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Effects of acoustic tag implantation on lake sturgeon *Acipenser fulvescens*: lack of evidence for changes in behavior

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Abstract

Background: An assumption of studies using acoustic telemetry is that surgical implantation of acoustic transmitters or tags does not alter behavior of tagged individuals. Evaluating the validity of this assumption can be difficult for large fish, such as adult sturgeons, not amenable to controlled laboratory experimentation. The purpose of this study was to determine if and when this assumption was valid for adult lake sturgeon *Acipenser fulvescens* tagged with large (34 g) acoustic transmitters and released into the St. Clair River during 2011–2014. The hypothesis that activity and reach-scale distributions of tagged and untagged lake sturgeon did not differ was tested by comparing movement frequencies, movement rates (speed-over-ground), and location-specific detection probabilities between newly-tagged lake sturgeon and presumably fully-recovered conspecifics tagged and released in prior years.

Results: Activity of acoustic-tagged lake sturgeon did not differ between newly-tagged individuals and conspecifics tagged in prior years. Movement frequencies and movement rates in all comparisons were similar between lake sturgeon observed during the first 15 days after surgery and simultaneously-observed conspecifics tagged in prior years. Likewise, lake sturgeon observed during the first 15 days after release were not more likely than conspecifics tagged in prior years to be distributed upstream or downstream of release sites. However, newly-tagged lake sturgeon were more likely than conspecifics tagged in prior years to be detected near release areas. Whether the cause for this ephemeral difference in detection probabilities was a behavioral response to surgery or a consequence of releasing newly-tagged individuals near receivers could not be determined.

Conclusions: Lack of evidence for changes in movement frequencies, movement rates, and distribution after surgical implantation of acoustic tags supported the assumption that movements of acoustic-tagged adult lake sturgeon were representative of untagged conspecifics. Thus, detection data gathered from recently tagged individuals is unlikely to bias data analyses in studies of lake sturgeon spatial ecology using telemetry. Our findings should apply to most tag sizes given that we used some of the largest acoustic tags currently available. The "staggered entry" design used in this study also may be useful for testing fundamental assumptions of biotelemetry studies for other large fish.

Keywords: Surgery effects, Testing assumptions, Biotelemetry

Background

Acoustic telemetry is a popular tool for the study of fish spatial ecology. In acoustic telemetry, fish are captured, surgically implanted with an acoustic transmitter or 'tag', and then released back into the environment. Acoustic hydrophones or 'receivers' then are used to detect and record acoustic signals from tagged individuals. Due to the large detection range of transmitters and the ability of receivers to concurrently monitor movements of multiple individuals, acoustic telemetry can be used to describe individual- and population-level patterns in habitat use or migration. Spatiotemporal patterns in the detection data generate information that can improve management

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decision making (e.g., design of dam passage structures; [1, 2]).

Understanding the effects of tag implantation on fish behavior is important for accurate interpretation of acoustic detection data. All mark-recapture and biotelemetry studies assume that the behavior of tagged individuals is representative of untagged conspecifics [3, 4]. Violations of this assumption can bias data analyses, and unaccounted for, can lead to incorrect inferences concerning fish movement patterns and habitat use.

Many gaps remain in the general understanding of how tag attachment and tag presence affect conformity to the assumption that tagged fish are representative of untagged conspecifics [4]. For example, previous research has not investigated prevalence and duration of surgery effects on behavior after intracoelomic tag implantation in large fish species despite the growing use of acoustic telemetry as a tool for the conservation of sharks (e.g., *Carcharodon carcharias*; [5]), sturgeons (*Acipenser* spp.; [6, 7]), and tunas (*Katsuwonus* spp., *Thunnus* spp.; [8]). Changes in the behavior of large fish after tag implantation is likely related to surgery or complications related to surgery rather than actual tag presence because most contemporary acoustic tags are proportionally small relative to the size of the animal ($\ll 1$ % by mass), and stress from capture and handling generally dissipates in less than 1 day [9, 10]. In contrast, complete healing of surgical incisions requires weeks to months [9, 11, 12], during which time fish may become agitated, disoriented, or reluctant to move [13]. Controlled laboratory experiments designed to identify and isolate the effects of surgery, handling stress, and tag presence on individual behavior are impractical or impossible for many large species due to logistical challenges of handling large fish in controlled environments. Yet, identification of the types and duration of surgery effects on behavior is important so that acoustic detection data can be properly interpreted and applied to management decisions.

In the absence of controlled laboratory observation, different strategies are needed to identify surgery effects on the behavior of large, wide-ranging fish species. One approach is to compare newly-released individuals to previously-tagged conspecifics after a substantial time interval has elapsed under the assumption that behavioral effects of tagging subside over time. This "staggered entry" approach lacks the same degree of experimental rigor as controlled laboratory studies, but has the advantage that fish are observed under ecologically realistic conditions. Differences in the detection patterns of acoustic-tagged individuals tagged and/or released at different times can help researchers determine if, and when, the movement patterns of tagged and untagged individuals converge.

This study employed the staggered entry approach to explore the effects of intercoelomic tag implantation on the behavior of adult lake sturgeon *Acipenser fulvescens*. Lake sturgeon are the largest native fish species in the Laurentian Great Lakes (adults routinely exceed one meter in length and weigh up to 60 kg), and are listed as rare, threatened, or endangered over much of their native range [14]. The potential effects of acoustic tag implantation on lake sturgeon behavior have not been evaluated despite the increasing use of acoustic telemetry to address information needs for lake sturgeon management. Objectives of the current study were (1) to determine if activity and reach-scale distributions differed between newly-tagged lake sturgeon and co-located conspecifics tagged in prior years and (2) to determine if and when the behaviors of these groups converged if behavioral differences were observed. Some species become less active after surgical implantation of electronic tags, and in a riverine environment, may move or drift downstream after release [13]. However, given the possibility that agitation after surgery could lead to increased activity and upstream dispersal, we tested the two-sided null hypotheses that activity and distributions of acoustic-tagged lake sturgeon would not differ between newly-tagged individuals and conspecifics tagged in prior years (and that presumably have healed and fully recovered from surgery).

Methods

Study site

Behavior of acoustic-tagged lake sturgeon was assessed in the lower St. Clair River, which is part of the waterway that connects Lake Huron to Lake Erie (Fig. 1). The lower St. Clair River is core habitat for a large remnant lake sturgeon population [15]. Many of these fish remain in the North and Middle Channels year-round or move between the lower river and Lake St. Clair [16], which increased the likelihood that individuals tagged in a given year would be detected nearby in subsequent years. Lake sturgeon in this study were captured and tagged as part of a project designed to elucidate lake sturgeon population structure in the Lake Huron-to-Lake Erie corridor.

Lake sturgeon capture and tagging

Lake sturgeon used in this study were captured during May–June as part of an annual population survey conducted by the Michigan Department of Natural Resources (MDNR). Lake sturgeon were captured using baited set lines deployed from a research vessel in the afternoon and retrieved the following morning [17]. Between 2011 and 2014, a total of 86 adult lake sturgeon (total length 120–180 cm) were surgically implanted with Vemco 69 kHz V16-6L acoustic tags (Table 1). The V16-6L tags had a 10-year battery life, were 16 mm in diameter,

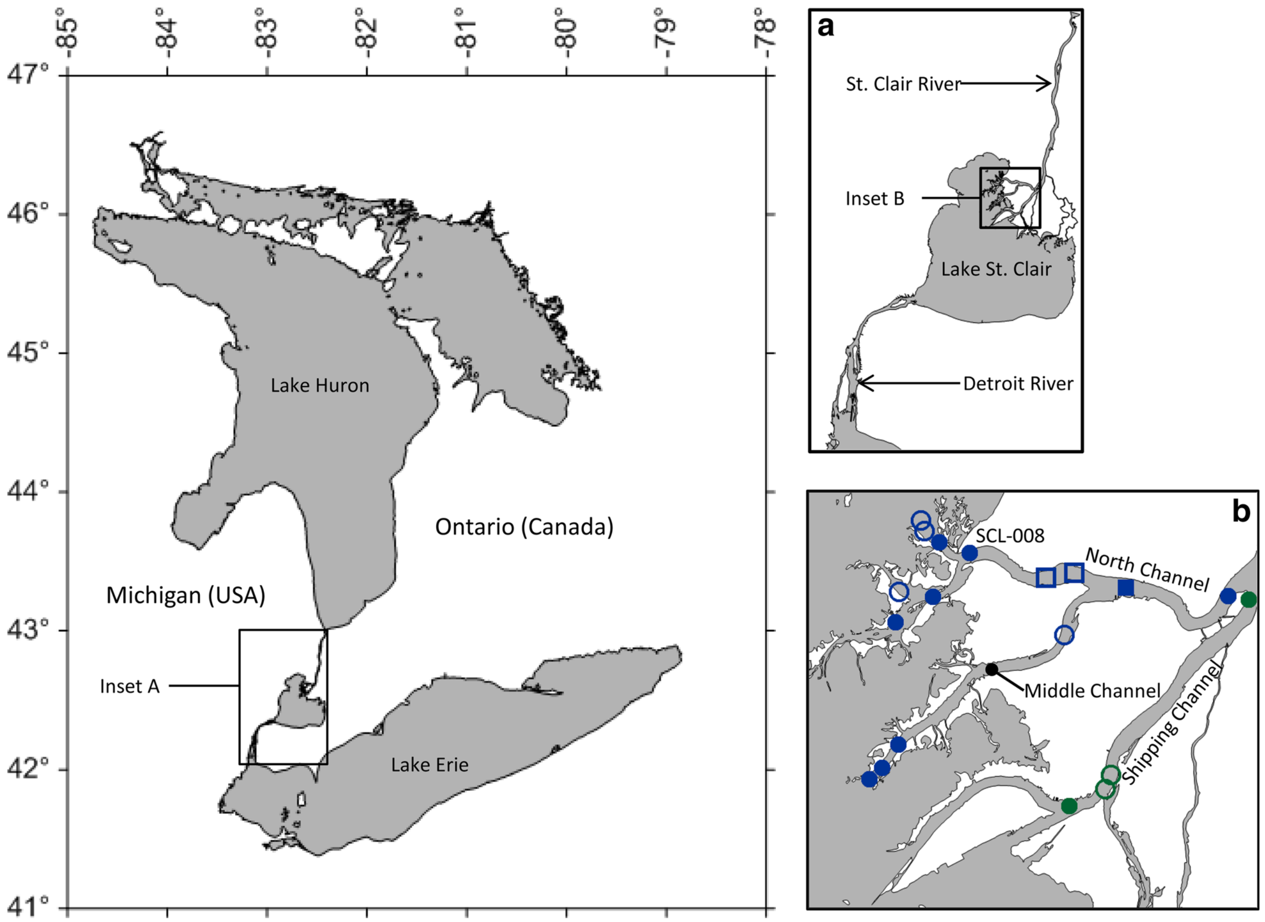

Fig. 1 Map of the Lake Huron-to-Lake Erie corridor showing the Detroit-St. Clair River system (panel **a**) and the locations of acoustic receivers in the lower St. Clair River (panel **b**). *Filled symbols* indicate receivers deployed in 2012. *Unfilled symbols* represent receivers added to the network in 2013 and 2014. Site SCL-008 was discontinued after May 2012. Detection efficiency was estimated for the three receivers denoted by *square symbols*. Data from receivers in the shipping channel (*green symbols*) were not included in the current study

Table 1 Sample sizes and biological characteristics of acoustic-tagged lake sturgeon

Year	*n*	TL (min–max)	Weight (min–max)	Sex ratio (M:F:U)	Release dates
2011	8	145 (126–166)	20.5 (10.4–33.9)	0:1:7	28 Jun
2012	28	149 (126–178)	22.0 (12.0–37.0)	3:4:21	30 May–8 Jun
2013	24	145 (121–180)	21.1 (10.0–45.6)	6:5:13	30 May–5 Jun
2014	26	146 (122–175)	20.9 (9.8–36.0)	4:2:20	29 May–5 Jun

Sample size (*n*), mean total length (TL, in cm), and mean weight (kg) of lake sturgeon marked with intracoelomic acoustic tags in the lower St. Clair River during 2011–2014

M male, *F* female, *U* sex unknown

95 mm long, and weighed 34 g in air. Transmission delay averaged 120 s but was varied randomly between 60 s and 180 s. Tag mass represented 0.05–0.35 % (mean 0.18 %) of lake sturgeon body mass. Total length (nearest cm) and wet weight were recorded for each individual (Table 1). Sex was not included as an explanatory variable in any analyses because sex could not be determined for 75 % of acoustic-tagged individuals (North American sturgeon are difficult to sex unless captured in spawning-ready condition [18]). All acoustic-tagged lake sturgeon were captured and released upstream of the Chenal a bot Rond confluence and downstream of Pt. aux Chenes (Fig. 2). Percent of individuals tagged in a given year that were detected in subsequent years in the North and Middle

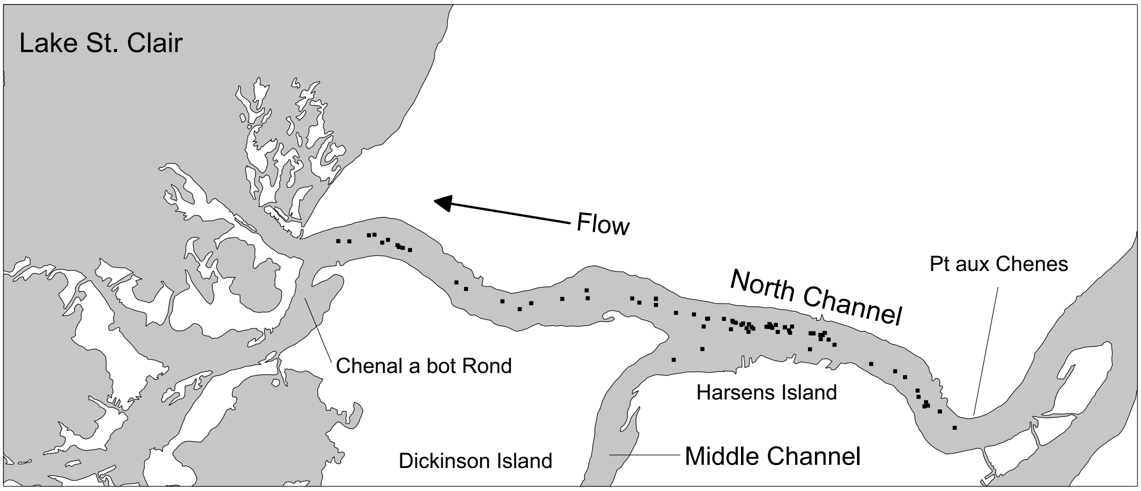

Fig. 2 Release locations of acoustic-tagged lake sturgeon in the lower St. Clair River

Channels ranged between 42 and 71 %, confirming that many lake sturgeon released in a given year returned to the same habitats the following year(s).

Lake sturgeon were not anesthetized prior to surgery because a proven and widely-accepted method for anesthetizing adult sturgeon was not available at the time of this study (but see [6] for a new electronarcosis method). Instead, individuals implanted with acoustic tags were immobilized ventral-side up in a mesh sling with head and gills immersed in a 379 liter (100 US gallons) tank continuously supplied with river water. A 3–4 cm incision was made in the abdomen approximately half way between the pectoral and pelvic girdles and 2 cm off the linea alba. The acoustic transmitter then was inserted into the peritoneal cavity, and the incision was closed with 3–4 simple, interrupted sutures (Ethicon PDS-II size 0 with OS-6 half-circle reverse cutting needle or MONO-DOX size 0 with NCP-1 half-circle reverse cutting needle). Surgical tools and tags were sterilized with a 0.02 % chlorhexidine or 5 % povidone-iodine solution before each surgery. Post-operative fish were held for 5–10 min in a second tank supplied with river water and then released within 0.2 km of the capture site. Total time from capture to release for acoustic-tagged lake sturgeon ranged from 10 to 25 min.

Acoustic monitoring network and acoustic data filtering

Movements of acoustic-tagged lake sturgeon were monitored on a network of 10 Vemco 69 kHz VR2W receivers deployed in the North and Middle Channels in April 2012 (Fig. 1). The network was expanded to 15 receivers in 2013 and 16 receivers in 2014. Receivers were deployed on the river bottom at depths ranging from 6 to 13 m. Each receiver was mounted in a 7.6 cm diameter (3 in.) PVC pipe embedded into a 68 kg (150 lb.) concrete footing. Receivers were recovered by grappling for a 23 m (75 ft.) grab line attached to each footing. Receivers were recovered, downloaded, and replaced twice per year (spring and fall).

Acoustic detection data were downloaded from each recovered receiver using Vemco VUE software. As recommended by Pincock [19], suspected false positives were identified and removed by eliminating detections for which the minimum time between the last or next detection for the same transmitter on the same receiver was greater than 30× the average tag delay (=3600 s in our study). Application of this filter eliminated 11,255 (0.78 %) of ca. 1.45×10^6 detections available for analysis, suggesting that code collisions were not common.

Data analyses assumed that sturgeon did not pass adjacent receivers undetected. To evaluate this assumption, we estimated detection efficiency for each of three receivers in the North Channel located about half way between the channel head and mouth (Fig. 1) from detection histories of tagged lake sturgeon that transited the entire length of the channel. Detection efficiency was estimated as the proportion of transits in which a fish was correctly observed (detected) at each site during all years that a receiver was present at that site. These three sites were assumed representative of the main channel habitats in which remaining receivers were deployed and thus provided an indication of array performance.

Data analyses: overview

To test for effects of intracoelomic tag implantation on lake sturgeon behavior (objective 1), acoustic detection data were used to describe lake sturgeon activity and reach-scale distributions, which then were compared between individuals tagged and released in a given year ("newly-tagged") with co-located individuals tagged and released in prior years (the "staggered entry" approach). Individuals tagged in 2011 contributed only to the reference population (i.e., fish tagged in prior years) as the acoustic monitoring system was not completed until 2012. Detection data from receivers in the shipping channel were excluded from all analyses to insure that local variability in physical habitat and environmental conditions did not confound comparisons of the behavior of acoustic-tagged lake sturgeon. Reach-scale distributions were estimated using only data from receivers in the North Channel given that receiver coverage was more extensive than in the Middle Channel. To determine the duration of surgery effects on lake sturgeon behavior (objective 2), lake sturgeon activity and distributions were summarized and compared over 15-day intervals beginning the day of release for newly-tagged individuals and beginning on the 1-, 2-, or 3-year post-release date for individuals released in prior years. If a significant difference in behavior was observed during the first 15-day period, analyses were continued with data from subsequent periods until the behavior of newly- and previously-tagged individuals was not significantly different. Complete convergence in the activity and distributions of newly- and previously-tagged lake sturgeon was expected within 60 days as surgical incisions in other fish species typically heal in less than 60 days [11, 12].

Generalized linear models (GLM) were used to compare activity and distributions of acoustic-tagged lake sturgeon. In each analysis, several candidate models were constructed, and the best-fit model was used for statistical inference. The independent variable of interest in all analyses was release group, which identified an individual as (a) newly-tagged (i.e., having been tagged and released in the current year of observation) or (b) tagged in a previous year.

Sets of candidate models were developed, compared, and ranked using a phased, forward selection process that balanced parsimony and model fit (described in detail in [5]). In phase I, we fit models that included only a single main term. In subsequent phases, we evaluated sets of models in which an additional main term was added to the best-fit model from the previous phase. Thus, all phase II models included two independent variables: the single main term from the best-fit phase I model plus an additional main term. If deemed necessary, models containing interaction terms were defined a priori and evaluated in a final phase. All phase I models were additionally compared with the null (intercept only) model. If the null model was selected as the best model at the conclusion of phase I, we concluded that none of the independent variables were significant predictors of lake sturgeon behavior and model construction was discontinued. Within a given phase, the model with the lowest Akaikes's Information Criterion (corrected for small sample sizes; AICc,) was identified as the best model. Pairs of models with AICc's that differed by <2 units were considered equivalent with regard to strength of inference [20]. The overall best model then was identified as the model with the largest Akaike weight, which measured the probability that the ith model was the best model in the set of candidate models. The Akaike weight of the ith model (w_i) was calculated as:

$$w_i = \exp(-0.5\Delta_i)/\sum_i^k \exp(-0.5\Delta_i)$$

where $\Delta_i = \mathrm{AICc}_i - \mathrm{AICc}_{\mathrm{min}}$, $\mathrm{AICc}_{\mathrm{min}}$ was the lowest observed AICc, and k was the number of models in the set [21]. Inspection of residual diagnostic plots (not shown) and analyses of scaled deviance (D^*) were performed to verify model assumptions and to examine model fit. Scaled deviance follows a Chi square distribution with degrees of freedom (*df*) equal to model *df*. The null hypothesis that model i was a reasonable fit to the data was rejected at high values of D^*. To evaluate the effects of release group and other predictor variables on lake sturgeon behavior, likelihood ratio tests (LRT) were used to test the null hypothesis that the parameter coefficients (β) in the best-fit model were equal to zero. The LRT test statistic follows a Chi square distribution with *df* equal to the number of factor levels minus one. All statistical analyses were performed using PROC GENMOD in SAS 9.4 with $\alpha = 0.05$.

Data analyses: activity

Movement frequency (number of moves observed in a given time interval) and movement rate (speed-over-ground) were used as measures of lake sturgeon activity. Two analyses of movement frequency were performed to account for variation in lake sturgeon migratory behavior in the lower St. Clair River, which ranges from year-round river residency to adfluvial potamodromy [16]. In the first analysis, the response variable was the frequency of "short-distance" movements made by individual acoustic-tagged lake sturgeon within a given observation period. Short-distance movements were identified as detection events in which the time lag between successive detections of the same tag on the same receiver was 45–60 min (60 min threshold set by false detection filter), indicating that an individual briefly moved outside the detection radius of a given receiver or moved a short distance to a location within the detection radius at which some physical feature obscured line-of-sight with the receiver. Although actual distance moved during such events could not be precisely determined, we assumed that no other factors (other than those used in our models) would have differentially affected the number of short-term movements of one release group over the other because the behaviors of the two groups of lake sturgeon were compared contemporaneously and in the same general area. In the second analysis, the response variable was the frequency of "long-distance" movements made by individual acoustic-tagged lake sturgeon. Long-distance movements were defined as changes in location with a linear displacement greater than 2 km and were identified as detection events in which successive detections of the same tag code occurred on two different receivers separated by at least 2 km. A GLM with a negative binomial error structure and a log-link function was used to analyze the frequency of short- and long-distance movements made by acoustic-tagged lake sturgeon. Predictor variables in both analyses included release group, observation year (2012, 2013, 2014), and residence time—a covariate representing the number of days spent by an individual in the North and Middle channels during a given observation period. Observation year was included to adjust model predictions for annual variability in environmental conditions, the number and distribution of acoustic receivers, and other uncontrollable variables. Residence time was included to compensate for individual variability in the amount of time spent in the study area.

Movement rates of acoustic-tagged lake sturgeon were compared between newly-tagged individuals and those tagged in prior years using a GLM with a gamma error structure and a log-link function. The response variable was speed-over-ground, which was calculated as the distance moved between pairs of receivers divided by travel time. Travel time was estimated as the difference in time between the first detection at the arrival site and the last detection at the departure site. Speed over ground was expressed in body lengths per second (BL/s) to account for possible size-based variation in swimming speeds, and was estimated only for movements between pairs of receivers separated by 2 km or greater. Movement rates likely differed from actual swimming speeds due to uncertainties in the actual path swum by individual lake sturgeon and variability in receiver detection ranges. Movement rates for each individual in a given observation period were averaged. Explanatory variables included release group, observation year, direction of movement (upstream, downstream), and the release group × movement direction interaction. Movement direction was included as predictor variable because lake sturgeon travelling upstream were expected to move more slowly than individuals travelling downstream, especially in the St. Clair River where current velocities can reach 1.0 m/s [22]. The release group × movement direction interaction was included to address the possibility that surgery may limit speed-over-ground only when vigorous swimming is required, such as when moving upstream in heavy current.

Data analyses: distribution

To determine if acoustic-tagged lake sturgeon were differentially distributed in the North Channel of the St. Clair River, we used a GLM with a binary error structure and logit link to model detection probability at receiver locations near the release site (i.e., within 2 km), greater than 2 km downstream of release sites, and greater than 2 km upstream of release sites. The dependent variable was the proportion of acoustic-tagged lake sturgeon detected at one or more of these locations during a given 15-day observation period. Individuals were considered present at a given location so long as the sum of individual detections from the receivers representing that location was 25 or larger. Explanatory variables included release group, location relative to the release site (near, downstream, upstream), and observation year as well as the location × release group, location × year, and year × release group interactions. A significant location × release group interaction indicated that newly-tagged lake sturgeon and conspecifics tagged in prior years were differentially distributed relative to their release locations (e.g., one group was significantly more likely than the other to be detected downstream of release sites).

Results

Acoustic array performance

The probability that sturgeon passed adjacent receivers undetected was low. A total of 38 North Channel transits were made by 27 individuals during 2012–2014. Detection efficiencies of the three receivers that must have been passed during these movements were 91, 93, and 93 %, respectively.

Activity

Activity of acoustic-tagged lake sturgeon did not differ between individuals observed during the first 15 days after release and co-located conspecifics released in prior years. Numbers of short-distance movements made by acoustic-tagged lake sturgeon did not depend on release group (Table 2; Fig. 3), but increased significantly with residence time (LRT, $\beta_{\text{residence time}} = 0.14$, $df = 1$, $\chi^2 = 61.63$, $P < 0.01$; Fig. 4) and were higher in 2013 than in other years (LRT, $df = 2$, $\chi^2 = 7.37$, $P = 0.03$). The significant effect of year on the number of short distance movements was attributable to one individual that made 31 such movements in 2013. Movement frequencies adjusted for residence time and year effects did not differ

Table 2 Output of GLMs used to analyze short-distance movement frequencies of acoustic-tagged lake sturgeon

Phase	Model	IV(s)	*df*	AICc	*w*	*D** (*P*)
I	1	Null (intercept only)	122	691.4	0.00	141.3 (0.11)
	2	Residence time	121	637.5	0.13	139.5 (0.12)
	3	Release group	121	693.3	0.00	141.3 (0.10)
	4	Year	120	693.9	0.00	141.4 (0.09)
II	5	Residence time, release group	120	639.5	0.05	139.4 (0.11)
	6	*Residence time, year*	*119*	*634.4*	*0.58*	*139.2 (0.10)*
III	7	Residence time, year, release group	118	636.2	0.24	138.9 (0.09)

IVs independent variables, *df* degrees of freedom, *AICc* Akaike's Information Criterion, *w* Akaike weights, and goodness of fit statistics (scaled deviance, *D**, and *P* value of associated Chi square test) for generalized linear models used to analyze the frequency of short-distance movements made by acoustic-tagged lake sturgeon in the lower St. Clair River during 2012, 2013, and 2014. Residence time = total days spent in the North and Middle Channels. Release group identifies individuals observed 0–14 days post-surgery and simultaneously-observed conspecifics tagged in prior years. The highest-ranking (best) model is italicized

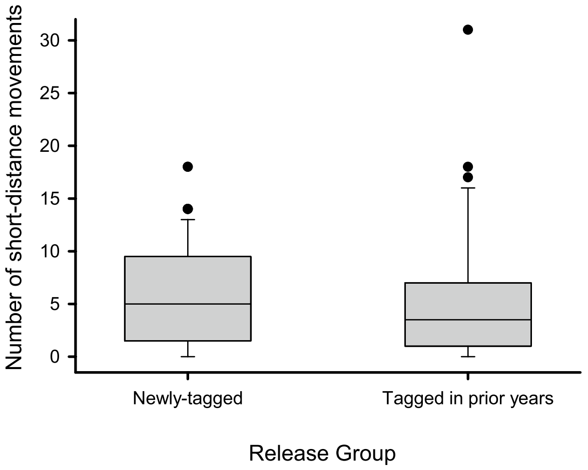

Fig. 3 Short-distance movement frequencies for acoustic-tagged lake sturgeon. Frequency of short-distance movements (median and quartiles) made by newly-tagged lake sturgeon observed during the first 15 days following surgery and release ($n = 77$) and simultaneously-observed conspecifics tagged in prior years ($n = 46$). *Error bars* represent the 10th and 90th percentiles

between newly-tagged lake sturgeon and conspecifics tagged in prior years (model 7; Table 2). Variation in the number of long-distance movements made by acoustic-tagged lake sturgeon was best explained by the null model (intercept only), which suggested that long-distance movement frequencies did not depend on release group, residence time, or year of observation (Table 3; Fig. 5).

Movement rates (speed-over-ground) of acoustic-tagged lake sturgeon did not differ between individuals observed during the first 15 days after release and simultaneously-observed conspecifics released in prior years (Fig. 6). The best model included only effects for movement direction (faster downstream than upstream; LRT, $\beta_{\text{direction}} = 0.92$, $df = 1$, $\chi^2 = 30.28$, $P < 0.01$) and year (slower in 2012–13 than 2014; LRT, $\beta_{\text{year}} = -0.58$, $df = 1$, $\chi^2 = 11.85$, $P < 0.01$; Table 4). A release group effect on lake sturgeon speed-over-ground was not evident after adjusting for direction and year effects nor the potential interaction between release group and movement direction (cf. models 6, 7, and 8; Table 4).

Distribution

Lake sturgeon observed during the first 15 days after release were not more likely than conspecifics tagged in prior years to be distributed upstream or downstream of release sites (Fig. 7). However, acoustic-tagged lake sturgeon observed during the first 15 days after release were more likely than conspecifics tagged in prior years to be found near release areas as indicated by the significant release group × location effect in the highest-ranking model (LRT, $\chi^2 = 9.44$, $df = 2$, $P = 0.01$; Table 5; Fig. 7). This difference may have been attributable to the large number of lake sturgeon that were released near the three receivers at the upstream end of Dickinson Island (cf. Figs. 1, 2). This contention is supported by the significant release group effect on detection probability (LRT, $\beta_{\text{release group}} = 1.70$, $\chi^2 = 13.00$, $df = 1$, $P < 0.01$), which indicated that newly-tagged lake sturgeon were detected at higher rates than conspecifics tagged in prior years. Detection probabilities of acoustic-tagged lake sturgeon after 30 days varied only with location and did not differ between release groups (Table 6), which suggests that newly-tagged lake sturgeon dispersed away from release areas during the third and fourth weeks after surgery (14–29 days post-surgery).

Discussion

This study found little evidence that surgical implantation of acoustic tags affected lake sturgeon behavior during the first 30 days after surgery. We failed to reject the null hypothesis that movement frequencies, movement rates, and reach-scale distributions were similar between

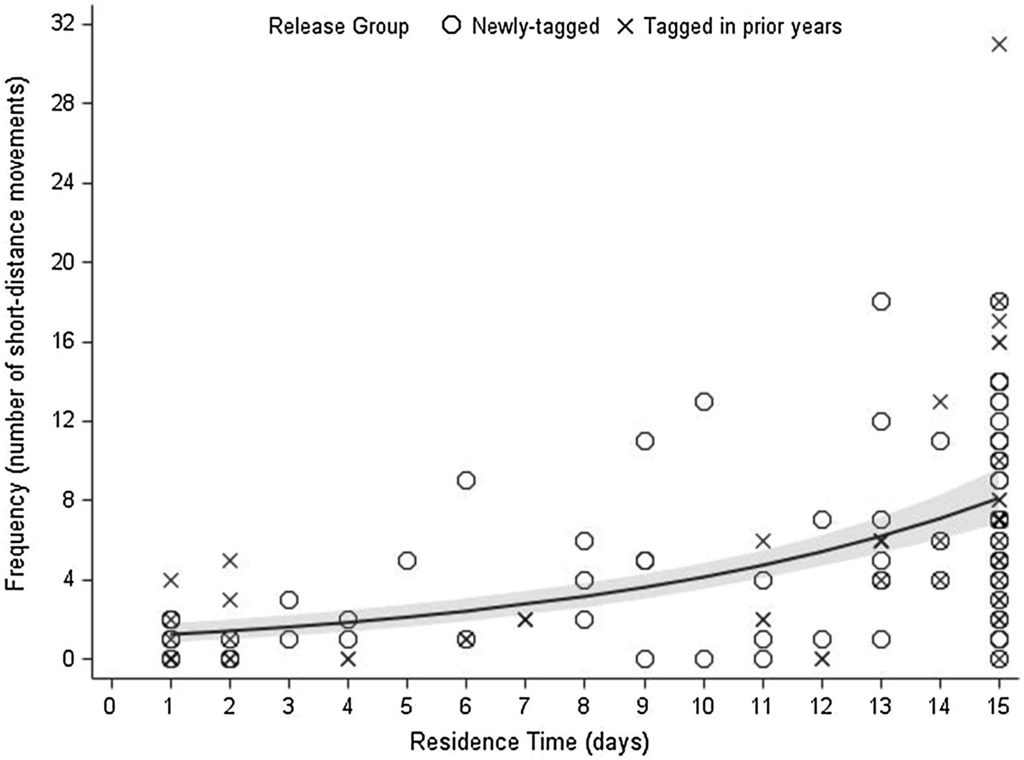

Fig. 4 Effect of residence time on the observed (*symbols*) and predicted (*line*) number of short-distance movements made by newly-tagged lake sturgeon (*circles*) and conspecifics marked with acoustic tags in prior years (*X*'s) during the initial 15-day observation period. *Shaded area* is the 95 % confidence interval for the predicted relationship

Table 3 Output of GLMs used to analyze long-distance movement frequencies of acoustic-tagged lake sturgeon

Phase	Model	IV(s)	*df*	AICc	*w*	*D** (*P*)
I	*1*	*Null (intercept only)*	*122*	*438.5*	*0.45*	*131.8 (0.26)*
	2	Residence time	121	439.4	0.29	131.8 (0.24)
	3	Release group	121	440.1	0.20	131.7 (0.24)
	4	Year	120	442.7	0.05	131.8 (0.22)

IVs independent variables, *df* degrees of freedom, *AICc* Akaike's Information Criterion, *w* Akaike weights, and goodness of fit statistics (scaled deviance, *D**, and *P* value of associated Chi square test) for generalized linear models used to analyze the frequency of long-distance movements made by acoustic-tagged lake sturgeon in the lower St. Clair River during 2012, 2013, and 2014. Residence time = total days spent in the North and Middle Channels. Release group identifies individuals observed 0–14 days post-surgery and simultaneously-observed conspecifics tagged in prior years. The highest-ranking (best) model is italicized

newly-tagged lake sturgeon and conspecifics tagged in prior years, which supports the contention that movements of tagged lake sturgeon are representative of the untagged population. Although sample sizes were relatively small for some of our analyses, confidence intervals (e.g., Figs. 6, 7) showed that our analyses would have detected biologically relevant differences in behavior between newly-tagged and previously-tagged individuals. Thus, non-significant results were not due to insufficient statistical power. Our findings were consistent with results of [6], who used a similar experimental approach to show that behavior of adult Atlantic sturgeon (*Acipenser medirostris*), as measured by the timing of river outmigration, did not significantly differ between new releases and conspecifics tagged and released in prior years. Probability of detection near release sites was determined to be greater for recently-tagged lake sturgeon than for conspecifics tagged in prior years, which suggested that surgery may delay dispersal as has been observed for juvenile lingcod *Ophiodon elongatus* [23].

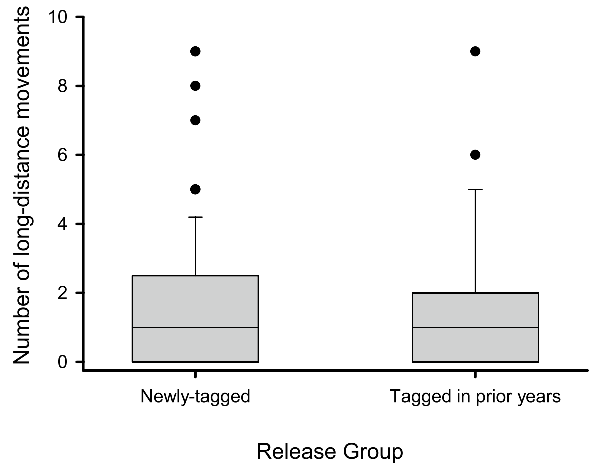

Fig. 5 Frequency of long-distance movements (median and quartiles) made by newly-tagged lake sturgeon observed during the first 15 days following surgery and release ($n = 77$) and simultaneously-observed conspecifics tagged in prior years ($n = 46$). *Error bars* represent the 10th and 90th percentiles

However, we suspect this difference is more likely related to the release of large numbers of newly-tagged individuals within a cluster of closely-spaced receivers. Discriminating between these two explanations will require additional experimentation.

For lake sturgeon, study results indicated a relatively low risk of biasing study conclusions by including all available detection data in data analyses. Some published telemetry studies have excluded as much as the entire first year of detection data due to concerns that behavior of newly-tagged individuals would not be representative of untagged conspecifics. Lack of evidence for changes in lake sturgeon behavior after intracoelomic tag implantation suggests that such measures are overly conservative for studies in which the goal is to describe migration or habitat use of long-lived species like sturgeon at seasonal or annual time scales. Effects of acoustic tag implantation on activity at hourly to daily time scales have been observed in some fish [23, 24], but would not have been detected in our study. Therefore, cautious interpretation of acoustic telemetry data remains warranted when the study objective is to use newly-tagged individuals to identify the timing of key biological events (e.g., spawning) or to pinpoint the locations of critical habitats (e.g., spawning sites) within 15 days of surgery and release.

Our results contribute to a growing body of literature suggesting that sturgeon are extremely resilient to handling and surgical implantation of electronic tags. We do not have direct estimates of mortality resulting from surgery, but expect that mortality from surgery was rare given that only one of the 86 lake sturgeon tagged in this study was never detected during the two-month study period. Lake sturgeon also seem to heal well from surgery, as we observed complete healing with excellent wound alignment in a lake sturgeon (transmitter ID = 27253) that was implanted with acoustic transmitter in 2013 (4 June 2013) and recaptured 360 days later (29 May 2014). These observations were consistent with laboratory studies on juveniles of other sturgeon species showing that surgical implantation of electronic tags did

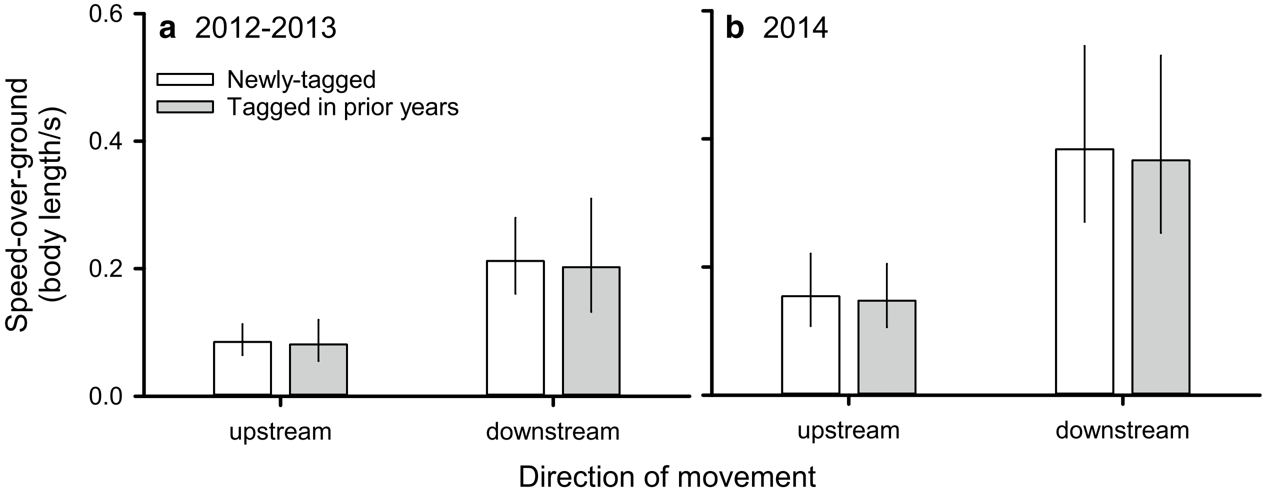

Fig. 6 Movement rates (speed-over-ground) of acoustic-tagged lake sturgeon by movement direction (upstream vs. downstream) during 2012–2013 (panel **a**) and 2014 (panel **b**). *Error bars* represent the 95 % confidence interval. Plot and data analyses were based on a total of 127 movements made by 59 newly-tagged individuals and 20 individuals tagged in prior years

Table 4 Output of GLMs used to analyze movement rates (speed-over-ground) of acoustic-tagged lake sturgeon

Phase	Model	IV(s)	*df*	AICc	*w*	*D** (*P*)
I	1	Null (intercept only)	121	−157.0	0.00	141.8 (0.09)
	2	Direction	120	−179.3	0.00	139.3 (0.11)
	3	Release group	120	−154.8	0.00	141.8 (0.08)
	4	Year	120	−163.6	0.00	140.9 (0.09)
II	5	Direction, release group	119	−178.0	0.00	139.2 (0.10)
	6	*Direction, year*	*119*	*−188.7*	*0.56*	*138.2 (0.11)*
III	7	Direction, year, release group	118	−186.6	0.19	138.2 (0.10)
IV	8	Direction, year, release group × direction	118	−187.0	0.24	138.1 (0.10)

IVs independent variables, *df* degrees of freedom, *AICc* Akaike's Information Criterion, *w* Akaike weights, and goodness of fit statistics (scaled deviance, *D**, and *P* value of associated Chi square test) for generalized linear models used to analyze movement rates (speed over ground) of acoustic-tagged lake sturgeon in the lower St. Clair River during 2012, 2013, and 2014. Release group identifies individuals observed 0–14 days post-surgery and simultaneously-observed conspecifics tagged in prior years. "Direction" (direction of movement) = upstream or downstream. The highest-ranking (best) model is italicized

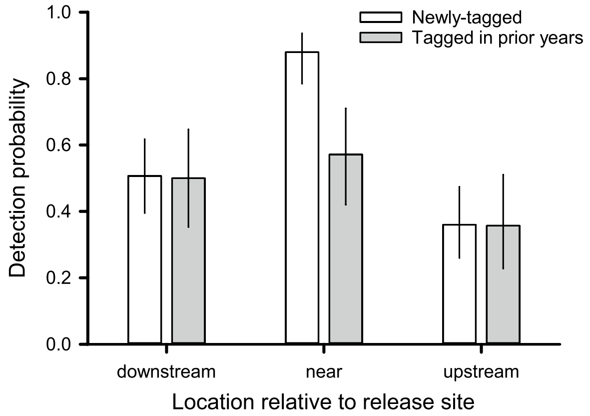

Fig. 7 Detection probabilities of acoustic-tagged lake sturgeon at locations <2 km from release sites ("near") and locations ≥2 km *downstream* or *upstream* of release sites for newly-tagged individuals during the first 15 days after release ($n = 75$) and simultaneously-observed conspecifics tagged in prior years ($n = 28$). *Error bars* represent the 95 % confidence interval

not increase mortality or limit wound healing, swimming performance, and/or growth [25–27]. Our findings also should apply to other makes and models of intracoelomic acoustic tags as the Vemco V16-6L acoustic tag used in this study is one of the largest available electronic transmitters designed for surgical implantation.

Difficulty with the determination of sex in the field limited our ability to detect whether being male or female affected behavior after tag implantation, and thus, may have introduced some bias into our analyses. The seriousness of this potential bias is difficult to assess given that sex-based differences in lake sturgeon activity, movements, and migration timing have been observed in some systems [28, 29] but not in others [30, 31]. Reproductive status also should be considered as an explanatory variable in future tagging effects studies on lake sturgeon given that activity may be greatest during the post-spawn phase [29, 30, 32]. Few (≤25 %) lake sturgeon in our study were spawning-ready, so results may be more representative of individuals in between spawning cycles than actively spawning fish.

Staggered-entry field movement studies provide a useful means to study the impacts of surgery on the behavior of acoustic-tagged fish, particularly in cases where laboratory experimentation is difficult or would influence fish behavior. Though lacking the same experimental rigor of controlled laboratory studies, field movement studies like the ones used here and in [6] are superior to longitudinal analyses of individual behavior from a single release event where variability in behavior due to surgery or tagging cannot be distinguished from responses to changes in the physical environment. Our approach took advantage of the ecological realism of an ongoing field study with multiple annual tagging events that is rarely available in laboratory assessments in which observed behaviors may not be representative of behavior observed in the field (e.g., [33]). Major assumptions of the staggered-entry approach are (1) that tag presence does not permanently alter the behavioral trajectory of an individual (a consequence of the absence of a sham treatment), and (2) that the behavior of tagged and untagged individuals converges at some point during the study (a consequence of the absence of a true control). The former has been taken as a given in most studies using large fish where tag burden is well below the common rule-of-thumb threshold of 2 % body mass [34]. Relative to the second assumption, we considered 1 year a reasonable timeframe given that surgical incisions closed with the same suture material as used in our study were completely healed without signs of inflammation after 140 days in 27 of 30 juvenile green sturgeon [27].

Table 5 Output of GLMs used to compare location-specific detection probabilities of acoustic-tagged lake sturgeon 0–14 days post-release and simultaneously-observed conspecifics tagged in prior years

Phase	Model	IV(s)	*df*	AICc	*w*	*D** (*P*)
I	1	Null (intercept only)	17	126.0	0.00	67.9 (<0.01)
	2	Release group	16	124.9	0.00	64.3 (<0.01)
	3	Year	15	131.2	0.00	67.7 (<0.01)
	4	Location	15	88.9	0.19	25.4 (0.04)
II	5	Location, release group	14	88.2	0.28	21.3 (0.09)
	6	Location, year	13	96.0	0.01	25.2 (0.02)
III	7	Location, release group, year	12	96.4	0.00	20.9 (0.05)
IV	*8*	*Location, release group, location × release group*	*12*	*86.9*	*0.53*	*11.4 (0.49)*
	9	Location, release group, year, location × release group	10	98.9	0.00	11.1 (0.35)
	10	Location, release group, year, location × year	8	119.8	0.00	12.6 (0.13)
	11	Location, release group, year, release group × year	10	108.6	0.00	20.8 (0.02)

IVs independent variables, *df* degrees of freedom, *AICc* Akaike's Information Criterion, *w* Akaike weights, and goodness of fit statistics (scaled deviance, *D**, and *P* value of associated Chi square test) for generalized linear models used to analyze probability of detection of acoustic-tagged lake sturgeon (0–14 days post-surgery vs. 1+ years post-surgery) at locations in the North Channel of the lower St. Clair River (≤2 km from release sites, >2 km upstream or downstream from release sites) during 2012, 2013, and 2014. Release group identifies individuals observed 0–14 days post-surgery and simultaneously-observed conspecifics tagged in prior years. The highest-ranking (best) model is italicized

Table 6 Output of GLMs used to compare location-specific detection probabilities of acoustic-tagged lake sturgeon 15–29 days post-release and simultaneously-observed conspecifics tagged in prior years

Phase	Model	IV(s)	*df*	AICc	*w*	*D** (*P*)
I	1	Null (intercept only)	17	74.4	0.04	21.5 (0.20)
	2	Release group	16	76.3	0.02	20.9 (0.18)
	3	Year	15	77.7	0.01	19.3 (0.20)
	4	*Location*	*15*	*68.8*	*0.68*	*10.5 (0.79)*
II	5	Location, release group	14	71.5	0.18	9.8 (0.78)
	6	Location, year	13	73.8	0.06	8.2 (0.83)
III	7	Location, release group, year	12	76.5	0.01	6.3 (0.90)
IV	8	Location, release group, location × release group	12	77.9	0.01	7.7 (0.81)
	9	Location, release group, year, location × release group	10	86.7	0.00	4.0 (0.95)
	10	Location, release group, year, location × year	8	107.3	0.00	5.3 (0.73)
	11	Location, release group, year, release group × year	10	86.7	0.00	4.0 (0.95)

IVs independent variables, *df* degrees of freedom, *AICc* Akaike's information criterion, *w* Akaike weights, and goodness of fit statistics (scaled deviance, *D**, and *P* value of associated Chi square test) for generalized linear models used to analyze probability of detection of acoustic-tagged lake sturgeon at locations in the North Channel of the lower St. Clair River (≤2 km from release sites, >2 km upstream or downstream from release sites) during 2012, 2013, and 2014. Release group identifies individuals observed 15–29 days post-surgery and simultaneously-observed conspecifics tagged in prior years. The highest-ranking (best) model is italicized

Conclusions

In summary, our study did not find evidence for surgery effects on activity or reach-scale distributions of acoustic-tagged lake sturgeon, which supports the validity of the assumption that tagged and untagged lake sturgeon behave similarly. Lack of evidence for changes in lake sturgeon behavior after surgical implantation of acoustic tags suggested that for many questions about lake sturgeon spatial ecology, analyses of all available lake sturgeon detection data will not bias study results. Our findings contribute to a growing scientific consensus that surgical implantation of acoustic tags has little, if any, effect on the behavior(s) of most sturgeon species. We argue that staggering the release of acoustic-tagged individuals across years as done in this study and in [6] or varying the delay between surgery and release as done in [23] provides a useful method to explore the effects of surgery on fish behavior in the field. Future studies may benefit from the staggered-entry design because it allows empirical evaluation of one of the most pervasive, untested assumptions in telemetry studies without tagging additional fish, conducting ancillary lab studies, or arbitrarily omitting data.

Availability of supporting data

The data supporting the results of this article are stored in the Great Lakes Acoustic Telemetry Observation System (GLATOS) database (http://data.glos.us/glatos). Data availability is subject to data sharing policies currently under development by GLATOS, the Great Lakes Fishery Commission, and the Unites States Geological Survey.

Authors' contributions

DWH led all aspects of study design, executed the field portion of the study, and drafted the manuscript. CMH and CCK participated in the design of the study, provided consultation on statistical analyses, and helped to draft the manuscript. All authors read and approved the final manuscript.

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Compliance with ethical guidelines

Competing interests

The authors declare that they have no competing interests.

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References

1. Steig T, Holbrook CM. Use of acoustic telemetry to evaluate survival and behavior of juvenile salmonids at hyrdoelectric dams: a case study from Rocky Reach Dam, Columbia River, USA. In: Adams NS, Beeman JW, Eiler JH, editors. Telemetry Techniques. Bethesda: American Fisheries Society; 2012. p. 361–87.
2. McDougall CA, Anderson WG, Peake SJ. Downstream passage of lake sturgeon through a hydroelectric generating station: route determination, survival, and fine-scale movements. N Amer J Fish Mgmt. 2014;34:546–58.
3. Bridger CJ, Booth RK. The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. Rev Fish Sci. 2003;11:13–34.
4. Cooke SJ, Woodley CM, BradEppard M, Brown RS, Nielsen JL. Advancing the surgical implantation of electronic tags in fish: a gap analysis and research agenda based on a review of trends in intracoelomic tagging effects studies. Rev Fish Biol Fish. 2010;21:127–51.
5. Kock A, O'Riain MJ, Mauff K, Meyer M, Kotze D, Griffiths C. Residency, habitat use and sexual segregation of white sharks, Carcharodon carcharias in False Bay, South Africa. PLoS One. 2013;8:e55048.
6. Balazik MT. Capture and brief invasive procedures using electronarcosis does not appear to affect postrelease habits in male atlantic sturgeon during the spawning season. N Amer J Fish Mgmt. 2015;35:398–402.
7. Lindley ST, Moser ML, Erickson DL, Belchik M, Welch DW, Rechisky EL, et al. Marine migration of North American green sturgeon. Trans Am Fish Soc. 2008;137:182–94.
8. Govinden R, Jauhary R, Filmalter J, Forget F, Soria M, Adam S, et al. Movement behaviour of skipjack (Katsuwonus pelamis) and yellowfin (Thunnus albacares) tuna at anchored fish aggregating devices (FADs) in the Maldives, investigated by acoustic telemetry. Aquat Liv Res. 2012;26:69–77.
9. Pickering AD, Pottinger TG. Stress responses and disease resistance in salmonid fish: effects of chronic elevation of plasma cortisol. Fish Phys Biochem. 1989;7:253–8.
10. Waring CP, Stagg RM, Poxton MG. The effects of handling on flounder (*Platichthys flesus* L.) and Atlantic salmon *(Salmo salar* L.). J Fish Biol. 1992;41:131–44.
11. Wagner GN, Stevens ED, Byrne P. Effects of suture type and patterns on surgical wound healing in rainbow trout. Trans Am Fish Soc. 2000;129:1196–205.
12. Wagner GN, Stevens ED, Harvey-Clark C. Wound healing in rainbow trout following surgical site preparation with a povidone-iodine antiseptic. J Anim Health. 1999;11:373–82.
13. Mulcahy DM. Surgical implantation of transmitters into fish. ILAR J. 2003;44:295–306.
14. Peterson D, Vecsei P, Jennings C. Ecology and biology of the lake sturgeon: a synthesis of current knowledge of a threatened North American Acipenseridae. Rev Fish Biol Fish. 2007;17:59–76.
15. Thomas MV, Haas RC. Abundance, age structure, and spatial distribution of lake sturgeon *Acipenser fulvescens* in the St. Clair system: State of Michigan, Division DoNRF. 2004. Report No.: 2076.
16. Boase JC, Diana JS, Thomas MV, Chiotti JA. Movements and distribution of adult Lake Sturgeon from their spawning site in the St. Clair River, Michigan. J Appl Icthy. 2011;27:58–65.
17. Thomas MV, Haas RC. Capture of lake sturgeon with setlines in the St. Clair River, Michigan. N Amer J Fish Mgmt. 1999;19:610–2.
18. Vecsei P, Litvak MK, Noakes DLG, Rien T, Hochleithner M. A noninvasive technique for determining sex of live adult North American sturgeons. Env Biol Fish. 2003;68:333–8.
19. Pincock DG. False detections: what they are and how to remove them from detection data: VEMCO2012, April 17, 2012. Report No.: DOC-004691-03 Contract No.: DOC-004691-03.
20. Arnold TW. Uninformative parameters and model selection using Akaike's information criterion. J Wildl Mgmt. 2010;74:1175–8.
21. Burnham KP, Anderson DR. Model selection and multimodel inference: a practical information-theoretic approach. New York: Springer; 2002.
22. Griffiths RW, Thornley S, Edsall TA. Limnological aspects of the St. Clair River. Hydrobiologia. 1991;219:97–123.
23. Lee JS, Tezak EP, Berejikian BA. Telemetry tag effects on juvenile lingcod *Ophiodon elongatus* movement: a laboratory and field study. J Fish Biol. 2013;82:1848–57.
24. Thoreau X, Baras E. Evaluation of surgery procedures for implanting telemetry transmitters into the body cavity of tilapia *Oreochromis aureus*. Aquat Liv Res. 1997;10:207–11.
25. Collins MR, Cooke DW, Smith TIJ, Post WC, Russ DC, Walling DC. Evaluation of four methods of transmitter attachment on shortnose sturgeon, *Acipenser brevirostrum*. J Appl Icthy. 2002;18:491–4.
26. Crossman JA, Hammell KL, Litvak MK. Experimental examination of surgical procedures for implanting sonic transmitters in Juvenile shortnose sturgeon and Atlantic sturgeon. N Am J Fish Mgmt. 2013;33:549–56.
27. Miller EA, Froehlich HE, Cocherell DE, Thomas MJ, Cech JJ, Klimley AP, et al. Effects of acoustic tagging on juvenile green sturgeon incision healing, swimming performance, and growth. Env Biol Fish. 2013;97:647–58.
28. Bruch RM, Binkowski FP. Spawning behavior of lake sturgeon (*Acipenser fulvescens*). J Appl Icthy. 2002;18:570–9.
29. Gerig G, Moerke A, Greil R, Koproski S. Movement patterns and habitat characteristics of Lake Sturgeon (*Acipenser fulvescens*) in the St. Marys River, Michigan, 2007–2008. J Great Lakes Res. 2011;37:54–60.

30. Auer NA. Population Characteristics and movements of lake sturgeon in the sturgeon river and lake superior. J Great Lakes Res. 1999;25:282–93.
31. Forsythe PS, Scribner KT, Crossman JA, Ragavendran A, Baker EA, Davis C, et al. Environmental and lunar cues are predictive of the timing of river entry and spawning-site arrival in lake sturgeon Acipenser fulvescens. J Fish Biol. 2012;81:35–53.
32. Rusak JA, Mosindy T. Seasonal movements of lake sturgeon in Lake of the Woods and the Rainy River, Ontario. Can J Fish Sci. 1997;74:383–95.
33. Moser ML, Ogden DA, Sandford BP. Effects of surgically implanted transmitters on anguilliform fishes: lessons from lamprey. J Fish Biol. 2007;71:1847–52.
34. Winter JD. Underwater biotelemetry. In: Nielsen LA, Johnson DL, editors. Fisheries techniques. Bethesda: American Fisheries Society; 1983. p. 371–95.