t = 1.76$, $df = 49$ $P = 0.085$), total length ($t = 0.23$, $df = 43$, $P = 0.821$) or weight ($t = 1.49$, $df = 49$, $P = 0.144$) in the age-2 fish or fork length ($t = 0.59$, $df = 43$, $P = 0.560$) and total length ($t = 1.87$, $df = 45$, $P = 0.068$) in the age-1 fish (Table 4). We did find significant differences in growth based on weight between age-1 control and experimental individuals ($t = 2.32$, $df = 48$, $P = 0.025$), with controls having a mean positive change in weight of 9 g compared to a mean change in growth of 6 g for experimental fish (Table 4).

**Table 4** Change in measured lake sturgeon length and weight characteristics over 30 days post experiment. Statistical significance of pairwise *t* tests are given, with significance ($P < 0.05$) denoted by an asterisk

| Year class | Metric | Control (mean ± SE) | Experimental (mean ± SE) | *T* test *P* value |
|---|---|---|---|---|
| Age-2 | Fork length | 11.7 ± 0.7 | 9.8 ± 0.8 | 0.085 |
| | Total length | 11.7 ± 0.6 | 11.5 ± 0.9 | 0.821 |
| | Weight | 17.2 ± 1.3 | 14.6 ± 1.2 | 0.144 |
| Age-1 | Fork length | 14 ± 0.8 | 13 ± 1.1 | 0.56 |
| | Total length | 16 ± 0.9 | 13 ± 1.2 | 0.068 |
| | Weight | 9 ± 0.7 | 6 ± 0.7 | 0.025* |

## Discussion

Our main objective was to assess the potential for the use of low-frequency electric fields to manipulate lake sturgeon behaviour with minimal physiological consequences. Throughout our experimental trials, we observed varying behavioural responses and individual variation to four levels of electric fields for both tested year classes. Despite being exposed to similar laboratory levels of low levels of electric fields, lake sturgeon did not display responses similar to the Russian and Sterlet sturgeon used in previous experiments (Basov, 1999). In Basov's study, both species displayed distinctive responses and behaviour patterns as the electric field increased, whereas in our study lake sturgeon exhibited greater behavioural variation and did not show a distinctive, uniform change in behaviour as the voltage increased. In general, lake sturgeon exposed to electricity in our study appeared to acclimatize to both the experimental tank and the presence of electricity at all tested voltages. Initially fish tended to be active but calmed down until the first level of electricity was introduced. By the second level of electricity, fish were acclimatized to its presence, despite voltage increases. Differences in responses by size (age) suggest size (age) dependency of the behavioural susceptibility to low-frequency electric fields. The smaller sized age-1 fish did show statistical significance in their response rate to electric fields, whereas age-2 fish did not display statistical significance in their response rate suggesting they are less affected by the presence of weak electric fields.

In general, larger fish have higher body voltage than smaller fish, absorb more electric current and are more susceptible to electroshock-induced immobilization than smaller fish (Emery, 1984; Dolan & Miranda, 2003). Despite being the older year class, the age-2 individuals showed no statistically significant response to low-frequency electric field exposure. Both year classes were very active upon entry to the testing area, and displayed behaviour patterns suggestive of acclimation to the presence of electric fields. The apparent contradictory nature of our test results when compared to electrofishing studies (e.g. Dolan & Miranda, 2003; Miranda & Dolan, 2004), where larger fish tend to be over-represented in sampling, may relate to the initial behavioural sensitivity of smaller fish, as observed in our study. Alternatively, as Ostrand et al. (2009) have suggested, a lack of observable activity such as swimming may be related to recovering from the physiological disturbance entailed by low-frequency/low-voltage electric field exposure. Differences may also have arisen as a result of age-related changes in scale and scute density. Electrical conductivity is known to positively correlate with tissue porosity (Gu et al., 2002), with the process of scute and scale ossification also known to be temporally dependent (Zhang et al., 2012) as structures thicken with time (Leprévost et al., 2017). Thus the reduced sensitivity of the age-2 test fish may have been related to reductions in scute and scale porosity associated with age-related increases in thickness. However, we believe the effect is likely to be evident only over the limited range of fish ages and electrical frequencies and voltages tested in this experiment.

Exposure of lake sturgeon to weak electric fields did impair weight gain over a period of 30 days. This impairment was only seen in the age-1 fish, as the age-2 fish did not display this trend. Previous studies have shown that extended exposure to electric fields can have negative consequences on long-term health.

Ostrand et al. (2009) noted that white sturgeon (*Acipenser transmontanus,* Richardson 1836) exposed to acute levels of electroshock had high survival rates (100%), whereas individuals that experienced chronic levels of electroshock had lower survival (93%). The difference in growth rates between the year classes in our study may be related to the differing behaviours, with the age-2 fish having shown less tendency to react to the low-frequency electric fields and, therefore, making less effort to avoid them. Thus, our data suggest the threshold response to low-frequency electric fields may also be related to fish size. For example, Basov (1999) reported consistent responses in Sterlet and Russian sturgeon in the size ranges, respectively, of 182 and 162 cm and we found responses in the age-1 fish (20.22 cm), but not in the larger age-2 fish (29.64 cm). There is, however, evidence of species-related differences given the consistency of the response patterns observed by Basov (1999) not observed in our similarly sized age-1 fish.

We did find physiological effects associated with exposure to electricity with lake sturgeon. Interestingly, significant effects were measured in both blood lactate and blood glucose only in the low-frequency, low-voltage electric fields. Previous studies have explored the effects associated with exposure of fish to electricity and the potential for physiological impairment (Thompson et al., 1997; Roach, 1999; Dwyer et al., 2001; Cho et al., 2002; Schreer et al., 2004). For example, electro-shocked brown trout (*Salmo trutta,* Linneaus, 1758) and rainbow trout (*Oncorhynchus mykiss,* Walbaum 1792) exhibited significantly poorer condition and/or weights than unshocked controls (Thompson et al., 1997). Similarly, Gatz et al., (1986) noted reduced instantaneous growth rate of the same species exposed to electrofishing. Furthermore, exposure to electricity may have significant delayed effects on fish growth, as noted by Redman et al. (1998) who reported that electrically immobilized brown trout broodstock only experienced growth impairments at 6 months post-exposure.

Timing of sublethal effects, particularly in relation to important life history stages such a spawning migration, can significantly impact fish physiology (Pankhurst & Van Der Kraak, 1997; Contreras-Sánchez et al., 1998; Pankhurst & Van Der Kraak, 2000; Ostrand et al., 2004). Similar to the behaviour responses observed for low-frequency electric fields, our physiological results may also illustrate acclimation to the presence of electric fields. Physiological studies of fish exposed to electric fields have shown that fish display elevated levels of plasma lactate for up to 4 h after exposure (Ostrand et al., 2009). Thus the lack of statistical significance at the extra high levels of electric exposure may relate to a study design decision to minimize handling stress, with the result that fish were a minimum of 7 days between exposure to the low and extra high levels of electricity that allowed for a decline in blood physiology and acclimation to electric fields. While size considerations precluded the collection of blood samples from the smaller sized age-1 fish, data from the age-2 fish physiological tests indicate some short-term physiological costs (e.g. elevated blood glucose) resulting from low electric field levels that is consistent with the slower growth over long-term observed in the age-1 fish.

## Conclusion

Acclimatization to electric fields in lake sturgeon and the differences in body size responses have implications for the use of electric fields as a deterrent mechanism at hydro dams and other locales where entrainment may occur and, in turn, for the management of lake sturgeon. Our results show that individuals can acclimatize to low-voltage electric fields in a relatively short time period and that larger individuals tend to be less affected by low-frequency/low-voltage electric fields than smaller fish. This would suggest that low-voltage fields will not prove as effective deterrents to lake sturgeon. Additionally, as exposure to electricity causes weight loss by small lake sturgeon, low-voltage electric deterrents are unlikely to be favoured because of the negative physiological effects on smaller fish. As Seyler et al. (1996) have noted, a critical criterion in the selection of an effective barrier mechanism is that it must not have adverse environmental effects on the target species. Future studies would benefit from testing the effects of electric fields on lake sturgeon in a larger arena, such as a flume, and over longer periods of time. Furthermore, the use of flowing water within the flume would more accurately simulate the conditions present near dam facilities, where this diversion technique may be used. Flow volume and speed have the potential to influence the electric field and the associated behaviour of fish with respect to the level of electricity. As studies with white sturgeon (Ostrand et al., 2009) have shown, larger-scale experiments facilitate the appropriate measurement of avoidance behaviour, which is critical to limiting fatalities. Testing the utility of electric deterrents in a more realistic riverine setting using pulsating electric field, therefore, is highly recommended to ensure decisions regarding the implementation of electric barrier systems to reduce entrainment adequately account for possible sublethal effects on lake sturgeon.

**Acknowledgements** The authors would like to thank M. Alexander, S. Backhouse, C. Klassen and Y. Michaluk from Manitoba Hydro for the use of facilities and access to fish in addition for assistance in the completion of the experiment. Funding for the research was provided by NSERC Engage and Discovery Grants to MP, with supplementary funding and logistical support provided by Ontario Power Generation and Manitoba Hydro.

## References


Amaral, S., 2001. Evaluation of angled bar racks and louvers for guiding juvenile lake sturgeon (age 1). United States Fish and Wildlife Service, Green Bay Ecological Services Field Office, New Franken, WI.

Baker, E. A. & D. J. Borgeson, 1999. Lake sturgeon abundance and harvest in Black Lake, Michigan, 1975–1999. North American Journal of Fisheries Management 19: 1080–1088.

Barton, B. A., 2002. Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integrative Comparative Biology 42: 517–525.

Basov, B. M., 1999. Behavior of Sterlet *Acipenser ruthenus* and Russian Sturgeon *A. gueldenstaedtii* in low-frequency electric fields. Journal of Ichthyology 39: 782–787.

Basov, B. M., 2007. On electric fields of power lines and on their perception by freshwater fish. Journal of Ichthyology 47: 656–661.

Baxter, R., 1977. Environmental effects of dams and impoundments. Annual Review of Ecology, Evolution, and Systematics 8: 255–283.

Bibko, P. N., L. Wirtenan & P. E. Kueser, 1973. Preliminary studies on the effects of air bubbles and intense illumination on the swimming behavior of the striped bass (*Morone saxitalis*) and the gizzard shad (*Dorosoma cepedianum*). Entrainment and Intake Screening Workshop. Johns Hopkins University, Baltimore, Maryland: 293–304.

Billard, R. & G. Lecointre, 2001. Biology and conservation of sturgeon and paddlefish. Reviews in Fish Biology and Fisheries 10: 355–392.

Bouyoucos, I., P. Bushnell & R. Brill, 2013. Potential for electropositive metal to reduce the interactions of Atlantic sturgeon with fishing gear. Conservation Biology 28: 278–282.

Bracewell, P., I. G. Cowx & R. F. Uglow, 2004. Effects of handling and electrofishing on plasma glucose and whole blood lactate of *Leuciscus cephalus*. Journal of Fish Biology 64: 65–71.

Bruch, R. M., T. J. Haxton, R. Koenigs, A. Welsh & S. J. Kerr, 2016. Status of Lake Sturgeon (*Acipenser fulvescens* Rafinesque 1817) in North America. Journal of Applied Ichthyology 32: 162–190.

Bullen, C. R., & T. J. Carlson, 2003. Non-physical fish barrier systems: their development and potential applications to marine ranching. Reviews in Fish Biology and Fisheries 13: 201–212.

Burns, T. A. & K. Lantz, 1978. Physiological effects of electrofishing on largemouth bass. The Progressive Fish-Culturist 40: 148–150.

Čada, G. F., 2001. The development of advanced hydroelectric turbines to improve fish passage survival. Fisheries 26: 14–23.

Cho, G. K., J. W. Heath & D. D. Heath, 2002. Electroshocking influences Chinook salmon egg survival and juvenile physiology and immunology. Transactions of the American Fisheries Society 131: 224–233.

Contreras-Sánchez, W. M., C. B. Schreck, M. S. Fitzpatrick & C. B. Pereira, 1998. Effects of stress on the reproductive performance of rainbow trout (*Oncorhynchus mykiss*). Biology of Reproduction 58: 439–447.

COSEWIC 2006. COSEWIC assessment and update status report on the lake sturgeon *Acipenser fulvescens* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xi + 107 pp.

Davis. R.W., J.A. Matousek, M.J. Skelly, & M.R. Anderson, 1988. Biological evaluation of Brayton Point Station Unit 4 angled screen intake. In Proceedings: Fish Protection at Steam and Hydro-Electric power plants. EPRI/AP-5663. Electric Power Research Institute. Palo Alto, CA 3:23–42.

Dolan, C. R. & L. E. Miranda, 2003. Immobilization thresholds of electrofishing relative to fish size. Transactions of the American Fisheries Society 132: 969–976.

Dwyer, W. D., B. B. Shepard & R. G. White, 2001. Effect of backpack electroshock on westslope cutthroat trout injury and growth 110 and 250 Days posttreatment. North American Journal of Fisheries Management 21: 646–650.

Emery, L, 1984. The physiological effects of electrofishing. Cal-Neva Wildlife Transactions.

Enami, S., 1960. Studies on the bubble net. II. Experiments on some sea water fishes performed on the driving and intercepting effects. Bulletin of the Japanese Society for the Science of Fish 26: 269–272.

ESA Consulting 2002. Mattagami River Lake sturgeon mark recapture study. Study prepared for OPG.

Ferguson, M. M. & G. A. Duckworth, 1997. The status and distribution of lake sturgeon, *Acipenser fulvescens*, in the Canadian provinces of Manitoba, Ontario and Quebec: a genetic perspective. Environmental Biology of Fishes 48: 299–309.

Fore, P. L., 1969. Responses of freshwater fishes to artificial light. Ph.D. Thesis, Southern Illinois University, Carbondale IL.

Gatz Jr., A. J., J. M. Loar & G. F. Cada, 1986. Effects of repeated electroshocking on instantaneous growth of trout. North American Journal of Fisheries Management 6: 176–182.

Golder Associates Ltd. 2011. Recovery strategy for Lake Sturgeon (*Acipenser fulvescens*)—Northwestern Ontario, Great Lakes-Upper St. Lawrence River and Southern Hudson Bay-James Bay populations in Ontario. Ontario Recovery Strategy Series. Prepared for the Ontario Ministry of Natural Resources, Peterborough, Ontario.vii + 77 pp.

Gu, W. Y., M.-A. Justiz & H. Yao, 2002. Electrical conductivity of lumbar annulus fibrosis: effects of porosity and fixed charge density. SPINE 27: 2390–2395.

Gurgens, C., D. F. Russell & L. A. Wilkens, 2000. Electrosensory avoidance of metal obstacles by the paddlefish. Journal of Fish Biology 57: 277–290.

Hanson, B. N., W. H. Bason, B. E. Beitz, & K. E. Charles, 1977. A practical intake screen which substantially reduces the entrainment and impingement of early life stages of fish. In Fourth National Workshop on Entrainment and Impingement. Chicago, IL:393–407.

Harkness, W. J. K. & J. R. Dymond, 1961. The Lake Sturgeon. Ontario Department of Lands and Forests, Toronto.

Hatch Energy Consulting. 2012. ESA Consulting Mattagami River Lake Sturgeon mark re-capture study. Study prepared for OPG.

Haxton, T., G. Whelan & R. Bruch, 2014. Historical biomass and sustainable harvest of Great Lakes lake sturgeon (*Acipenser fulvescens* Rafinesque, 1817). Journal of Applied Ichthyology. 30: 1371–1378.

Haxton, T. J. & T. M. Cano, 2016. A global perspective of fragmentation on a declining taxon the sturgeon (*Acipenseriformes*). Endangered Species Research 31: 203–210.

Haymes, G. T. & P. H. Patrick, 1986. Exclusion of adult alewife, *Alosa pseudoharengus*, using low-frequency sound for application at water intakes. Canadian Journal of Fisheries and Aquatic Science 43: 855–862.

Hogan, T. W., G. F. Cada & S. V. Amaral, 2014. The status of environmentally enhanced hydropower turbines. Fisheries 39: 164–172.

Houston, J. J., 1987. Status of the lake sturgeon, *Acipenser fulvescens*, in Canada. Canadian Field Naturalist 101: 171–185.

Hutchison, J. B. & J. A. Matousek, 1988. Evaluation of a barrier net used to mitigate fish impingement at a Hudson River power plant intake. Science, Law and Hudson River Power Plants: A case study in environmental impact assessment. American Fisheries Society, Bethesda, Maryland: 280–285.

Jager, H. I., J. A. Chandler, K. B. Lepla & W. Van Winkle, 2001. A theoretical study of river fragmentation by dams and its effects on white sturgeon populations. Environmental Biology of Fishes 60: 347–361.

Jørgensen, J. M., Å. Flock & J. Z. Wersäll, 1972. The Lorenzinian ampullae of Polyodon *spathula*. Zeitschrift für Zellforschung 130: 362–377.

Katopodis, C., E. M. Koon & L. Hanson, 1994. Sea Lamprey Barriers: New Concepts and Research Needs. Great Lakes Fishery Commission (1994), Ann Arbor, MI.

Leprévost, A., T. Azais, M. Trichet & J.-Y. Sire, 2017. Vertebral development and ossification in the Siberian sturgeon (*Acipenser baerii*), with new insights on bone histology and ultrastructure of vertebral elements and scutes. The Anatomical Record 300: 437–449.

Levy, K. J., 1979. Pairwise comparisons associated with the K independent sample median test. American Statistician 33: 138–139.

Matousek, J. A., T. E. Pease, J. G. Holsapple & R. C. Roberts, 1988. Biological evaluation of angled-screen test facility. Journal of Hydraulic Engineering 114: 641–650.

McDougall, C. A., P. J. Blanchfield, S. J. Peake & W. G. Anderson, 2013. Movement patterns and size-class influence entrainment susceptibility of Lake Sturgeon in a small hydroelectric reservoir. Transactions of the American Fisheries Society 142(6): 1508–1521.

McKinley, S., G. Van Der Kraak & G. Power, 1998. Seasonal migrations and reproductive patterns in the lake sturgeon, *Acipenser fulvescens*, in the vicinity of hydroelectric stations in northern Ontario. Environmental Biology of Fishes 51: 245–256.

Miranda, L. E. & C. R. Dolan, 2004. Electrofishing power requirements in relation to duty cycle. North American Journal of Fisheries Management 24: 55–62.

Noatch, M. R. & C. D. Suski, 2012. Non-physical barriers to deter fish movements. Environmental Reviews 20: 71–82.

Ostrand, K. G., S. J. Cooke & D. H. Wahl, 2004. Effects of stress on largemouth bass reproduction. North American Journal of Fisheries Management 24: 1038–1045.

Ostrand, K. G., W. G. Simpson, C. D. Suski & A. J. Bryson, 2009. Behavioural and physiological response of White Sturgeon to an electrical Sea Lion barrier system. Marine and Coastal Fisheries 1: 363–377.

Pankhurst, N. W. & G. Van Der Kraak, 1997. Effects of stress on growth and reproduction. Fish Stress and Health in Aquaculture. Cambridge University Press, Cambridge: 73–93.

Pankhurst, N. W. & G. Van Der Kraak, 2000. Evidence that acute stress inhibits ovarian steroidogenesis in rainbow trout in vivo, through the action of cortisol. General and Comparative Endocrinology 117: 225–237.

Patrick, P.H., R. S. McKinley & W. C. Micheletti, 1988a. Field testing of behavioral barriers for cooling water intake structures—Test Site 1—Pickering Nuclear Generating Station. In Proceedings: fish protection at steam and hydroelectric power plants. EPRI/AP-5663. Electric Power Research Institute. Palo Alto, CA:4:13–25.

Patrick, P. H., R. S. McKinley, A. E. Christie & J. G. Holsapple. 1988b. Fish protection: sonic deterrents. In Proceedings: fish protection at steam and hydro-electric power plants. EPRI/AP-5663. Electric Power Research Institute. Palo Alto, CA:4: 1–2.

Pikitch, E. K., P. Doukakis, L. Lauck, P. Chakrabarty & D. L. Erickson, 2005. Status, trends and management of sturgeon and paddlefish fisheries. Fish and Fisheries 6: 233–265.

Redman, S. D., J. R. Meinertz & M. P. Gaikowski, 1998. Effects of immobilization by electricity and MS-222 on brown

trout broodstock and their progeny. The Progressive Fish-Culturist 60: 44–49.
Reynolds, J. B., 1996. Electrofishing. In Murphy, B. R. & D. W. Willis (eds), Fisheries Techniques, 2nd ed. American Fisheries Society, Bethesda, MD: 221–253.
Roach, S. M., 1999. Influence of electrofishing on the mortality of Arctic graylings eggs. North American Journal of Fisheries Management 19: 923–929.
Schreer, J. F., S. J. Cooke & K. B. Connors, 2004. Electrofishing-induced cardiac disturbance and injury in rainbow trout. Journal of Fish Biology 64: 996–1014.
Scott, W. B. & E. J. Crossman, 1998. Freshwater Fishes of Canada. Galt House Publications, Oakville.
Seyler, J., J. Evers, S. McKinley, R. R. Evans, G. Prevost, R. Carson & D. Phoenix, 1996. Mattagami River lake sturgeon entrainment: little long generating station facilities. Ontario Ministry of Natural Resources, Northeast Science & Technology, TR-031.
Sheehan, R. & R. S. McKinley, 1992. Mattagami River lake sturgeon mark-recapture population study, 1991. Report No 92-164-K. Ontario Hydro Research Division. 106 p.
Sopinka, N. M., M. R. Donaldson, C. M. O'Connor, C. D. Suski & S. J. Cooke, 2016. Stress indicators in fish, fish physiology. In Schreck, C. B., L. Tort, A. P. Farrell & C. J. Brauner (eds), Biology of Stress in Fish, Vol. 35. Academic Press, Amsterdam: 406–436.
Stober, Q. J., R. W. Tyler & C. E. Petrosky, 1983. Barrier net to reduce entrainment losses of adult kokanee from Banks Lake, Washington. North American Journal of Fisheries Management 11: 149–154.
Stoot, L. J., N. A. Cairns, F. Cull, J. J. Taylor, J. D. Jeffrey, F. Morin, J. W. Mandelman, T. D. Clark & S. J. Cooke, 2014. Use of portable blood physiology point-of-care devices for basic and applied research on vertebrates: a review. Conservation Physiology 2: 1–21.
Thiem, J. D., D. Hatin, P. Dumont, G. Van der Kraak & S. J. Cooke, 2013. Biology of lake sturgeon (*Acipenser fulvescens*) spawning below a dam on the Richelieu River, Quebec: behaviour, egg deposition, and endocrinology. Canadian Journal of Zoology 91: 175–186.
Thompson, K. G., E. P. Bergersen, R. B. Nehring & D. C. Bowden, 1997. Long-term effects of electrofishing on growth and body condition of brown trout and rainbow trout. North American Journal of Fisheries Management 17: 154–159.
Welsh, A. B. & D. T. McLeod, 2010. Detection of natural barriers to movement of lake sturgeon (*Acipenser fulvescens*) within Namakan River, Ontario. Canadian Journal of Zoology 88: 390–397.
Wickahm, D. A., 1973. Attracting and controlling coastal pelagic fish with nightlights. Transactions of the American Fisheries Society 102: 816–825.
Wilkens, L. A., D. F. Russel, X. Pei & C. Gurgens, 1997. The paddlefish rostrum functions as an electrosensory antenna in plankton feeding. Proceedings of the Royal Society of London B 264: 1723–1729.
Zar, J. H., 2010. Biostatistical Analysis, 5th ed. Pearson Prentice Hall, Upper Saddle River, NJ: 944.
Zhang, K., K. Shimoda, K. Ura, S. Adachi & Y. Takagi, 2012. Developmental structure of the vertebral column, fins, scutes and scales in bester sturgeon, a hybrid of beluga Huso huso and sterlet Acipenser ruthenus. Journal of Fish Biology 81: 1985–2004.
Zielinski, D. P. & P. W. Sorensen, 2015. Field test of a bubble curtain deterrent system for common carp. Fisheries Management and Ecology 22: 181–184.