SHOCKING RESULTS: ASSESSING THE INJURY RATES OF FISHES FROM PULSED-DC ELECTROFISHING

BY

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THESIS

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Abstract

Electrofishing is one of the most widely used methods to sample fishes in freshwater ecosystems. There was an early consensus that alternating current (AC) electrofishing was more injurious to fishes than direct current (DC) electrofishing, but this was based on a relatively small number of empirical investigations. Since the late 1980's, more than 45 studies have documented high injury rates of fishes from DC electrofishing. However, these studies are biased towards laboratory research on cool- and coldwater species and *in-situ* investigations of injury rates to warmwater fishes from DC electrofishing are critically underrepresented.

My study assessed injuries from pulsed-DC (PDC) boat electrofishing in seven fish species in the Upper Mississippi River System (UMRS). I examined five native species, Bluegill *Lepomis macrochirus*, Channel Catfish *Ictalurus punctatus*, Freshwater Drum *Aplodinotus grunniens*, Largemouth Bass *Micropterus salmoides*, Gizzard Shad *Dorosoma cepedianum*, and two invasive species, Common Carp *Cyprinus carpio* and Silver Carp *Hypophthalmichthys molitrix* that were captured in the Mississippi and Illinois rivers from June 15th to October 31st, 2013 for evidence of spinal injuries from PDC boat electrofishing. Fishes were collected by electrofishing crews conducting routine standardized sampling for two long-term monitoring programs. Of the species examined, Silver Carp and Channel Catfish were the only fishes that had injuries. Channel Catfish had a 26% rate of spinal injury and Silver Carp had an injury rate of over 62%. Injury rate for Silver Carp was significantly (χ_1^2=11.192; p<0.001) greater in the Illinois River (71%) compared with the Mississippi River (32%). Although Secchi disk transparency, dissolved oxygen concentration, and water temperature were similar between the two rivers, conductivity was higher on the Illinois River (725 ±21 µS/cm) than on the Mississippi River (422 ±30 µS/cm). Silver Carp between 500 - 549 mm had a greater injury rate than other length groups, whereas the length distribution of Channel Catfish did not differ between injured and uninjured fish. Injury rate did not vary with condition factor for either Channel Catfish or Silver Carp.

Reflex action mortality predictor (RAMP) scores have been effective at predicting the mortality of fishes after exposure to physical stressors such as capture with commercial fishing gear and handling. I tested whether RAMP scores could accurately predict spinal injuries from electrofishing for Channel Catfish. I found no significant relationship between any RAMP score and the presence of spinal injuries in Channel Catfish.

To test whether pulse frequency affects injury rates of Silver Carp, I conducted PDC electrofishing in a side channel of the Illinois River at two pulse frequency setting. Pulse frequency appears to have a significant ($\chi_1^2=8.076$; $p=0.005$) effect on injury rate. Injury rate of Silver Carp was 33.3% at a pulse frequency of 30 Hz and 70% at a pulse frequency to 120 Hz.

Collectively, these results demonstrate that Silver Carp and Channel Catfish in the UMRS are being injured from PDC electrofishing. Injury rate for Silver Carp varied with size class, conductivity, and power output, but additional investigation needs to be undertaken to establish cause and effect among these highly correlated variables. In contrast, injury rate of Channel Catfish did not vary with length, condition factor, electrofishing settings, or any environmental factor. My results suggest it may be possible to adjust pulse frequency and other electrofishing settings to increase rates of injury and mortality for invasive Silver Carp. Managers may want to further explore the potential of using electric fields as a management tool both for impeding the movements of Silver Carp and potentially reducing their populations as a control or eradication approach.

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Introduction

Electrofishing is a widely used method for sampling fishes in freshwater ecosystems (Hauck 1949; Maxfield et al. 1971; Snyder 2003). Electrofishing dates back to the late 19th century and is the production of electric fields in water to immobilize and capture fishes (Vibert 1967). The most common systems used to sample fishes include electrofishing boats, backpack electrofishing units, and electric seines (Reynolds 1996). Electrofishing boats are typically flat bottomed aluminum boats and are used to sample fishes in bodies of water that are too deep to be effectively sampled with backpack electrofishing units or electric seines. Backpack electrofishing units use hand-held electrodes, are more portable than boat electrofishing units, and are used primarily in wadeable streams. Electric seines are similar to backpack electrofishing units, but use a series of electrodes suspended from a floating line connected between two poles, powered by a shore-based or towed generator or battery. All three electrofishing systems use either a battery or generator to produce electricity and a variable control unit to deliver a specific current field to the electrodes (Reynolds 1996).

Electrofishing systems can use either alternating current (AC) or direct current (DC). Alternating current flows between two nodes that continually switch polarity (i.e., the anode and cathode alternate many times per second). Direct current flows between fixed anodes and cathodes (Vibert 1967; Reynolds 1996). Pulsed-DC (PDC) current alters the waveform of DC by varying the pulse frequency, pulse shape, and pulse duration. PDC is preferred by many managers and researchers because PDC increases the field strength by producing bursts of power that are effective at immobilizing fishes (Novotny 1990; Reynolds and Holliman 2000). Electrofishing is generally considered an effective method for sampling fishes that causes minimal injury and mortality to fishes stunned by the electric field (Horak and Klein 1967; Schill and Elle 2000). Nevertheless, some studies have demonstrated that exposure to electric fields produced by electrofishing units can injure fishes (Spencer 1967; Snyder 2003; Dolan and Miranda 2004).

As early as the 1940's, studies documented injuries in fishes from electrofishing (Hauck 1949; Spencer 1967; Sharber and Carothers 1988) including tissue hemorrhaging, spinal compressions and fractures, and mortality (Reynolds 1996; Snyder 2003). Early studies suggested that the type of electric current used can account for the frequency of mortality and injury, with AC causing more spinal injuries and mortality to fishes than DC electrofishing (Pratt 1955; Spencer 1967; Hudy 1985). For example, Spencer (1967) observed about 12% spinal injury rate in fishes using AC electrofishing and about 1% spinal injury rate when using DC electrofishing. Similarly, Pratt (1955) showed about 11% mortality rate for AC electrofishing compared to about 2% mortality from DC electrofishing. Examination of injury from PDC electrofishing reported that injuries to fishes often healed and did not cause mortality or growth impairment (Horak and Klein 1967; Maxfield et al. 1971; Lamarque 1990). Several studies have documented low injury (e.g., ≤ 1%) and mortality rates (e.g., ≤ 2%) to fishes from PDC electrofishing (McCrimmon and Bidgood 1965; Mitton and McDonald 1994; Beaumont et al. 2000); however, most of this research was focused on salmonids and may not be indicative of injury rates in non-salmonids.

Because of the perceived increased risk of fish injury and mortality associated with AC electrofishing, the use of PDC electrofishing increased through the second half of the 20th century (Cowx 1990). This shift to PDC electrofishing, however, was based on limited and surprisingly weak evidence (Sharber and Carothers 1988; Snyder 2003). As this supposition has been explored more deeply, evidence is mounting that injury rate to warmwater fishes from PDC electrofishing can be substantial. Several studies have documented injury rates as high as 90% and mortality rates as high as 60% for warmwater fishes exposed to PDC electrofishing in laboratory studies (Dolan et al. 2002; Henry and Grizzle 2003; Miranda and Kidwell 2010). Reynolds and Holliman (2004) also found a 60% injury rate to American Eel *Anguilla rostrata* captured with PDC electrofishing from the St. Lawrence River. With the exception of Reynolds and Holliman (2004), all of these studies on non-salmonid fishes were conducted in laboratory settings, demonstrating a critical need for further investigation of the effects of PDC boat electrofishing on fishes from studies conducted *in-situ*.

To further our understanding of injuries to fishes from electrofishing, I assessed injury rates for fishes collected with PDC boat electrofishing in the Mississippi and Illinois rivers. I accompanied electrofishing crews for The Long Term Resource Monitoring Program (LTRMP, a component of the US Army Corps of Engineers' Upper Mississippi River Restoration Program) and the Long-term Illinois, Mississippi, Wabash, and Ohio Rivers Fish Monitoring Program (LTEF, USFWS Sport Fish Restoration Program) and examined fishes for injuries. I tested whether Reflex action mortality predictor (RAMP) scores could provide me with an accurate method of predicting internal injuries by assessing fishes in a non-lethal manner. RAMP scores were developed to help researchers predict the mortality of fishes collected from commercial fishing (Davis 2005; Davis 2010). Davis (2007) found RAMP scores were effective at predicting the mortality of fishes after exposure to physical stressors, but no studies have tested whether RAMP scores can accurately predict injuries caused by electrofishing. Reynolds and Holliman (2000) suggested that the pulse frequency (Hz) used in PDC electrofishing was a critical to the injury rates sustained by fishes. Therefore, I conducted a manipulative study to examine the effect of pulse frequency on injury rate to Silver Carp *Hypopthalmichthys molitrix* to complement my observational assessments. The four specific objectives of my study were to: 1) assess injury rates from PDC electrofishing for seven fish species: Bluegill *Lepomis macrochirus*, Channel Catfish *Ictalurus punctatus*, Freshwater Drum *Aplodinotus grunniens*, Largemouth Bass *Micropterus salmoides*, Gizzard Shad *Dorosoma cepedianum*, Common Carp *Cyprinus carpio* and Silver Carp, 2) determine if these injury rates varied with environmental factors and electrofishing settings, 3) test whether RAMP scores accurately predict spinal injuries from electrofishing, and 4) assess the manipulation of pulse frequency settings used for PDC electrofishing that may change injury rates.

Background

My thesis research was derived as a result of logistical challenges I experienced attempting to study competitive interactions between invasive Silver Carp and native planktivores using *in-situ* mesocosms. Research has shown that Asian carp, including Silver Carp, may be negatively affecting native fishes in the Mississippi River System (Schrank et al. 2003; Irons et al. 2007; Sampson et al. 2009). To assess potential competitive interactions between Silver Carp and native planktivores, I constructed octagonal mesocosms (4.8 m^2 × 2-m deep) for *in situ* deployment in a backwater lake contiguous with Pool 26 of the Mississippi River. The nets were built to allow seston (phytoplankton, zooplankton, and other particulate organic matter) to flow freely into and out of the mesocosms. I collected fish for the mesocosm study using PDC boat electrofishing following protocols established by Gutreuter et al. (1995). Mortality rates of Silver Carp during preliminary trials of this study were high (50-83%) and necropsies revealed hemorrhaging along the spine in many of the Silver Carp mortalities.

After observing high mortality and injury rates to Silver Carp during the preliminary trials of the mesocosm study, I investigated the use of alternative electrofishing settings in an attempt to reduce injury and mortality of Silver Carp. Because alterations of pulse frequency and duty cycle have been suggested to reduce injury and stress to fishes (Lamarque 1967; Reynolds and Kolz 1995; Reynolds and Holliman 2000), I collected fishes using combinations of alternative pulse frequencies (15, 40, 60, 70, and 400Hz) and duty cycles (20, 30, 35, and 90%). Silver Carp collected using these alternative methods of electrofishing still exhibited high levels of mortality and hemorrhaging (averaging 50 and 54%, respectively). As a result of the observed high levels of Silver Carp injury and mortality from PDC boat electrofishing, I changed my thesis research to assessing injuries to fishes from PDC boat electrofishing. As an initial step in developing my study plan, I accompanied LTRMP and LTEF sampling crews in the autumn of 2012 and collected 48 Silver Carp from the Mississippi and Illinois rivers using standard LTRMP electrofishing settings. A high percentage of the Silver Carp I collected (56%) exhibited spinal injuries. Although there are many published studies on injuries to fishes from electrofishing, none of these studies have documented injuries to Silver Carp from electrofishing, though these injuries have been observed in the field by research biologists (D. Chapman, USGS Columbia Environmental Research Center, personal communication).

To identify gaps in our understanding of injuries to fishes from electrofishing, I conducted a comprehensive search for, and review of, peer-reviewed publications on this topic. I grouped these studies into several categories: type of current used (AC or DC), species examined, research setting (e.g., lab vs. field), and electrofishing method (e.g., boat, backpack, or simulated; Appendix A). I reviewed 47 peer-reviewed publications that assessed injury rates from electrofishing for 31 fish species.

Although a general consensus developed among researchers from the 1940s – 1980s that AC electrofishing is more harmful to fishes than DC electrofishing (Lamarque 1990; Snyder 2003), my review suggests that there are surprisingly few published studies that have examined injury rates to fishes using AC electrofishing (Table 1). Prior to the 1980's, I identified only four studies that assessed injury rates to fishes from electrofishing, and only one study that directly compared injury rates using AC and DC electrofishing in the field (Van Zee et al. 1994; Table 1). The first study to challenge the consensus that AC electrofishing was more injurious to fishes than DC electrofishing was Sharber and Carothers (1988) who documented high injury rates (>50%) in Rainbow Trout collected in the Colorado River using DC boat electrofishing. A sharp increase in the number of studies focusing on injury rates to fishes from electrofishing has occurred subsequent to the Sharber and Carothers (1988) publication (Table 1).

Although injury rates for 31 fish species has been documented, a relatively few species of interest have been disproportionately studied (Table 2). A majority of the 47 studies (68.1%) examined injuries in 11 species of cool- and coldwater fishes, which includes Rainbow Trout, Brown Trout *Salmo trutta*, and Walleye *Sander vitreus* (Conover 1986; Wydoski 1986). The number of studies that examined cool- and coldwater fishes is more than double the number of studies that addressed warmwater fishes and more than five times the number of studies that evaluated small-bodied fishes (Table 2). Of the 12 studies evaluating warmwater species (Smith and Reeves 1986), six focused on Largemouth Bass, six on Bluegill, and four on Channel Catfish. Six studies assessed injury rates of small-bodied fishes (e.g., chubs, darters, and shiners), evaluating injuries in nine fish species.

As with the distribution of studies over taxonomic groups, the distribution of peer-reviewed studies across the different research settings also suggested a research bias. The majority of studies (59.6%) were conducted in laboratories and hatchery raceways, where conditions could be controlled and fish closely monitored during experiments. Many laboratory studies used simulated electrofishing with aluminum plate electrodes used rather than electrodes typically used for backpack or boat electrofishing units. Twenty-one studies (44.7%) were conducted in the field using either backpack or boat electrofishing units, of which 11 were conducted in wadeable streams using backpack electrofishing, eight studies used boat electrofishing in non-wadeable rivers, and two studies used boat electrofishing in lentic systems. The surprisingly few published studies conducted in lakes and ponds is consistent with the observation that a majority of studies focused on cool- and coldwater species that are more commonly found in lotic systems.

Although I focused my review on studies evaluating spinal injuries, there is a large body of literature that has documented other negative effects of electrofishing on fishes. Studies have suggested that fish experience short-term interruptions to normal cardiac activity (Taylor et al. 1957; Schreck et al. 1976). Fishes in these studies typically experienced mild cardiac episodes following the initial application of electricity to the water; however, in most cases heart rate quickly returned to normal (<5 minutes) after electrofishing ceased. Other studies have documented a significant increase in mortality of eggs and early life stages when exposed to electrofishing (Marriott 1973; Dwyer et al. 1993; Roach 1996). Additional studies assessed mortality rates of fishes, but did not test for injuries (Whaley et al. 1978; Eloranta and Cowx 1990; Henry et al. 2003).

Because of the wide array of electrofishing methods, experimental settings, and environmental factors, assessments of injury and mortality rates vary greatly, ranging from no injuries reported to 100% (Schneider 1992; Snyder 2003; Henry et al. 2004). Some experiments with the voltage gradient used for electrofishing suggested that increased voltages corresponds with increased injury rates (Roach 1992; Henry et al. 2004). In contrast, other investigations have reported no significant relationship between injury rate and voltage field intensity (Walker et al. 1994). Additionally, many publications have suggested that as fish size increases, they become more sensitive to electric fields; however, in reviewing the literature, I found no general agreement or discernable pattern between researchers as to whether smaller fishes or larger fishes are more susceptible to injury (Collins et al. 1954; Bardygula-Nonn et al. 1995; Habera et al. 1996). Finally, increased susceptibility to electrofishing injury has been suggested through casual observations for fish in poor condition (Snyder 2003), but there have been no published studies assessing condition and its relationship with injury rate.

Of all of the studies that have documented negative responses of fishes to electrofishing, only four studies assessed the injury rates of warmwater species *in-situ* using PDC boat electrofishing. Further, only two of these studies (Cowdell and Valdez 1994; Reynolds and Holliman 2004) were conducted on non-wadeable rivers, and no published study of injury from DC electrofishing has been conducted on the UMRS. My preliminary research with Silver Carp suggests that there may be significant injuries to fishes caused by PDC boat electrofishing. Because PDC boat electrofishing is used widely by agencies, NGOs and academic researchers throughout the world, it is critically important to test whether other fishes are experiencing similar injury rates as those I observed for Silver Carp. Additionally, all of the studies that I reviewed have been conducted with the goal of reducing injury rates to fishes. In contrast, if my initial observations of high injury rates to invasive Silver Carp prove accurate, management agencies may want to consider the use of electrofishing as a tool to reduce populations of this invasive species if such a use does not greatly impact native species.

Methods

Study Site

My study area included the Mississippi River from its confluence with the Kaskaskia River (Mississippi River km [MRKM] 188) upstream to Lock and Dam 24 (MRKM 440), and the Alton and LaGrange reaches of the Illinois River located between its confluence with the Mississippi River (Illinois River km [IRKM] 0) and Peoria Lock and Dam (IRKM 254) (Figure 1). These reaches were selected because they are monitored by the LTRMP and LTEF programs.

Data Collection

The fish species examined for injuries were chosen based on several criteria. First, I wanted to examine species from common families found in the Mississippi and Illinois rivers, including cyprinids, clupeids, and centrarchids. Second, I wanted to examine injury rate on important sport fishes found within these rivers. Finally, I wanted to target species that previous monitoring data suggested would be captured by electrofishing in sufficient numbers to accurately assess injury rate ($n \geq 50$ for each species). To accomplish these goals, I selected Bluegill, Channel Catfish, Freshwater Drum, and Largemouth Bass because they are popular sport fishes and Gizzard Shad because they are the main forage species for piscivores in the Mississippi and Illinois rivers. I also selected Common Carp and Silver Carp because they are two invasive cyprinids that are altering habitat in the Mississippi and Illinois rivers and may negatively affect native fishes.

Fishes were collected by PDC boat electrofishing from June 15 - October 31, 2013 in the main channel, side channels, and backwater lakes using LTEF and LTRMP electrofishing sampling methods established by Gutreuter et al. (1995). No fish that jumped into the boat were used for injury assessment. Electrofishing boats were 5.5-6.1 m long and equipped with two forward-mounted booms ending in “Wisconsin-ring” anodes with four droppers attached. Electricity was regulated by a MBS-1D “Wisconsin” style control box (ETS Electrofishing, LLC of Verona, Wisconsin). Pulse frequency was set at 60 Hz and duty cycle was set at 25%, and electrofishing runs consisted of 15 minutes of shocking time, covering an area about 200 m long and 30 m wide. At each site, water temperature (°C), dissolved oxygen (mg/L), and specific conductivity (µS/cm) were collected using a YSI® Model 85 meter (Yellow Springs Instruments, Yellow Springs, Ohio) taken 20 cm below the surface and water velocity was measured using a Marsh-McBirney Flo-Mate^{TM} flow meter.

After fishes were collected, I measured total length to nearest mm, total weight to the nearest g, and recorded scores for five binary RAMP tests. Fishes were restrained by hand against the measuring board to test for active resistance against restraint (RAMP score 1). Fishes were then held with the caudal fin unrestricted to test for active movement of the caudal fin (RAMP score 2). Operculum were manually opened and gills were observed for the presence of blood (RAMP score 3). Operculum were then released and observed for active closure of operculum (RAMP score 4). Fishes were then visually inspected for external hemorrhaging, often referred to as branding (RAMP score 5). Length, weight, and RAMP scores were recorded for each fish, and then were tagged along the dorsal fin with a uniquely numbered tag for individual identification. Recording RAMP scores for Silver Carp proved to be logistically unfeasible due to the relatively large numbers of individuals collected and their difficulty in handling, which added excessive time and effort to routine LTRMP and LTEF sampling. After tagging each fish with a unique identification number, fishes were euthanized using tricaine methanesulfonate (MS-222, 400mg/L). All fishes were kept on ice until the following day when necropsies were performed in the laboratory.

I used tissue hemorrhaging around the spine, quantified through necropsy, as the indicator of spinal injury. Necropsies consisted of filleting the length of the body laterally behind the pectoral fins to the caudal peduncle, and examining the tissue around the vertebral column for hemorrhaging. In previous studies that assessed both the rates of hemorrhaging with necropsy and spinal injuries with radiography, injury rates determined through necropsy and radiography were generally similar (Dolan et al. 2002; Dolan and Miranda 2004; Clement and Cunjak 2010; Holliman et al. 2010). Digital photographs (lateral view) of each necropsied fish were taken for reference.

Statistical Analyses

I estimated the percentage of fish injured for each species and tested whether injury rate was related to the electrofishing settings used, environmental conditions, and the length and condition of the fishes. Evaluating which physical and chemical factors may have influenced injury rate proved difficult because the various environmental measures were highly correlated with one another (Table 3). Furthermore, electrofishing voltage and amperage is adjusted according to water temperature and conductivity to standardize the power delivered to fishes (Burkhardt and Gutreuter 1995). Therefore, any pattern between one environmental factor or electrofishing setting with injury rate will likely be reflected for other environmental factors and/or electrofishing settings. As a result, I limited the factors evaluated to water conductivity, power output, and voltage, because they had the fewest significant correlations with other factors and previous research has suggested they likely influence injury rate (Collins et al. 1954; Hill and Willis 1994; Snyder 2003; Table 3). Logistic regression was used to test whether injury rate varied with water conductivity, power output, and voltage. I tested whether injury rate varied with length distribution and with K factor distribution ($K = \frac{W}{L^3}$; D'arcy 1917) using a χ^2 Test for Equality of Proportions. I also tested for differences in mean length and mean K factor between injured and uninjured fishes using ANOVA, and used a χ^2 Test for Equality of Proportions to test whether RAMP scores were accurate indicators of internal injury. All statistical analyses were performed using SAS 9.2 for Windows (SAS Institute 2008). I used $\alpha = 0.05$ to determine statistical significance.

Alternate Duty Cycle Study

I tested for the effect of pulse frequency on Silver Carp injury rate in the LaGrange Reach of the Illinois River on September 23, 2013. Electrofishing was conducted in a side channel of the Illinois River near Bath, Illinois. Thirty fish were collected at two alternative pulse frequency settings: 30Hz (half the pulse frequency used in LTRMP and LTEF) and 120Hz (twice the pulse frequency used in LTRMP and LTEF). Electrofishing and fish handling methods were identical to LTRMP settings except for the pulse frequency. Based on previous research, I would hypothesize that a reduction in the pulse frequency would result in a decrease in Silver Carp injury rate and I tested this against the null hypothesis that injury rate would not differ between the two pulse frequencies. I used a χ^2 test for Equality of Proportions to test whether injury rates differed for the different pulse frequencies. I used $\alpha = 0.05$ to determine statistical significance.

Results

Injury Assessment

Of the seven species collected (n=348), only Silver Carp and Channel Catfish exhibited injuries (Table 4). The number of Largemouth Bass collected (n=six) was insufficient to make inferences about injury rates, and were excluded from the analysis and discussion. Inferences for Bluegill (n=21) were less strong relative to other species due to low sample size. I detected no injuries for Common Carp (n=39), Freshwater Drum (n=51), Bluegill (n=21), or Gizzard Shad (n=52; Table 4). Injury rate for Channel Catfish (n=22 of 78) was >26%, and injury rate for Silver Carp (n=62 of 101) was >62% (Table 4).

Silver Carp injury rate differed significantly between the Mississippi and Illinois rivers, but Channel Catfish injury rate did not. Channel Catfish injury rate was 28% in the Mississippi River and 25% in the Illinois River, but this difference was not statistically significant (χ_1^2- =0.102; p=0.749; Figure 2A). Silver Carp injury rate differed significantly ($\chi_1^2=11.192$; $p<0.001$) between the Mississippi and Illinois rivers, with injury rate for the Illinois River (71%) more than double that in the Mississippi River (32%; Figure 2B).

Major differences in physical and chemical factors between the Mississippi and Illinois rivers were observed (Table 5), but fish length and condition were similar (Figure 3). The difference in conductivity between the two rivers was especially pronounced. I found no difference in mean length ($F_{1,76}=1.820$; $R^2=0.02$; p=0.181; Figure 3A) or condition ($F_{1,76}=2.060$; $R^2=0.03$; p=0.155; Figure 3B) for Channel Catfish and no difference in mean length ($F_{1,99}=0.060$; $R^2<0.01$; p=0.812; Figure 3C) or condition ($F_{1,99}=3.640$; $R^2=0.04$; p=0.059; Figure 3D) for Silver Carp between the two rivers.

Environmental Factors and Electrofishing Settings

I found differences between the length distribution of injured and uninjured Silver Carp but Channel Catfish length distribution was similar for injured and uninjured fish, and neither Silver Carp nor Channel Catfish condition differed between injured and uninjured fish. The distribution of Channel Catfish among length groups did not differ significantly (χ_2^2=2.139; p=0.710) for injured and uninjured fish, with the number of injured and uninjured fish greatest in the 350-399 and 400-449 mm groups (Figure 4A). Similarly, the distribution of Channel Catfish among K factor groups did not differ significantly (χ_2^2=2.149; p=0.341) between injured and uninjured fish, with most channel catfish in the 0.96-1.25 group (Figure 4B). The distribution of Silver Carp among length groups varied significantly (χ_3^2=11.607; p=0.009) between injured and uninjured fish: Silver Carp without injuries were equally distributed amongst length groups, whereas 500-549 mm group had the greatest number of injured Silver Carp. The 600+ mm group had the fewest (Figure 5A). The distribution of Silver Carp with K factor groups did not significantly (χ_2^2=0.018; p=0.991) between injured and uninjured Silver Carp (Figure 5B).

Mean lengths of injured and uninjured fish did not differ significantly for Channel Catfish ($F_{1,76}$=0.970; R^2=0.01; p=0.328) or Silver Carp ($F_{1,99}$=3.633; R^2=0.04; p=0.060; Figures 6A and C, respectively). The mean length of uninjured Silver Carp was higher than the mean length for injured Silver Carp, however the difference in mean length for injured and uninjured Silver Carp was small (20.8 mm; Figure 6C). Mean condition factor did not differ significantly between injured and uninjured Channel Catfish ($F_{1,76}$=0.110; R^2<0.01; p=0.739) or Silver Carp ($F_{1,99}$=0.090; R^2<0.01; p=0.766; Figures 6B and D, respectively).

Silver Carp injury rate varied with power output and conductivity but not with voltage, whereas Channel Catfish injury rate did not vary with any of these three factors. Channel

Catfish injury rates did not vary significantly with power output (χ_1^2=0.459; p=0.498), conductivity (χ_1^2=0.277; p=0.599), or voltage (χ_1^2=2.453; p=0.117; Figure 7). Silver Carp injury rate increased significantly with power output (χ_1^2=7.876; p=0.005) and conductivity (χ_1^2=5.110; p=0.024), but did not vary significantly (χ_1^2=1.736; p=0.188) with voltage (Figure 8).

RAMP Scores

None of the RAMP scores accurately predicted internal injury for Channel Catfish (Table 6). For the three movement indicators, I found no significant relationship between injury status and activity during handling (χ_1^2=0.348; p=0.555), caudal fin movement (χ_1^2=0.312; p=0.860), or operculum control (χ_1^2=0.454; p=0.501). The two external injury indicators, bleeding from the gills (χ_1^2=0.454; p=0.501) and branding (χ_1^2=2.515, p=0.113), also did not vary with injury status.

Pulse Frequency

Adjusting pulse frequency had a substantial effect on the injury rate of Silver Carp. Injury rate for the two pulse rates were significantly different (χ_1^2=8.076; p=0.005), with injury rate greatest (70%) at a pulse rate of 120 Hz, and lowest (33.3%) at a pulse rate of 30 Hz (Table 7).

Discussion

Since the late 1980's, many studies have documented high injury rates of fishes from DC electrofishing (Sharber and Carothers 1988; Lamarque 1990; Snyder 2003). This contrasts with the earlier consensus that DC electrofishing caused fewer injuries to fishes than AC electrofishing (Hauck 1949; Spencer 1967; Lamarque 1990; Snyder 2003). I did not detect injuries in Bluegill, Common Carp, Freshwater Drum, or Gizzard Shad; however, the injury rates I observed for Channel Catfish (26.9%) and Silver Carp (62.4%) are consistent with the growing body of literature documenting high levels of injury sustained by fishes from DC electrofishing (Sharber and Carothers 1988; Habera et al. 1999; Miranda and Kidwell 2010). To my knowledge there are no published injury rates for Common Carp, Freshwater Drum, Gizzard Shad, and Silver Carp. Past research has documented injury in Bluegill using DC electrofishing (Henry and Grizzle 2003; Dolan and Miranda 2004; Miranda 2005); however the number of Bluegill I examined (n=21) may not have been great enough to detect the low injury rates (e.g., ≤ 5%) observed in previous studies.

Necropsies to quantify hemorrhaging and radiography to quantify spinal fractures and compressions are used to assess injury to fishes from electrofishing. Several studies using these methods have reported similar rates for hemorrhaging determined from necropsy and spinal injuries determined from radiography (Van Zee et al. 1994; Dolan and Miranda 2004; Miranda 2005). I compared hemorrhaging rates from necropsy with injury rates from radiography from several published studies to assess how well the presence of hemorrhages reflects the presence of spinal fractures and compressions. With the exception of one outlier (Walsh et al. 2004), there was a strong relationship between hemorrhaging rates with spinal injury rates assessed through radiography (R^2=0.93; Figure 9). Therefore, my estimates of spinal injury rates based on hemorrhaging are unlikely to be compromised by not performing radiography. Regardless of how injuries were reported, it must be noted that some studies have documented pre-occurring vertebral column abnormalities and spinal injuries in fishes that had not been exposed to electrofishing. These pre-existing vertebral abnormalities cannot be reliably distinguished from electrofishing injuries (Gabriel 1944; Gill and Fisk 1966; Fredenberg 1992). Because my assessment of spinal injuries relied exclusively on the presence of hemorrhages, it is less likely that the injuries I observed originated from genetic abnormalities or old injuries from sources other than electrofishing.

The morphology of fishes may influence both their susceptibility to electrofishing and vulnerability to injury from electrofishing. For example, the lateral-line system of catfishes includes electroreceptors that have been reported to make catfishes more sensitive to capture and tetany, a seizure-like response to electricity also thought to cause spinal injuries (Peters and Buwalda 1972; Kramer 1990; Reynolds and Holliman 2000). These specialized electroreceptors are not found in the other species I examined. Vulnerability to electric shock has been suggested to be greater for bony fishes relative to cartilaginous fishes and for fishes with an elongated (fusiform) body shape (Zalewski and Cowx 1990; Reynolds 1996). Certain skeletal traits of Silver Carp (i.e. relative thickness and high number of vertebrae in their spine) may affect their susceptibility to injury from electrofishing (J. Reynolds, Professor Emeritus, University of Alaska-Fairbanks, personal communication); however, there has been no previous research conducted on Silver Carp vulnerability to injury from electrofishing. Of the fish I collected Freshwater Drum, Common Carp, Channel Catfish, and Silver Carp are fusiform in shape. The vertebral counts for Channel Catfish (42-44) and Silver Carp (39-40) are greater than Freshwater Drum (25-33) and Common Carp (35-36; Scott and Crossman 1973; Howes 1981). Gizzard

Shad and Bluegill are laterally compressed and deep-bodied fishes, and this body shape is thought to be less susceptible to electrofishing induced injury relative to elongated body forms (Zalewski and Cowx 1990; Reynolds 1996).

My study is one of the few to compare *in-situ* injury rates from electrofishing between different systems. Hollender and Carline (1994) reported that Brook Trout *Salvelinus fontinalis* injury rates varied among Pennsylvania streams. I found that Silver Carp injury rate in the Illinois River was more than double the injury rate observed on the Mississippi River, but Channel Catfish injury rate between the Mississippi (28%) and Illinois (25%) rivers was nearly identical. Several environmental variables and electrofishing power settings were different between the two rivers, but the environmental variable most likely to affect electrofishing was conductivity (Kolz 1989; Kolz and Reynolds 1989; Hill and Willis 1994; Burkhardt and Gutreuter 1995), which was significantly greater on the Illinois River (725 ±21 µS/cm) than on the Mississippi River (422 ±30 µS/cm). Electrofishing settings for the LTRMP and LTEF are adjusted for conductivity and water temperature to standardize the power delivered to fishes (Kolz 1989; Burkhardt and Gutreuter 1995; Gutreuter et al. 1995). As a result, the amperage and the total power output used on the Illinois River were also much higher than for the Mississippi River.

My results suggest that the LTRMP and LTEF adjustments to electrofishing settings for water temperature and conductivity (Burkhardt and Gutreuter 1995; Gutreuter et al. 1995) may not be yielding power output to fish as consistently as expected for Silver Carp. This may be a result of the electrofishing adjustments being predicated on the assumption that the effective conductivity of the fish themselves is constant. The conductivity of fishes is known to differ among species, size, and with environmental variables, so differences in conductivity between the Illinois and Mississippi rivers might lead to a differences in the conductivity of fishes between these systems (Haskell 1954; Monan and Engstrom 1963; Sternin et al. 1976). The ability of Silver Carp to filter seston and very small particles from water could increase the likelihood that their conductivity varies with water conductivity because they are more likely to uptake minerals and ions from seston as well as dissolved ions in the water column (Hem 2012).

My study suggests that Silver Carp between 500-549 mm in length may be more susceptible to electrofishing injury than other size classes. Previous studies have suggested size thresholds for injury from electrofishing in other fish species, but there is no general agreement between researchers as to whether smaller or larger sized fish are more susceptible (Collins et al. 1954; Bardygula-Nonn et al. 1995; Habera et al. 1996; Reynolds and Holliman 2000). My findings that condition of fish does not appear to influence injury rate is not consistent with the idea that fish in poor condition are more likely to be injured (Snyder 2003). To my knowledge there are no published studies assessing condition and its relationship with injury rate from electrofishing.

Researchers have been attempting to find a non-lethal field assessment technique that accurately predicts injury and/or mortality of fishes from capture and holding methods. The use of RAMP scores was initially developed to help researchers predict the mortality of fishes collected from commercial fishing (Davis 2005; Davis 2010). Past research assessing the effectiveness of RAMP scores found that they were effective at predicting the mortality of fishes up to 20 days after they had been exposed to physical stressors (Davis 2007). I found no significant relationship between any RAMP scores and spinal injuries of Channel Catfish caused by electrofishing. Some of the external reflex impairment indicators that I tested have been observed in fishes exposed to electrofishing. External hemorrhages or branding, and bleeding from the gills, are injuries in and of themselves (Barham et al. 1989; Walker et al. 1994); however, I found no evidence that they can predict spinal injuries. The lack of positive response RAMP scores (i.e. few fish bleeding from the gills, few fish exhibiting branding) in my study suggests that none of the scores were effective for the Channel Catfish, but there may be other external stress indicators that could predict internal injuries on other species where the external indicators are more effective.

Along with power output, pulse frequency appears to be a key factor influencing fish injury rates from PDC boat electrofishing. Injury rates for the lower pulse frequency I tested (30 Hz) were significantly lower than the higher pulse frequency setting (120 Hz), a finding consistent with several studies reporting a negative relationship between injury rate and pulse frequency (Collins et al. 1954; Lamarque 1967; Reynolds and Holliman 2000). The standard LTRMP pulse frequency is 60 Hz, and doubling this frequency (120 Hz) resulted in an injury rate for Silver Carp that was only slightly greater (70%) than the overall mean from my study (62%). This suggests that there may be an upper limit to how much injury rate can be increased through pulse frequency adjustments. Electric barriers are used in the Chicago Sanitary and Ship Canal to prevent the movement of Silver Carp from the Illinois River to Lake Michigan (Moy et al. 2011; Olson and Chick 2013). The barriers use PDC electricity and currently operate at 2.3 volts/inch and a pulse frequency of 30 Hz. My results suggest that it may be possible to adjust pulse frequency and other settings to increase rates of injury and mortality for Silver Carp encountering these barriers. Managers may want to further explore the potential of using electric fields for both impeding the movements of Silver Carp and potentially reducing their populations.

Conclusion

My research demonstrates that fishes in the Upper Mississippi River System are being injured from PDC boat electrofishing. The results of my study are consistent with a growing body of literature that shows DC electrofishing is injuring several species of fish at high rates, and provides further evidence that the assumption that DC electrofishing rarely injures fishes is false. However, even with the recent sharp increase in research demonstrating that DC electrofishing causes high levels of injury to several fishes, many biologists still consider DC electrofishing the safest form of electrofishing. A reevaluation of the notion that AC electrofishing is more injurious to fishes than DC electrofishing is needed. There are relatively few studies that have examined AC electrofishing and assessed its effects on fishes and minor adjustments to AC electrofishing might be found that reduce injuries to fishes. The use of electrofishing as a sampling method in many monitoring and research programs is done under the assumption that fishes are not being adversely affected. Therefore, a better knowledge of what species are being injured, what their injury and mortality rates are, and whether morphology of fishes can influence their susceptibility to electrofishing is critically needed.

My results also suggest that injury rates to fishes from electrofishing may differ among ecosystems and/or habitats. The differences I observed in injury rate between the Mississippi and Illinois rivers likely arose from a combination of multiple environmental variables, fish morphology, the conductivity of the fish themselves, and electrofishing settings. When developing future monitoring programs, I recommend that a more comprehensive understanding of the differences between systems is needed. Because environmental factors can vary substantially both within and between systems, it is also important for researchers to determine whether catchability of electrofishing and injury rates of fishes are affected. Further, our understanding of how electrofishing catchability and its effects on fishes vary among different ecosystems and habitats. Until we understand this, our ability to compare across and within systems may be compromised.

One of the many electrofishing settings that can be adjusted is the pulse frequency and it is important to understand how pulse frequency influences fish injuries. My research suggests that Silver Carp injury rate is positively correlated with pulse frequency. However, I observed asymptotic behavior of the injury rate between pulse frequencies of 60 Hz and 120 Hz. There may be a threshold at which Silver Carp injury rate does not continue to increase with pulse frequency. With further research, it may be possible to find a pulse frequency setting that maximizes Silver Carp injuries, while minimizing native fish injuries.

Even with the increase in studies assessing injury rates to fishes using electrofishing, there is still much to learn about electrofishing and its potential effects on fishes. Of all of the peer-reviewed publications I reviewed, only 31 species of fish have been studied worldwide, with only a handful of species examined in more than one study. For perspective, the LTRMP sampling that is conducted on Pool 26, a 56 km reach of the Mississippi River, routinely captures more than 60 fish species each year. Given the vast numbers of fish species that exist, it is imperative that predictive relationships are identified between injury rates and environmental variables, morphological traits, and electrofishing settings that would allow us to predict the species most likely to be injured from electrofishing. Developing these relationships would prevent researchers from needing to assess injury rates for every species and every size class of fish from the multiple ecosystems types that are sampled via electrofishing.

Tables

Table 1. Temporal distribution of the 47 studies published in peer-reviewed journals assessing injury rate to fishes from electrofishing and the type of current used.

Time Period	Alternating Current	Direct Current	Both	Total
1940s-1970s	1	2	1	4
1980s	1	1	0	2
1990s	3	15	1	19
2000’s-present	3	19	0	22

Table 2. The number and percentages of 47 peer-reviewed publications that assessed the injury rates of fishes from electrofishing among several categories: the type of current used (AC = alternating current, DC = direct current); species examined; the research setting (e.g., lab vs. field); and electrofishing method (e.g., backpack, boat, or simulated). Studies were published between 1940 and 2013 (Appendix A). Values from this table are non-additive.

Category		Total	Percentage
Electrofishing Current	AC	10	21.3%
	DC	40	85.1%
Fishes	Cool and Coldwater	32	68.1%
	Rainbow Trout	21	44.7%
	Brown Trout	6	12.8%
	Brook Trout	4	8.5%
	Other	11	23.4%
	Warmwater	13	27.7%
	Largemouth Bass	6	12.8%
	Bluegill	6	12.8%
	Channel Catfish	4	8.5%
	Other	9	19.2%
	Small-bodied	6	12.8%
Research Setting	Laboratory	28	59.6%
	Field	21	44.7%
	Wadeable Stream	11	23.4%
	Non-wadeable River	8	17.0%
	Lentic	2	4.3%
Electrofishing Method	Backpack	12	25.5%
	Boat	10	21.3%
	Simulated	25	53.2%

Table 3. Correlations between physical and chemical characteristics from sites on the Illinois and Mississippi rivers. Data were collected during June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program. Data to the right of dashed lines (i.e., upper diagonal) are p-values with statistically significant correlations ($P \leq 0.05$) bolded, and data to the left of dashed lines (i.e., lower diagonal) are Pearson's Correlation Coefficients (r).

	Power Used	Volts	Amps	Depth	Secchi	Conductivity	DO	Water Temp	Water Vel
Power Used	-----	0.987	**<0.001**	0.061	0.933	**<0.001**	0.334	**0.015**	0.053
Volts	-0.002	-----	**0.001**	0.725	0.940	0.204	**0.018**	0.788	0.358
Amps	0.898	-0.434	-----	**0.047**	0.951	**<0.001**	0.985	**0.012**	0.169
Depth	-0.262	0.050	-0.277	-----	0.108	0.102	0.701	0.961	**0.014**
Secchi	0.012	0.010	-0.009	0.226	-----	0.753	**<0.001**	0.085	0.410
Conductivity	0.935	-0.181	0.933	-0.236	-0.045	-----	0.999	0.109	0.216
DO	0.139	0.333	0.003	0.057	0.551	<-0.001	-----	**0.033**	0.141
Water Temp	0.340	-0.039	0.349	0.007	0.244	0.227	0.302	-----	0.859
Water Vel	-0.265	-0.128	-0.190	0.338	-0.115	-0.176	-0.211	-0.026	-----

Table 4. The number of injured and uninjured fishes from seven species collected using PDC electrofishing from the Mississippi and Illinois rivers. Data were collected during June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

Species	Total Captured	Uninjured	Injured	Injury Rate
Bluegill	21	21	0	0.0%
Common Carp	39	39	0	0.0%
Channel Catfish	78	57	21	26.9%
Freshwater Drum	52	52	0	0.0%
Gizzard Shad	51	51	0	0.0%
Largemouth Bass	6	6	0	0.0%
Silver Carp	101	38	63	62.4%
Total	**348**	**264**	**84**	**24.1%**

Table 5. Differences in physical and chemical characteristics of sampling sites and different habitat types of the Mississippi and Illinois rivers. Data were collected from June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

	Mississippi	Illinois
Depth (m)	2.2 (±0.2)	1.5 (±0.2)
Secchi (cm)	24 (±2)	23 (±1)
Conductivity (µS/cm)	422 (±30)	725 (±21)
Dissolved Oxygen (mg/L)	5.7 (±0.5)	6.8 (±1.0)
Water Temperature (°C)	24.3 (±1.6)	25.5 (±1.5)
Water Velocity (m/s^3)	0.45 (±0.06)	0.24 (±0.03)
Power Output (W)	4205 (±93)	5434 (±129)
Voltage (V)	211 (±5)	198 (±2)
Amperage (A)	20 (±1)	28 (±1)

Table 6. Results of the 5 RAMP tests given to Channel Catfish *Ictalurus punctatus* collected from the Mississippi and Illinois rivers. Fish were collected from June 15 – October 31, 2013 by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program. RAMP score is a binary qualitative assignment. Assignment of injury vs. uninjured was based upon necropsy.

RAMP	Category	Score	Uninjured	Injured
1	Activity During Handling	Y	35.1%	26.7%
		N	64.9%	73.3%
2	Caudal Fin Movement	Y	91.9%	93.3%
		N	8.1%	6.7%
3	Operculum Control	Y	97.3%	93.3%
		N	2.7%	6.7%
4	Bleeding from Gills	Y	2.7%	6.7%
		N	97.3%	93.3%
5	Branding	Y	0.0%	6.7%
		N	100.0%	93.3%

Table 7. Total and percentage of injured and uninjured Silver Carp *Hypopthalmichthys molitrix* collected using two different pulse frequencies (30 Hz and 120 Hz) in the LaGrange Reach of the Illinois River. Fish were collected with PDC boat electrofishing in a side channel of the Illinois River. For comparison, the overall injury rate of Silver Carp collected at a pulse frequency of 60 Hz by crews for the Long Term Resource Monitoring Program (LTRMP) and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program (LTEF) is also presented.

Pulse Frequency	Total	Uninjured	Injured	Injury Rate
30 Hz	30	31	9	33.3%
120 Hz	30	10	20	70%
From LTRMP and LTEF:				
60 Hz	38	63	101	62.4%

Figures

Figure 1. Map of the reaches on the Mississippi River between its confluence with the Kaskaskia River (Mississippi River km [MRKM] 188) upstream to Lock and Dam 24 (MRKM 440) and the Illinois River between its confluence with the Mississippi River (Illinois River km [IRKM] 0) and Peoria Lock and Dam (IRKM 254) where fish were collected from June 15 – October 31, 2013 by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program. Shapefiles for this map came from the Upper Mississippi Environmental Sciences Center.

Figure 2. Injury rate of Channel Catfish *Ictalurus punctatus* (A) and Silver Carp *Hypopthalmichthys molitrix* (B) in the Mississippi and Illinois rivers collected during June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program. n = total number captured.

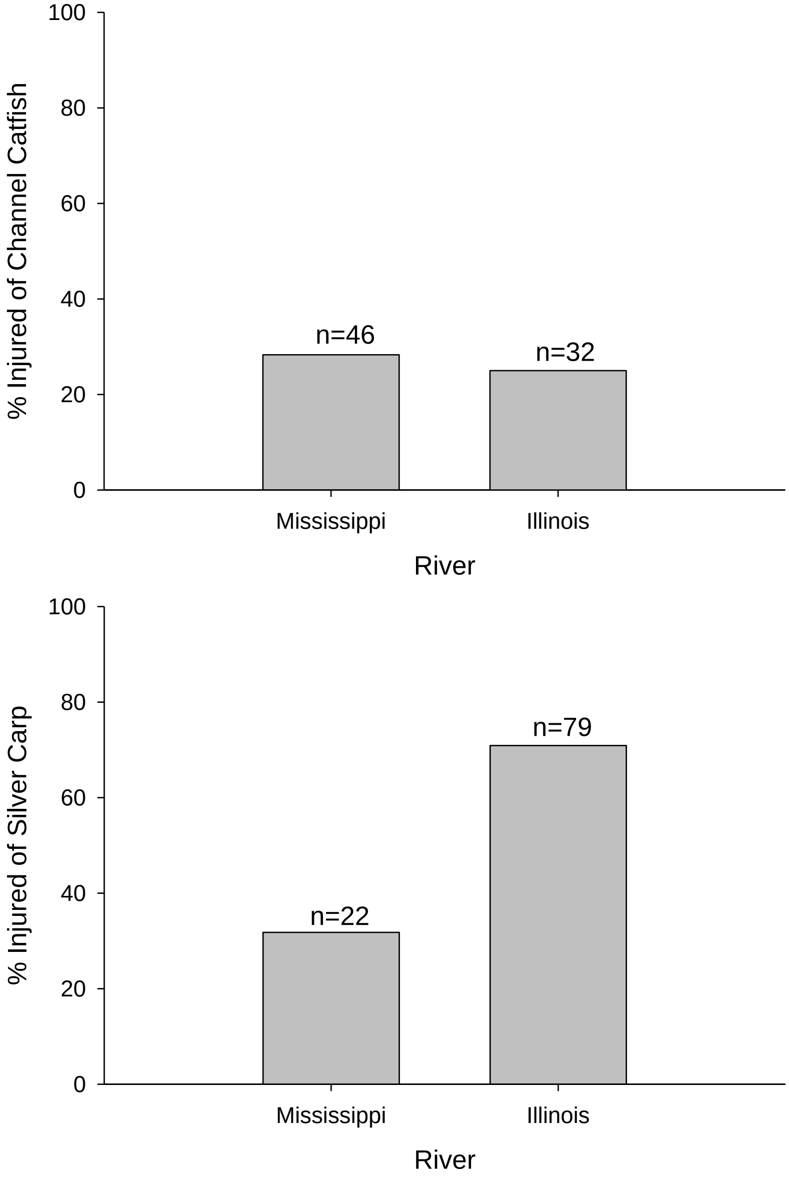


Figure 3. Mean length ± standard error (A) and mean condition ± standard error (B) of Channel Catfish *Ictalurus punctatus* and mean length ± standard error (C) and mean condition ± standard error (D) of Silver Carp *Hypopthalmichthys molitrix* collected during June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

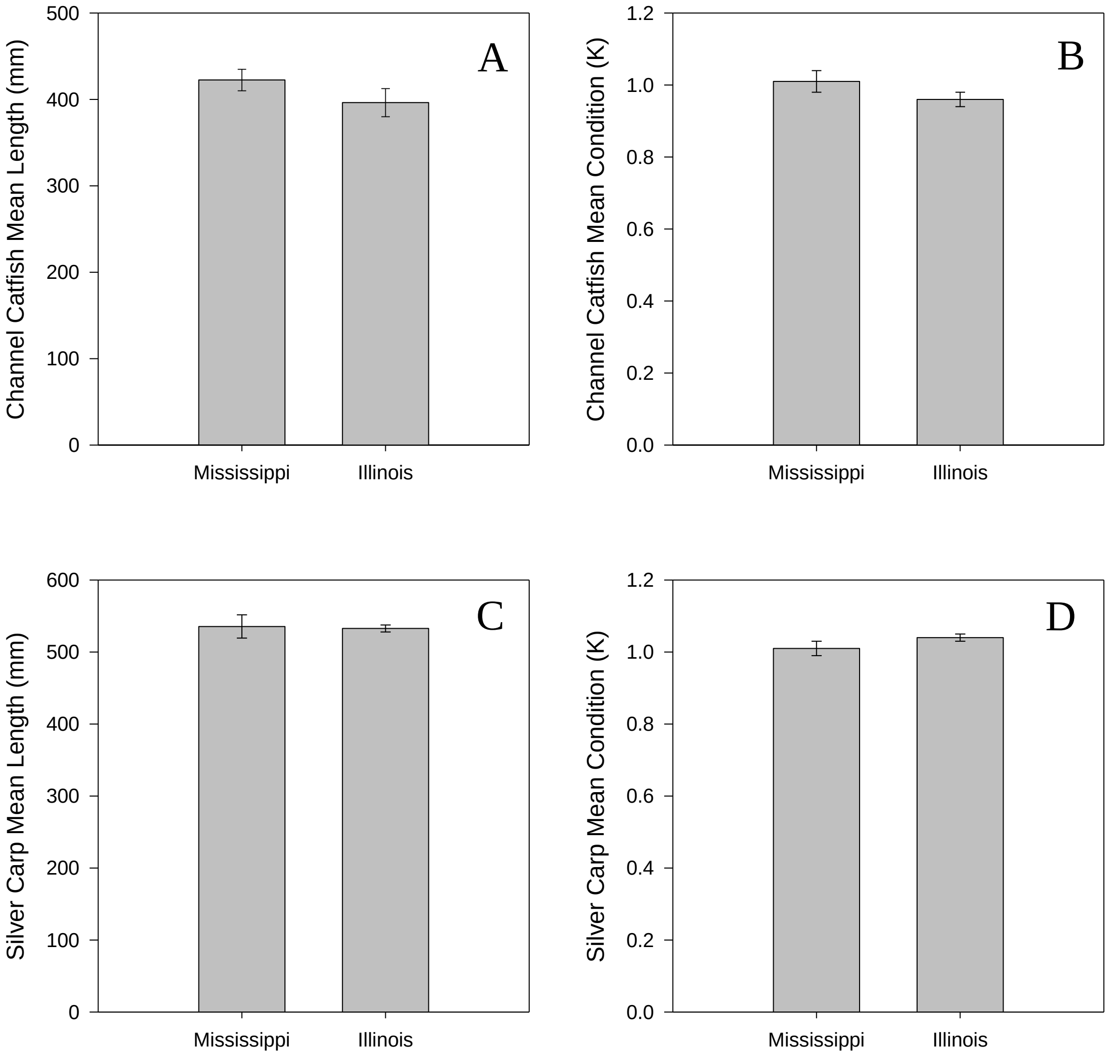


Figure 4. Length distribution (A) and condition distribution (B) of injured and uninjured Channel Catfish *Ictalurus punctatus* collected from June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

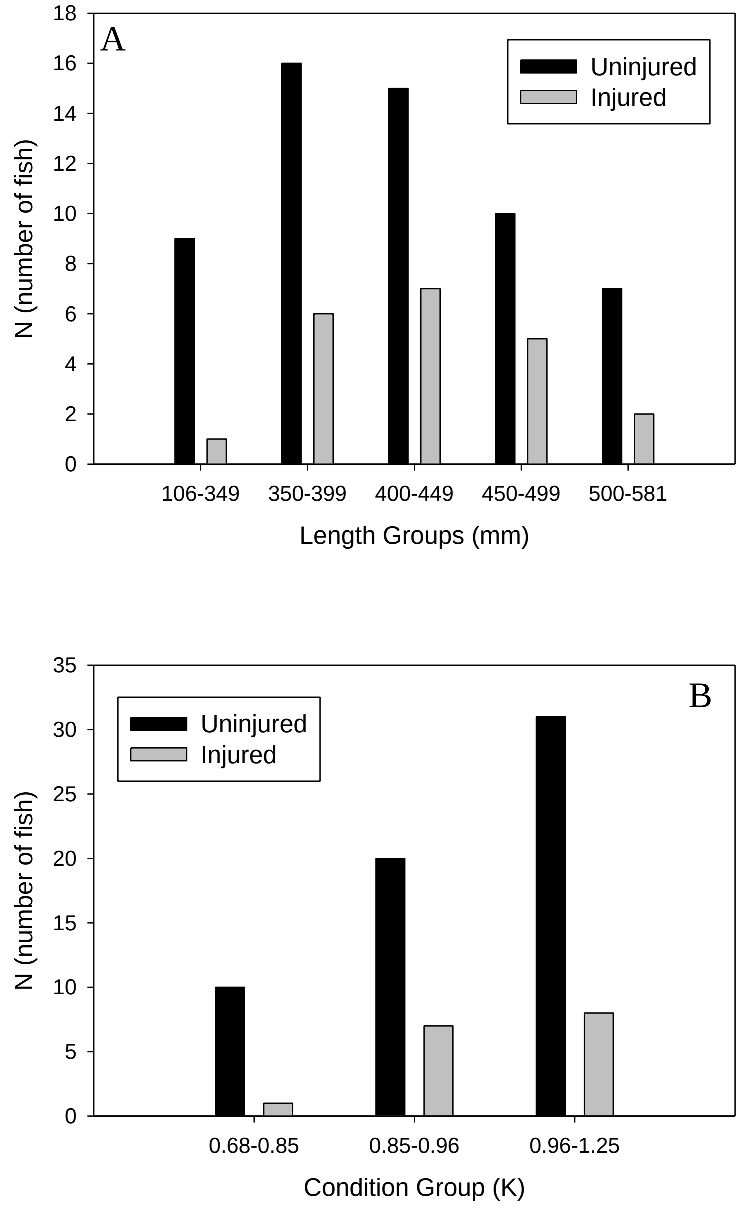


Figure 5. Length distribution (A) and condition distribution (B) of injured and uninjured Silver Carp *Hypopthalmichthys molitrix* collected from June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

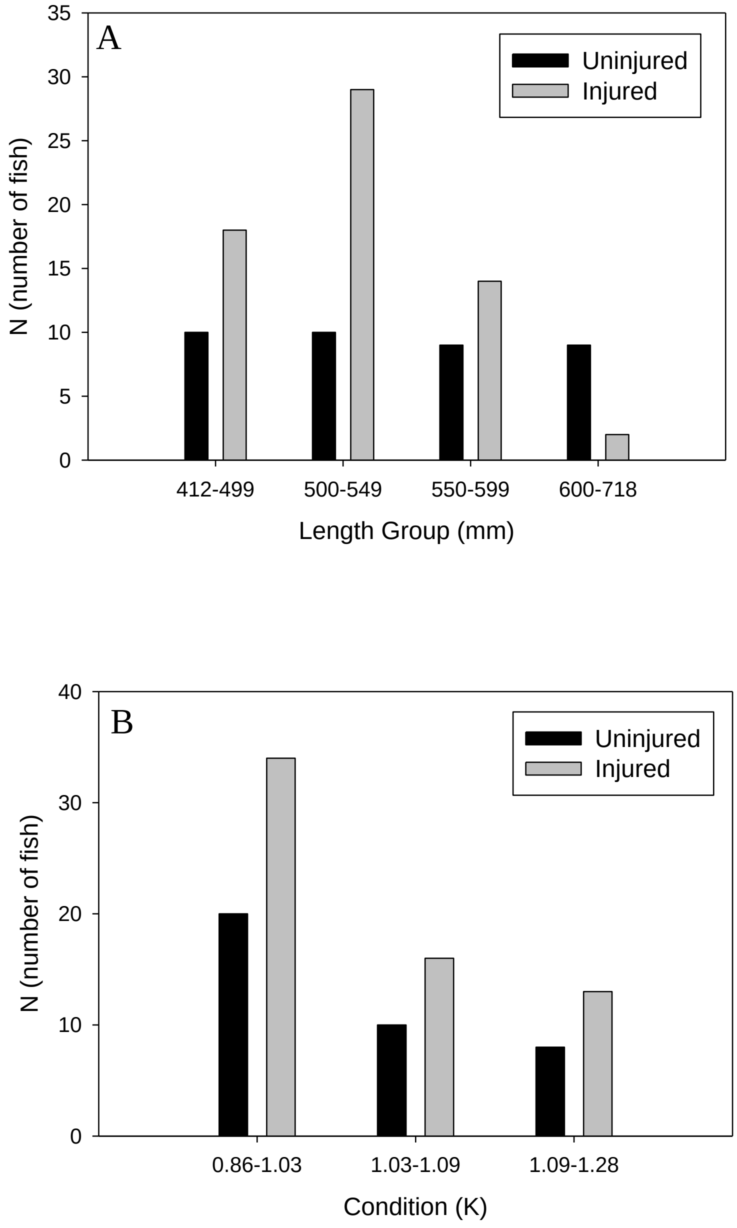


Figure 6. Observed mean length ± standard error (A) and mean condition ± standard error (B) for injured and uninjured Channel Catfish *Ictalurus punctatus* and observed mean length ± standard error (C) and mean condition ± standard error (D) for injured and uninjured Silver Carp *Hypopthalmichthys molitrix* collected from June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

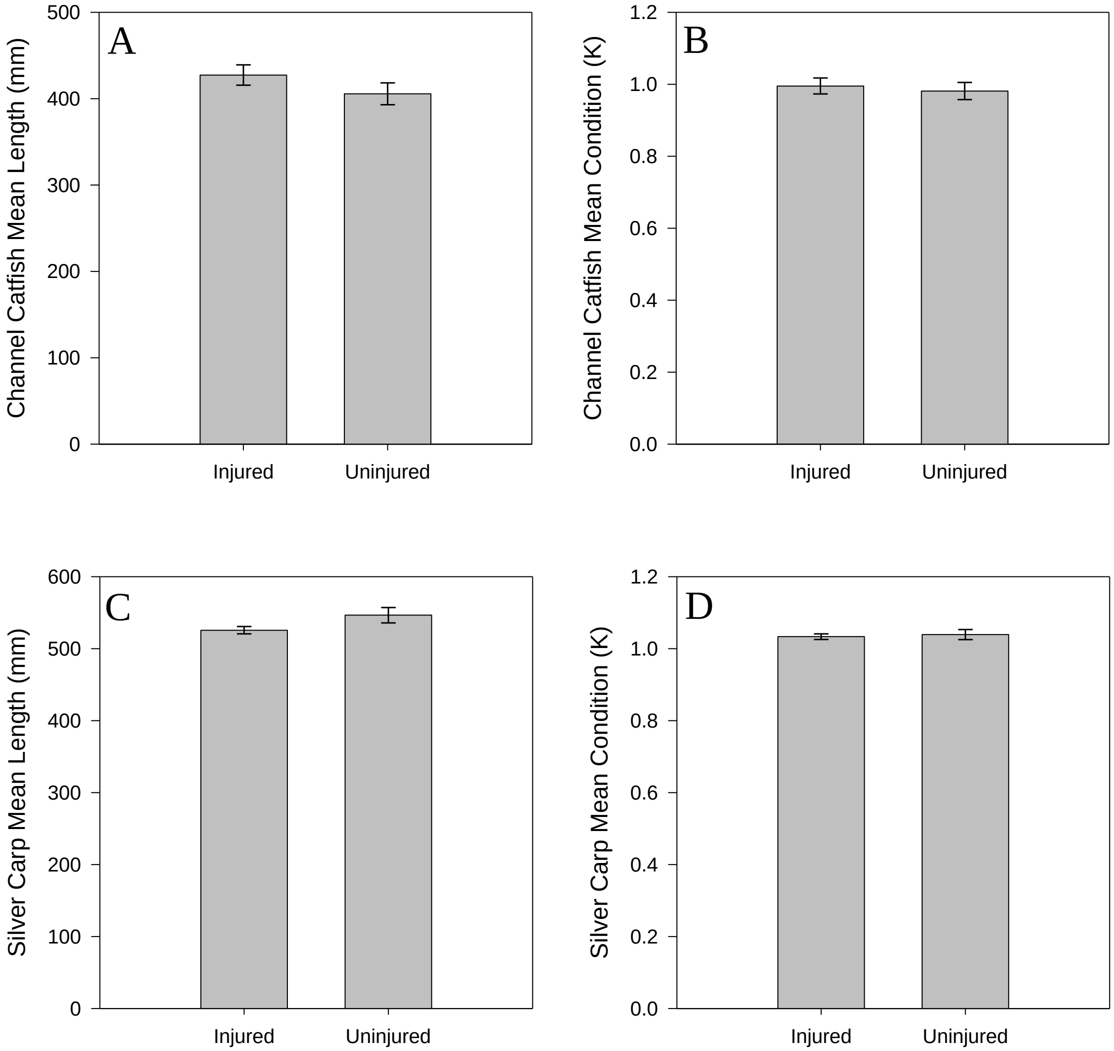


Figure 7. Logistic regression plots for Channel Catfish *Ictalurus punctatus* injury rates and their associated potential explanatory variable: A) Power Used (Wald χ^2_1=0.370; p=0.543); B) Conductivity (Wald χ^2_1=0.028; p=0.866); and C) Voltage (Wald χ^2_1=0.028; p=0.866). Bubbles are scaled according to the number of fish. Data were collected from June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program

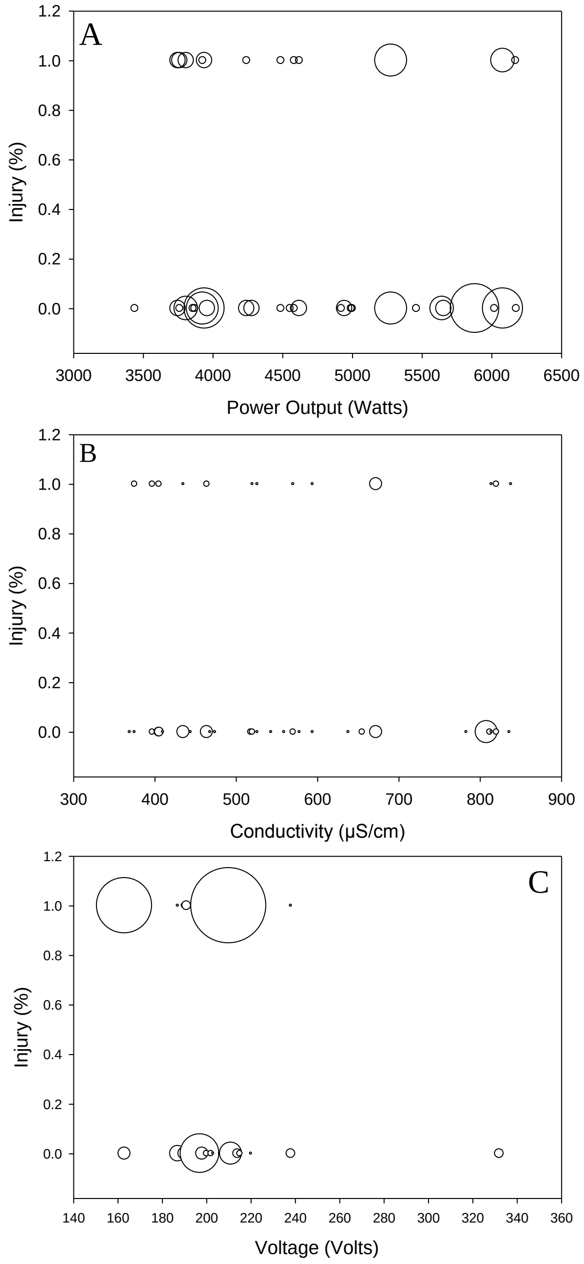


Figure 8. Logistic regression plots for Silver Carp *Hypopthalmichthys molitrix* injury rates and their associated potential explanatory variable: Power Used (Wald χ^2_1=8.022; p=0.005) (A); Conductivity (Wald χ^2_1=8.660; p=0.003) (B); and Voltage (Wald χ^2_1=1.575; p=0.210) (C). Bubbles are scaled according to the number of fish. Data were collected from June 15 – October 31, 2013, by electrofishing crews sampling fishes for the Long Term Resource Monitoring Program and Long-term Illinois, Mississippi, Wabash and Ohio Rivers Fish Monitoring Program.

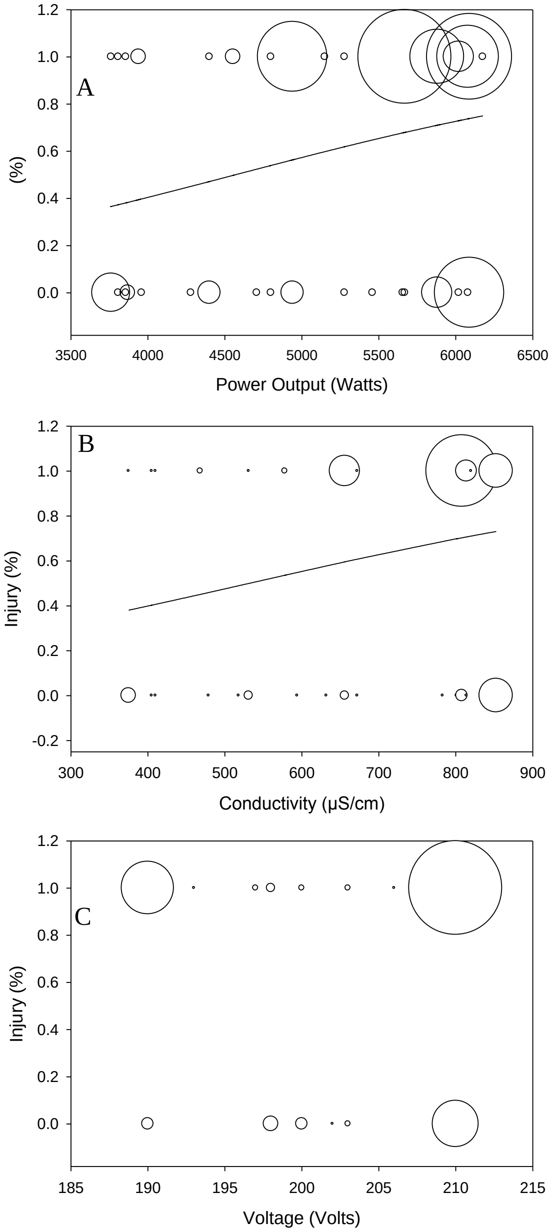
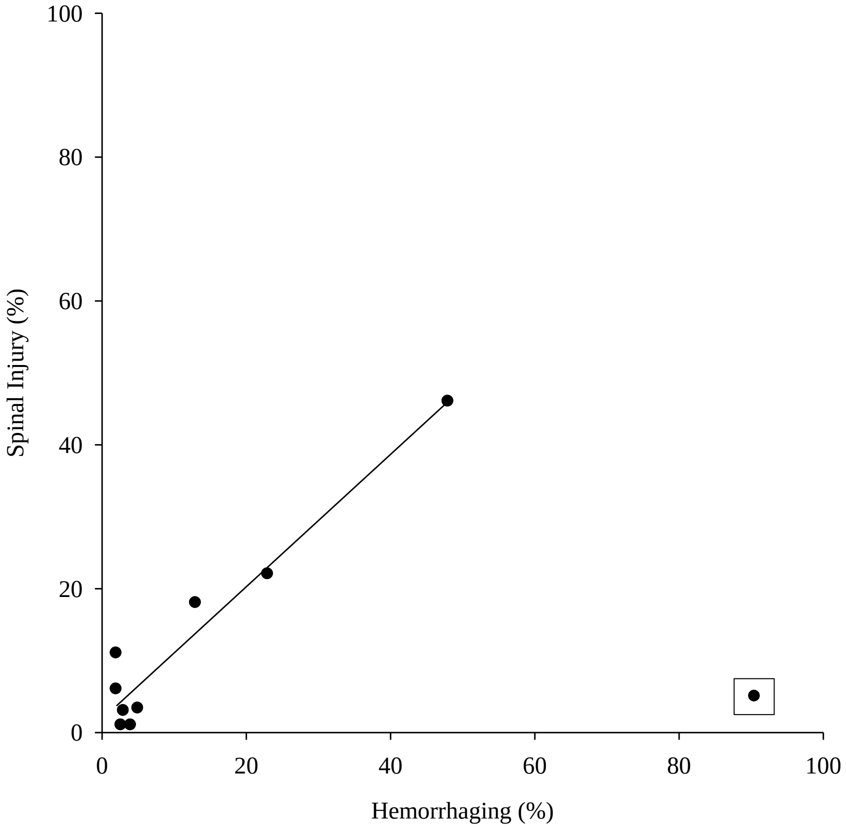


Figure 9. A comparison of the rates of spinal injury measured with radiography with hemorrhaging measured through necropsy published in peer-reviewed journals. Data are from the following studies: (Hollender and Carline 1994; Van Zee et al. 1994; Dolan et al. 2002; Dolan and Miranda 2004; Walsh et al. 2004; Miranda 2005; Clement and Cunjak 2010; Miranda and Kidwell 2010). Data point in square is an outlier (Walsh et al. 2004) omitted from the regression.



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Appendix A

Table A1. Fourty-seven peer-reviewed journal articles assessing electrofishing injury studies.

Author	Year	Fish	Current	Field/Lab	Type	Spinal Injury	Hemorrhage	Mortality
Ainslie et al	1998	Rainbow Trout	60 Hz PDC	Lab	Backpack	39		1
		Largemouth Bass						
		Smallmouth Bass	30 Hz PDC					1.3
		Bluegill	60 HZ PDC					.7
Bardygula-Nonn et al	1995	Pumpkinseed	120 Hz PDC	Field	Boat			5.3
Bearlin et al	2008	Murray Cod	60 Hz PDC	Lab				
Beaumont et al	2000	Rainbow Trout	60 Hz PDC	Lab			1	0-2
Carline	2001	Brown Trout	800 Hz PDC	Field	Backpack	38-44		
			60 Hz PDC	Lab		46	48	
Clement and Cunjak	2012	Atlantic Salmon	60 Hz PDC	Field	Backpack	11	2	
			80 Hz PDC		Backpack			8-9
Cooke et al	1998	Greenside Darters	60 Hz PDC	Field	Backpack			4-8
Cowdell and Valdez	1994	Roundtail Chub	40 Hz PDC	Field	Boat		5	
Dalbey et al	1996	Rainbow Trout	60 Hz PDC	Field	Boat	54		
			110 Hz PDC				0-20	0-14
				Lab		0-15	0-25	
								0-15
			15 Hz PDC			0-22		0-54
						0-8	0-8	0-50
		Channel Catfish						
		Largemouth Bass	60 Hz PDC				6-7	14
Dolan and Miranda	2004	Bluegill					7-14	0-52
			110 Hz PDC			20-45	43-50	0
			60 Hz PDC			10	33	0
Dolan et al	2002	Black Crappie	15 Hz PDC	Lab		20-27	7-15	0-15

Table A1 (cont.)

Author	Year	Fish	Current	Field/Lab	Type	Spinal Injury	Hemorrhage	Mortality
Dwyer et al	2001	Westslope Cutthroat Trout	50 Hz PDC	Lab		27		
		Brown Trout	60 Hz PDC	Field		13-68	57-91	
Fredenberg	1992	Walleye Sauger	60 Hz PDC					
Habera et al	1996	Rainbow Trout	500 V AC	Field	Backpack	3	3	9
Habera et al	1999	Brown Trout	60 Hz AC	Field	Backpack	35	60	
Hauck	1949	Rainbow Trout	110 V AC	Field	Backpack			26
	2003	Striped Bass	120 Hz PDC	Lab		1	1	44
	2003	Rainbow Trout	30 Hz PDC	Lab				14
		Largemouth Bass	60 Hz PDC				1	60
		Bluegill	60 Hz PDC				1	13-43
		Channel Catfish	60 Hz PDC				3	53
		Nile Tilapia	60 Hz PDC			1	3	14
Henry and Grizzle	2003	Rainbow Trout	60 Hz PDC	Lab			2	55
			250-300 Hz AC	Field	Backpack	18	13	
Hollender and Carline	1994	Brook Trout	60 Hz PDC	Field	Backpack	13	13	
Holliman and Reynolds	2002	White Sturgeon	60 Hz PDC	Lab			60-75	
Holliman et al (a)	2003	Spotfin Chub	60 Hz PDC	Lab				0-25
			60 Hz PDC					0
			120 Hz PDC					25
Holliman et al (b)	2003	Cape Fear Shiner	Cont. DC	Lab				38

Table A1 (cont.)

Author	Year	Fish	Current	Field/Lab	Type	Spinal Injury	Hemorrhage	Mortality
Holliman et al	2010	Chinook Salmon	60 Hz PDC	Lab				16
Horak and Klein	1967	Rainbow Trout	45 V DC	Lab				5
Hudy	1985	Rainbow Trout	300, 700, 760 V AC	Lab				2
Keefe et al	2000	Brook Trout	600 V PDC	Lab				2.5-90
Kocovsky et al	1997	Brook Trout Brown Trout Rainbow Trout Longnose Chub	100 Hz PDC	Field	Backpack			
McCrimmon and Bidgood	1965	Rainbow Trout	120 Hz PDC	Field Lab	Backpack			
McMichael	1993	Rainbow Trout	30 Hz DC 90 Hz DC	Lab		22 35	35 53	
McMichael et al	1998	Rainbow Trout	30 Hz PDC	Field	Boat	0-48		
Meyer and Miller	1990	Brown Trout Rainbow Trout	60 Hz PDC 60 Hz PDC	Field		82-86 60-78		

Table A1 (cont.)

Author	Year	Fish	Current	Field/Lab	Type	Spinal Injury	Hemorrhage	Mortality
Miranda	2005	Channel Catfish Largemouth Bass Bluegill Black Crappie	60 Hz PDC	Lab		1	4	4
Miranda and Kidwell	2010	Bluntnose Minnow Creek Chub Tadpole Madtom Channel Catfish Redfin Darter	110 Hz PDC	Lab		0-25	0-35	0-40
			15 Hz PDC			0	0-10	0-90
			60 Hz PDC			0-10	0-20	0-50
			DC			0-5	0-10	0-15
Mitton and McDonald	1994	Rainbow Trout	60 Hz PDC	Lab		<1		0
Muth and Ruppert	1996	Razorback Sucker	60 & 240-Hz PDC			14-50		
Muth and Ruppert	1997	Razorback Sucker	30, 60, 80, 240 Hz PDC	Lab				5-15
Nordgreen et al.	2008	Atlantic Herring	50 Hz AC	Lab		60		
Reynolds and Holliman	2004	American Eel	30 Hz PDC	Field	Boat	56	28	
Roth et al.	2003	Atlantic Salmon	50 Hz AC	Lab		0-46	0-73	

Table A1 (cont.)

Author	Year	Fish	Current	Field/Lab	Type	Spinal Injury	Hemorrhage	Mortality
Ruppert and Muth	1997	Bonytail Chub	30, 60, 80-Hz PDC	Lab		13		
Schill and Elle	2000	Rainbow Trout	60 Hz PDC	Lab			82	1
Schreer et al	2004	Rainbow Trout	10 Hz PDC 30 Hz PDC 90 Hz PDC 80 Hz PDC	Lab	Backpack	4	29-100	
Sharber and Carothers	1988	Rainbow Trout	60 Hz PDC	Field	Boat	44-67		
Sharber et al	1994	Rainbow Trout	15 Hz PDC	Field	Boat	3		
			30 Hz PDC		Boat	24		
			60 Hz PDC		Boat	42		
			512 Hz PDC		Boat	62		
Spencer	1967	Largemouth Bass Bluegill	230 V AC	Lab		12.2		
			115 V AC			4.6		
			115 V PDC			1.5		
Thompson et al	1997	Rainbow Trout	60 Hz PDC	Field	Boat	18-64		
		Brown Trout	60 Hz PDC		Boat	18-54		
Van Zee et al	1994	Bluegill Largemouth Bass Smallmouth Bass	AC PDC	Field	Boat	10 AC / 3 DC	3 AC / 8 PDC 0 AC 13 AC	
Walsh et al	2004	Rainbow Trout	60 Hz AC	Field	Boat	5	90	

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