Journal of Great Lakes Research 46 (2020) 589–596

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/ijglr

You can't just use gold: Elevated turbidity alters successful lure color for recreational Walleye fishing

Chelsey L. Nieman *, Jeremy T. Bruskotter, Eugene C. Braig IV, Suzanne M. Gray

The Ohio State University, 2021 Coffey Road, 210 Kottman Hall, Columbus, OH 43210, United States

ARTICLE INFO

Article history:
Received 22 November 2019
Accepted 27 February 2020
Available online 18 March 2020
Communicated by R. Michael McKay

Keywords:
Algal blooms
Citizen science
Recreational fishing
Turbidity
Visual ecology
Walleye (*Sander vitreus*)

ABSTRACT

Increasing anthropogenic turbidity alters underwater visual environments, leading to disrupted perception of visual cues with a variety of consequences, such as diet shifts and reduced prey consumption. In this study, we used novel techniques, including a citizen science mobile phone application (app), to investigate the effects of altered water clarity on recreational fisheries. Our objectives were to determine if elevated turbidity (suspended sediments or algae) alters lure success in the recreational Walleye (*Sander vitreus*) fishery and if the behavior of recreational anglers shifts with algal blooms. We developed a mobile phone app to gather real time data on lure success across water clarity conditions in collaboration with Lake Erie charter captains. Citizen science data collected with the app showed that lure color success shifted with water color and clarity: white lures were most successful in clear water, yellow in sedimentary turbidity, and black in algal conditions. A survey of charter captains suggested that fishing practices and lure usage may change over the long term if algal blooms persist.

Introduction

Recreational fisheries are important generators of food, income, and social capital worldwide (Arlinghaus et al., 2002). The potential fish harvest from recreational fisheries is thought to represent around 12% of the global fish harvest annually (Cooke and Cowx, 2004). Many communities that have a long history of recreational fishing depend heavily on revenues brought in from these fisheries and fisheries-related tourism (Hushak et al., 1988; Lichtkoppler et al., 2015). Although declines in recreational fishing participation have been linked to shifting demographics (Fedler and Ditton, 2001; Arlinghaus, 2006), anglers are also sensitive to the quality of the environment (Holland and Ditton, 1992). Indeed, water quality and natural beauty are rated among the most important factors that influence recreational fishing enjoyment (Moeller and Engelken, 1972; Slagle et al., 2014). Thus, environmental change may be key to understanding shifting trends in recreational fishing participation.

Recreational fishing is likely to be altered by changes to the aquatic environment through alterations to ecological function, including how anglers interact with target species across a range of environmental conditions. Excessive sediment and nutrient loading are considered particularly detrimental to freshwater ecosystems, leading to elevated sedimentary turbidity and increased occurrence and severity of harmful algal blooms, respectively (Donohue and García Molinos, 2009; Michalak et al., 2013). Sedimentary turbidity can be elevated through increased sediment run-off from land use change, resuspension from more severe storm events associated with climate change, and increased dredging (reviewed in Dudgeon et al., 2006; Reid et al., 2018). Organic turbidity results from algal growth that is enhanced by nutrient inputs and eutrophication (Pearl and Otten, 2013). These stressors can result in physical damage to fish (e.g., abrasion of sensitive gill structures; Sutherland and Meyer, 2007), indirect impacts via altered visual landscapes (e.g., reduced visual sensitivity and foraging efficiency; Nieman et al., 2018; Nieman and Gray, 2019), and ultimately population shifts that alter the aquatic community (Kemp et al., 2011). Further, these stressors can result in drastic changes to the underwater visual environment.

Elevated turbidity from both inorganic and organic sources causes light entering the water to be scattered and absorbed. Thus, elevated turbidity decreases the amount of light available for vision, shifts the spectrum of light that may alter the perceived color and contrast of an object, and blurs visual resolution of objects (Lythgoe, 1979; Utne-Palm, 2002). Sedimentary turbidity typically reduces the amount of light with shifts in the color of light depending on the type of sediment. For example, suspended

---

* Corresponding author at: Cary Institute of Ecosystem Studies, United States.
E-mail address: niemanc@caryinstitute.org (C.L. Nieman).

https://doi.org/10.1016/j.jglr.2020.03.002

sand and volcanic ash can shift the light spectrum toward longer wavelengths (Storlazzi et al., 2015), whereas gray, clay-based sediments tend to have little impact on color of water (Nieman et al., 2018). Organic or algal turbidity reduces overall light intensity while also shifting the spectrum of available light towards green wavelengths (Levine and MacNichol, 1982; Sridhar and Vincent, 2007; Cronin et al., 2014).

From an angler's perspective, these changes to water clarity and color may imply that changing lure color would enhance the likelihood of success. Indeed, shifts in the available underwater light have been shown to shift prey selection, as well as alter foraging success (Benfield and Minello, 1996). As certain prey items become more or less visible, fish will strike on different prey objects. For example, the planktivorous bleak (*Alburnus alburnus*) reduces prey selectivity under increased levels of sedimentary turbidity (Liu and Uiblein, 1996). Largemouth bass (*Micropterus salmoides*) select alternative prey items in high turbidity, shifting from preying on a variety of fish and crayfish at low turbidities (0–5 Nephelometric Turbidity Units,NTU) to predominantly foraging on bluegill (*Lepomis macrochirus*) at higher turbidities (≥40 NTU; Shoup and Wahl, 2009). It is likely that shifts in the clarity and color of water associated with elevated turbidity will also alter fishes' probability of detecting certain lure colors and types.

Many factors influence the vulnerability of a fish to being caught by hook and line, including variability in the individual fish (e.g., boldness; Klefoth et al., 2017), and external factors, such as the environment in which the fish is found (reviewed in Lennox et al., 2017). For example, a fish motivated by hunger to forage is more likely to strike on bait (Sutter et al., 2012). Arlinghaus et al. (2008) found a positive relationship between gear size and size of captured fish, with larger natural bait attracting larger northern pike (*Esox lucius*) and reducing the incidence of small northern pike being hooked. A key factor that increases the likelihood of a fish striking a lure or hook is the sensory perception of that specific lure. Thus, the fish must have the sensory physiology to detect shapes and colors in particular environments. Anglers recognize this connection between the perceptual abilities of target species and water conditions, as evidenced in the design of lures to be generally shaped, and with color patterns similar to, prey items, and even designed to move in ways that make them appear as living prey organisms within the water column.

Lake Erie supports a robust recreational fishery; however, the lake is subject to elevated anthropogenic turbidity that has likely already altered the ecology of the lake and also influenced changes in recreational angler activity. For example, Gill et al. (2018) found in a series of qualitative interviews with Lake Erie charter captains that, overall, algal blooms detract from the appeal of fishing in Lake Erie. A 2014 survey found that 96% of anglers who fish on Lake Erie are aware of seasonal harmful algal blooms, and 50% of respondents either changed their desired fishing location or decided not to fish (Sohngen et al., 2015), likely resulting in significant decreases in the level of participation in recreational fishing within Lake Erie. Waterbodies that have historically high fishing pressure may no longer be able to support the economic systems that arose from historic efforts as anglers choose to fish in alternative locations. Many anglers will not fish in bloom conditions, citing a belief that fish avoid them (Gill et al., 2018). The substantial press coverage of current algal blooms in North America will therefore likely reduce participation in the fishery as anglers are less likely to fish in areas they perceive to be degraded (Gill et al., 2018).

Walleyes (*Sander vitreus*) are an economically and ecologically important species in Lake Erie. The Laurentian Great Lakes recreational fishery is one of the largest freshwater recreational fisheries, valued at around US$1.9 billion annually (U.S. Department of the Interior et al., 2011). Within the Great Lakes, over 584,000 anglers target primarily walleye (U.S. Department of the Interior et al., 2011). In fact, over 60% of private boat anglers and 82% of charter boat operations in Ohio's Lake Erie waters specifically target walleye (Ohio Department of Natural Resources, 2017). Walleye possess color vision, with two color-absorbing cones, a green cone (max absorbance 533 nm) and an orange-yellow twin cone (max absorbance 605 nm; Burkhardt et al., 1980). Walleyes also possess a specialized morphological structure, the *tapetum lucidum*, which is a layer of reflective material in the back of the retina that increases low light visual abilities (Ali and Anctil, 1977). Owing to their low-light visual capabilities, walleyes are known to forage primarily at low light levels such as dawn and dusk (Ryder, 1977); however, they will also forage during daylight hours in waters that exhibit moderate levels of turbidity (2.0–4.9 m Secchi depth; Einfalt et al., 2012). In a laboratory study, visual detection thresholds, or the turbidity level at which fish can no longer determine black and white contrast (3 cm wide stimulus, 18 cm diameter cylindrical tank, 9.5 degrees maximum angular size of stimulus), have been determined for both sedimentary (mean ± se: 100 ± 5.3 NTU) and algal (mean ± se: 40 ± 2.4 NTU) turbidities (Nieman et al., 2018). Further, research indicates that walleye foraging is more negatively affected by algal turbidity than sedimentary turbidity (Nieman and Gray, 2019), suggesting increased algal blooms in Lake Erie may detrimentally impact both walleye populations and the anglers who pursue them.

The objectives of this study were (1) to use novel citizen science techniques to understand how elevated turbidity affects lure color success in the recreational walleye fishery and (2) to understand how altered water clarity conditions alter behavior of recreational anglers. Here, we define lure success as the likelihood that a walleye is landed (following a strike and successful catch) by a specific lure or color contained on that lure, regardless of catch rate. We developed a mobile phone application (*The Walleye Tracker*) to collect citizen science data on the relationship between water clarity and recreational fisheries. To examine the changes to the success of lures of various colors, we collaborated with charter boat captains who operate in the western and central basins of Lake Erie. Our approach allowed us to collect data on which lure colors were successful in Lake Erie in a variety of water color and clarity conditions over two fishing seasons (2017–2018). This study is novel in the use of real-time collection of recreational fisheries data by anglers to link visual ecology with angling. In addition, we conducted a survey that was distributed to charter captains throughout United States waters of Lake Erie. This survey was used to gauge how factors such as the seasonal harmful algal blooms in western Lake Erie already influence fishing practices and how these environmental changes are perceived by those whose livelihood depends on the recreational fishing industry in Lake Erie.

Methods

Lure success citizen science project

We developed a mobile phone application (app), *The Walleye Tracker*, to collect citizen science data on walleye catches in Lake Erie under different water clarity conditions and to provide users with information about the project (Fig. 1). We provided each participant with a measurement card (Fig. 2) including instructions for using the app. For each submission through the app, captains were asked to provide spatiotemporal information about the catch and attach two photographs: one of the fish on the measurement card and one of the surface of the lake. Data collected in the app included date, location (latitude and longitude), boat ID, depth of lure at time of capture (ft), water temperature (°F), and cloud cover (%). The measurement cards included a color wheel and box for lure placement, a ruler for fish placement, and

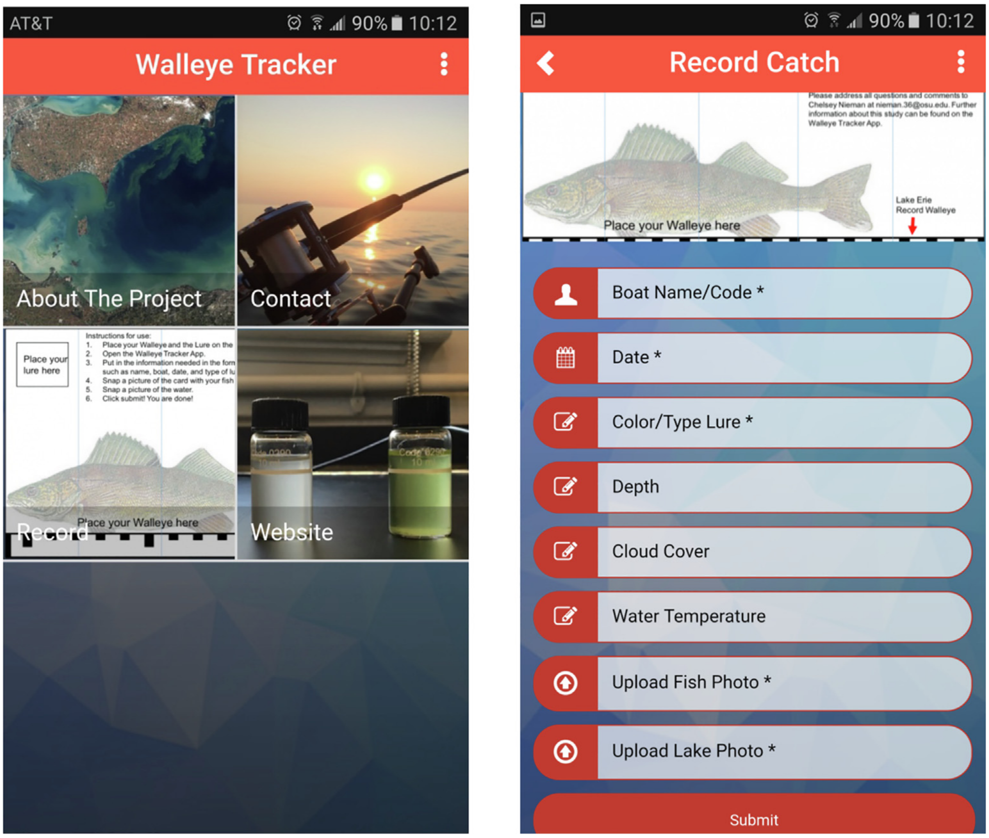
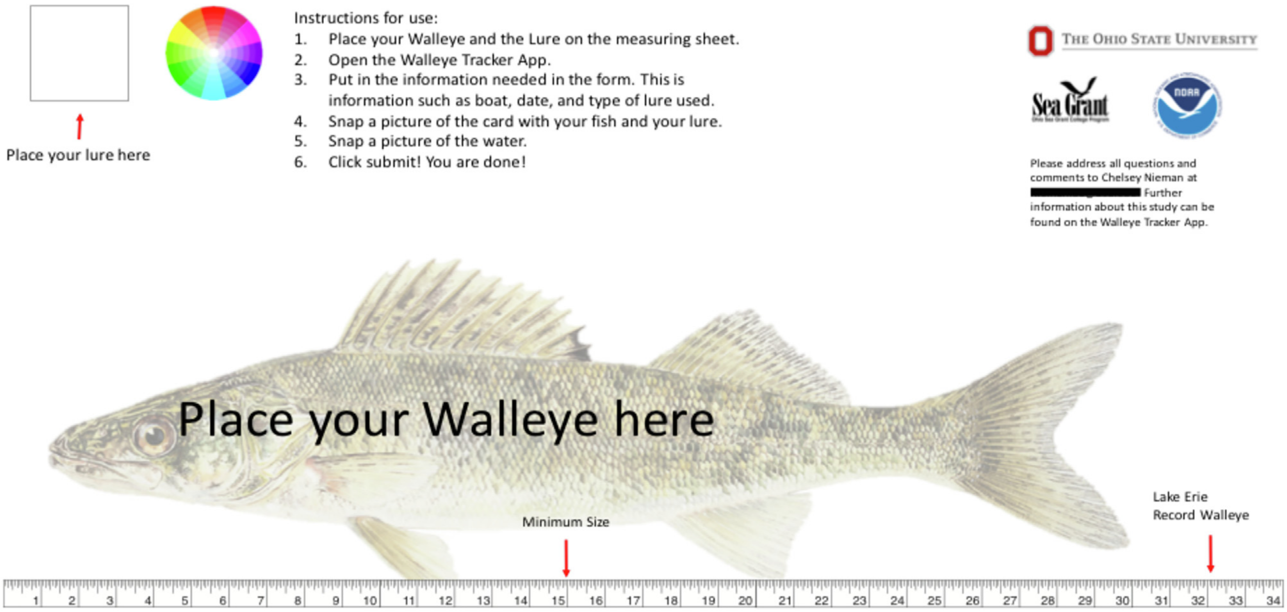


Fig. 1. Screenshots of the *Walleye Tracker* phone application interface used for data collection (developed by Chelsey Nieman).



Instructions for use:

1. Place your Walleye and the Lure on the measuring sheet.
2. Open the Walleye Tracker App.
3. Put in the information needed in the form. This is information such as boat, date, and type of lure used.
4. Snap a picture of the card with your fish and your lure.
5. Snap a picture of the water.
6. Click submit! You are done!

Please address all questions and comments to Chelsey Nieman at [redacted] Further information about this study can be found on the Walleye Tracker App.

Fig. 2. Example of the walleye measurement card that was distributed to charter captains who participated in the citizen science study.

general instructions to ensure all captains had a consistent format for photographs (Fig. 2). Measurement cards were distributed to 19 charter captains and anglers in the western (N = 16) and central (N = 3) basins of Lake Erie over two seasons. Submissions were filtered based on the presence of both photographs, georeferenced location availability, catch within the western basin, and all of the criteria present in fish photographs (i.e., lure, color wheel, full fish, and at least a portion of the ruler). Of 176 submissions, 66 were found to meet all appropriate criteria and were used for analysis.

Lure photographs were white-balanced using the white background of the measurement card in Adobe Photoshop (Adobe Acrobat Software, CC 2019). Photographs were cropped to extract only the lures. Lure images were saved as portable network graphics (png) files and imported into R (using the R package ‘png’ [Urbanek, 2015]) to analyze pixel color content (modified from coloration code by Logan James). Total pixel counts for red (hue = 0–26, 232–255), yellow (hue = 27–59), green (hue = 60–99), blue (hue = 100–180), and purple (hue = 181–232) were calculated using HSV (hue, saturation, value) hue criteria with a minimum saturation level of 40. Hue values ranged from 0 to 255. Colored pixels were then divided by total pixel count to determine the proportion of each lure that fell into each color category (proportion of color used for further analyses). Photographs were additionally imported into MATLAB (Mathworks), and total pure white and pure black pixels within the RGB (red green blue) image were counted. Black and white pixels were divided by total pixel count to determine the proportion of pure black and pure white pixels on the lure. Fish photographs were analyzed to determine total length of walleyes using ImageJ (NIH Image J, V. 1.52, 2018) for those fish in which the entire fish was present in the photograph and at least part of the ruler was visible.

We used the lake surface photographs in combination with publicly available water quality data, to categorize each photograph into a water condition group based on turbidity level and type at date of capture. Hierarchical cluster analysis was used to bin photographs based on the following variables: proportion of blue, green, and yellow pixels (as calculated within R in a similar method to the lure photographs (above)), sonde data including turbidity (NTU), chlorophyll *a* (Relative Fluorescence Units, RFU), and blue-green algae levels (RFU), and Harmful Algal Bloom (HAB) severity index (NOAA, 2018) on the date the fish was caught, and MODIS satellite (NOAA Coastwatch, 2018). Sonde data was used from the nearest georeferenced Great Lakes Environmental Research Laboratory (GLERL) monitoring buoy on Lake Erie (GLERL, 2018). Satellite photographs were used to determine whether a bloom was present on the lake, and whether the specific location at which the fish was caught was within bloom conditions, as determined by MODIS satellite bloom thresholds (NOAA Coastwatch, 2018). The cluster analysis revealed five categories: low turbidity/clear conditions, moderate sedimentary turbidity, high sedimentary turbidity, moderate algal turbidity, and high algal turbidity (see Electronic Supplementary Material (ESM) Appendix S1). Low turbidity/clear conditions did not segregate into algal or sedimentary turbidity type and instead represented the clearest conditions found in our study area on Lake Erie. For analysis, moderate and high algal turbidity catch events were grouped together and moderate and high sedimentary turbidity were grouped together, creating three turbidity conditions: algal, sedimentary, and ‘clear’.

We investigated the relationship between depth and water conditions in which fish were caught using ANOVAs. Linear discriminant analysis was used to assess the variation among the discriminant group of turbidity type to determine which factors were driving catch successes in each visual environment. Factors included were those that were *a priori* determined to be significant (i.e., fish length, lure color as relative pixel proportion of each color and depth). Multivariate analysis of variance (MANOVA) was used to assess the relationship between water condition and lure coloration (with proportion of each potential color) to determine specific colors that were significant drivers of success. As most lures were comprised of more than one color category, our analysis included all colors contained within each lure for each color category. A secondary linear discriminant analysis was performed that included only those lure colors deemed important (i.e. significant) through the MANOVA. This analysis was used to determine which of the significant lure colors were driving success in different water clarity conditions. All statistical analyses were performed within the statistical program R (R Development Core Team, 2018).

Survey

Members of the Lake Erie Charter Boat Association (LECBA) were asked at the 35th Annual Lake Erie Charter Captains Conference in Huron, Ohio, if they would be willing to participate in a study, of which 37 captains (out of 80 in attendance or about 46%) indicated an interest in participation. The survey was created and distributed using Qualtrics survey software (Qualtrics, LLC) to the interested participants via email (ESM Appendix S2; Ohio State University Institutional Review Board Protocol 2016E0315). The survey focused on assessment of recreational walleye fishing practices on Lake Erie, and how algal blooms altered both personal angling activities and fishing activities undertaken with clients. Survey responses were analyzed on a 5-point bipolar response scale with values ranging from “definitely no” (score = −2) to “definitely yes” (score = +2). A value of 0 indicated indifference or no strong opinions one way or another. Deviation from zero was used to analyze the responses to understand the magnitude of the positive or negative responses.

Quality assurance

Survey results and citizen-science submissions were dissociated from respondent personal information to protect personal information. While citizen science allows for the collection of large volumes of data, we must address inherent likely sources of error and bias (Dickinson et al., 2010). For example, participation in the study was voluntary, and participants could submit as many or as few data points as was convenient to them. This led to highly varied participation rates, with participation being higher on those days that fewer fish were caught, as reported by charter captains. Additionally, there was substantial variation in photograph quality. For example, some pictures did not capture the full fish, were missing part of the lure, or obstructions were present in the photographs of the lake. Photographs in which the fish was partially obscured were still used as long as the entire eye and the snout and tail of the fish were present, as well as some portion of the measurement ruler.

Results

Citizen science lure color

Of 176 submissions, 66 data points fit all of our analysis criteria. Caught fish averaged 52.04 ± 1.472 cm (mean ± SE; 20.49 ± 0.579 in.) in total length. Lake images all fell under 1 of 5 categories: clear/low turbidity, moderate sedimentary turbidity, high sedimentary turbidity, moderate algal turbidity, or high algal turbidity. Catches in sedimentary turbidity occurred primarily during the spring or early summer, whereas catches in algal turbidity happened during late summer and early fall (Fig. 3), closely matching time of year in which these specific conditions occur. While half (5/10) of the catches that occurred in clear/low turbidity conditions occurred during the late fall, the remainder of these catches were interspersed throughout the year. There was a significant relationship between depth at which fish were caught and turbidity level, with fish in the highest turbidity caught at the shallowest depth ($F_{2,55} = 39.08$, $p < 0.001$; Fig. 4). Depth of lure at time of capture did not vary across turbidity type (i.e., algal or sedimentary).

Linear discriminant 1 (LD1) explained more than 88.3% of observed variation in discriminant analysis that included all potential factors (fish length, lure color as relative pixel proportion of each color, and depth caught) with those fish caught in the clear-water category, clearly separating from those caught in turbid-water categories (Fig. 5a). The second axis, LD2, explained most

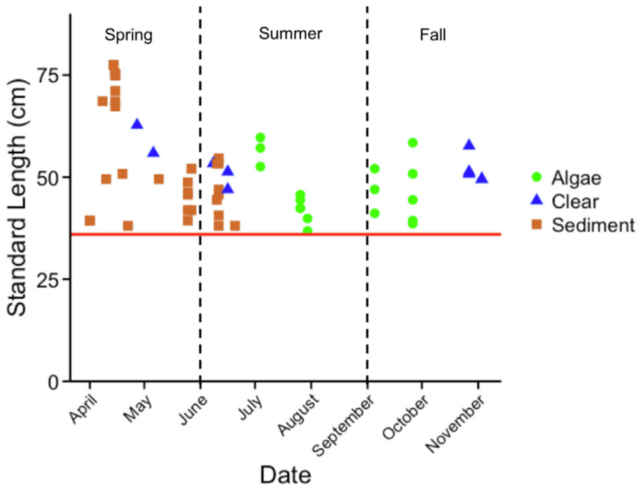


Fig. 3. Standard length (cm) of each fish caught by date (month and day). Points represent individual fish caught as reported by charter captains. Colors represent turbidity type at time of capture as determined by photo analysis (see methods; green = algal, blue = clear, brown = sedimentary). Vertical dashed lines represent seasonal distinctions. Minimum legal harvest size (15 in. or 38.1 cm) is denoted by the horizontal red line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

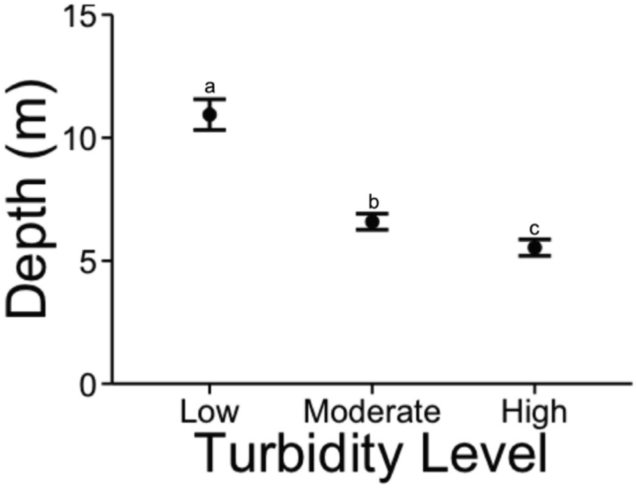


Fig. 4. Depth (m; mean ± se) of reported Walleye catch under three general turbidity categories: low, moderate and high (as determined by hierarchical cluster analysis). Lower-case letters represent significant differences (α = 0.05).

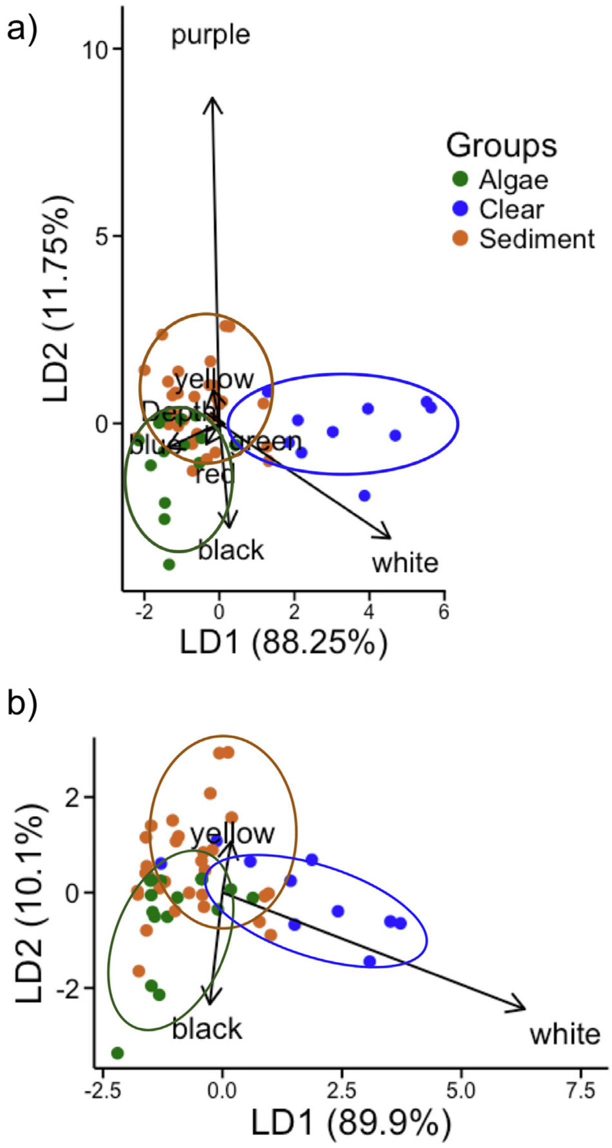


Fig. 5. Biplot of linear discriminant analysis that included (a) all factors driving lure success including fish length, lure color (red, yellow, blue, green, purple, black, or white), and depth; and (b) only those lure colors (black, white, or yellow) found significant in the multiple analysis of variance (MANOVA). Catch successes are represented by points and are grouped by turbidity type in which the fish water caught (clear = blue, sedimentary = brown, algal = green). Ellipsoids represent discriminant groupings of fish caught by turbidity type. Arrows represent relative contribution of each factor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the separation between algal and sedimentary turbidity (11.8%). Discriminant analysis revealed the importance of white in lure success in clear conditions (Fig. 5a). MANOVA revealed that the colors driving lure success with respect to turbidity type were black ($F_{2,55} = 4.47$, $p = 0.02$), white ($F_{2,55} = 25.43$, $p < 0.001$), and yellow ($F_{2,55} = 3.98$, $p = 0.02$). No relationship was found between lure success and purple ($F_{2,55} = 2.37$, $p = 0.10$), red ($F_{2,55} = 0.58$, $p = 0.56$), blue ($F_{2,55} = 1.50$, $p = 0.23$), or green ($F_{2,55} = 0.90$, $p = 0.41$). A discriminant analysis was also performed with only the three colors determined to be significant in the MANOVA (yellow, black, white; Fig. 5b). The LD1 of this second test explained 89.9% of the variation and highlighted the differences between fish caught in turbid vs. clear conditions. The second linear discriminant explained 10.1% of the variation and again highlighted the distinction between lure success in algal compared to sedimentary turbidity. We found that white coloration is related to lure success in clear conditions, while more ‘yellow’ (including ‘gold’) pixels associated with success in sedimentary turbidity, and black coloration with success in algal turbidity.

Survey

Response rate for the survey was 38%, with 14 out of 37 potential respondents fully completing the survey (of ~80 attendees at the conference). Charter captains surveyed had been working in the fishing industry on Lake Erie for an average of 10.33 ± 2.9 years. Respondents indicated that during the time they have been fishing, algal blooms have become an increasing concern, with the last 3–7 years (from 2016) having algal blooms directly affecting the recreational fishing industry on Lake Erie. Many respondents (69.2%) claimed a loss of 0–5 fishing days per year because of algal

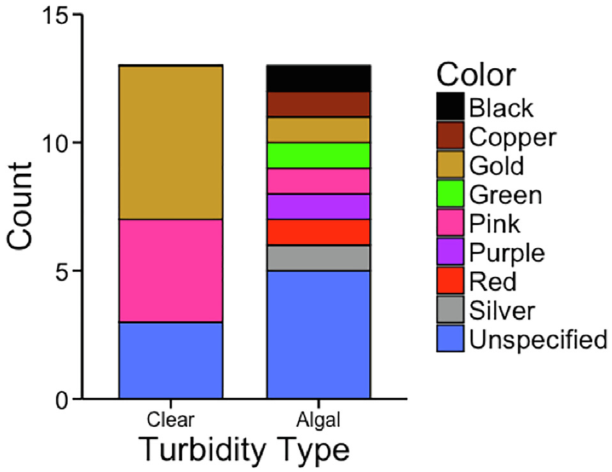


Fig. 6. Lure colors that charter captains (N = 14) indicated they use in conditions in which there is no algae present (Clear) and the colors they switch to in the presence of algal blooms (Algal).

blooms (mean = 4.2 days), with other captains (23%) citing between 5 and 15 days lost. Captains said they were likely (mean = 0.92 "probably yes"; median = 42% "definitely yes") to take clients fishing when algal blooms were present on the lake; however, they were less likely to fish themselves when bloom conditions were present (mean = 0.42, "slight yes"; median = 42% "definitely yes"). Captains were slightly unlikely (mean = −0.17, "very slight no"; median = 67% "might or might not") to take clients to fishing locations in an algal blooms but were neither likely nor unlikely to fish in these conditions themselves (mean = 0.0833; median = 42% "might or might not"). While captains travel 7.4 ± 0.9 miles (11.9 ± 1.4 km) from their harbor (range: 124 miles), it was found that they were likely to move away (mean = 0.75 "probably yes"; median = 75% "probably yes") from bloom conditions until they were about 2.6 ± 1.3 miles (4.2 ± 2.1 km) from the bloom. Many respondents moved away from bloom conditions until the bloom had thinned out.

Captains surveyed primarily trolled or drifted for walleyes and were not likely to change their gear based on the presence or absence of an algal bloom (mean = −1, "probably no"; median = 50% "probably no"). Half the respondents (50%) claimed to use primarily gold-colored lures in the absence of an algal bloom, while another 33% claimed they primarily use pink lures. While most respondents were slightly unlikely to change lure color in algal blooms (mean = −0.5 "slight no"; median = 33% "slight no"), of those that said they would switch lures in bloom conditions, there was no consensus on the color (Fig. 6). In fact, of all colors mentioned as a color a charter captain would switch to in algal bloom conditions, no one color was mentioned more than once, and the dominant color category was "other."

Discussion

This study focused on the usage of a citizen science data collection app (*The Walleye Tracker*) to collect real-time ecological data from recreational anglers in Lake Erie. This methodology allowed for relatively low-cost data collection and allowed for direct engagement of stakeholders who value the fishery. As mobile phone apps gain popularity among scientists (Silvertown, 2009), it is important to recognize not only the limitations, but also the possibilities for use. Our study design allowed us to draw from the vast source of local knowledge that anglers on Lake Erie already possess about the system in which they fish. We were able to increase our understanding of angler responses to algal bloom conditions, as well as assess likely fish responses to lure color based on visual physiological responses to altered water clarity conditions. Coupling human dimensions research with ecological research enhances our understanding of the dynamics at play in a complex recreational fisheries system.

We found lures with a higher proportion of white pattern elements were more successful in clear water with relatively low turbidity. While there was a high level of overlap between successful lure color in sedimentary and algal turbidity, lures with a higher proportion of black were more successful in algal conditions while yellow lures tended to be more successful in sedimentary turbidity. This may suggest that both brightness (achromatic) contrast (Cronin et al., 2014) and color (chromatic) contrast could play a role in lure success based on color in differing visual environments (Sibeaux et al., 2019). In a study focusing on the influence of color on catch rates, Moraga et al. (2015) found that the specific lure color did not significantly influence catch rates of largemouth bass under consistent water clarity conditions. However, brightly colored lures (e.g., orange or white) tended to attract larger fish than more natural-colored lures in that study. While the importance of lure color is considered common knowledge among anglers, few studies have directly quantified the relationship between species-specific visual abilities, the underwater visual environment, and lure color. For walleye, artificial baits tend to result in larger fish caught and decreased hooking mortality compared to natural baits (Payer et al., 1989). This may partly be due to the way artificial baits can take advantage of color contrast against the prevailing spacelight. Contrast of certain prey species, such as relatively transparent zooplankton, is higher at low to moderate turbidity and can actually increase success of foraging by planktivorous fish (Utne-Palm, 2002). The constraints of our study do not allow for us to assess catch per unit effort of specific lure colors in different conditions; however, we did find evidence that differently colored lures are in fact more successful in different water conditions. Additionally, it is likely that there are drivers other than lure color that influence lure success. Future work on this system should incorporate other lure elements, such as texture, shape, and smell that likely contribute to walleye strikes on certain lures.

Fish in turbid conditions were more vulnerable to being caught at shallow depths. This correlated with the way that light penetrates the water column, with low light levels occurring at shallower depths in high turbidity compared to low turbidity. Depth of fish caught may be related to foraging depth. Turbidity can alter fish distributions in the water column, with elevated turbidity resulting in larval shad (*Dorosoma* spp.) and larval freshwater drum (*Aplodinotus grunniens*) distributing higher in the water column than they would in clear waters (Matthews, 1984). Walleyes forage optimally at specific light levels, therefore, elevated turbidity will likely alter distribution of thermal-optical habitat (Lester et al., 2004), allowing walleyes to shift higher in the water column than in clearer conditions.

While fish caught in sedimentary turbidity were longer than fish in algal turbidity, this is likely related to the relationship between length and seasonal variation in size distributions (Kershner et al., 1999). Fish caught in spring are likely walleyes that will migrate towards the central and eastern basins of Lake Erie and no longer be present in the western basin. Additionally, it is likely that larger fish are caught and removed earlier in the spring, and so these fish are no longer available within the lake to catch later in the fishing season. There is also the possibility that the increased size of spring fish reported in our study may be related to effort and reporting bias as it is likely that increased effort in spring relates to a reporting bias by charter captains in our data set. Our study does not allow us to disentangle the effects of size, water clarity, and fishing effort.

Our survey showed that while algal blooms are likely not ruining entire fishing seasons, there is an indication of likely economic loss (as measured by loss in days fishing) for charter captains when harmful algal blooms are present. Additionally, the perceived bias of algal blooms being ''low quality water'' (Sohngen et al., 2015), might shift recreational fishing that would traditionally occur in western Lake Erie to alternative locations; a consequence that would result in long-lasting negative regional economic impacts on the Lake Erie walleye fishery. A survey of over 100 anglers by Moeller and Engelken (1972) found that high water quality was consistently rated as one of the most important factors in determining success of a fishing endeavor—rated higher even than size and number of fish caught. We found a similar trend, with charter captains indicating a relatively negative view of fishing in algal blooms; while they were more likely to fish in bloom conditions with paying clients, they were less likely to fish themselves, indicating that economic considerations might outweigh the negative perceptions of algal blooms.

The survey also indicated that, while some captains chose to change their preferred lure color in reduced water clarity, there was no consensus on the color to which captains would switch. Many captains chose lure color based on previous experience and successes (Captain D. Spangler, personal communication). As algal bloom conditions are somewhat novel, there may not be a strong base of conventional knowledge on which colors will be successful. The shallow, western basin of Lake Erie tends to have elevated sedimentary turbidity during and after storm events, particularly in the spring (Lick et al., 1994). Conditions of high sedimentary turbidity are common in Lake Erie – especially in spring time. Many captains cited the use of gold lures for these conditions, and our study suggests that these lures are likely more effective in low to moderate levels of sedimentary turbidity often found in the western basin. However, algal turbidity is avoided and as such, charter captains have less experience fishing in these conditions. Although it is logical to apply knowledge of lure use under sedimentary turbidity to algal turbidity, our study suggests such application would lead to decreased success.

The novel use of citizen science in this study provides a key new strategy for natural resource managers. While some of the data were ultimately deemed unusable for our specific analyses, the use of citizen science allowed us to reach a larger audience than is usual within traditional research methodologies. We were able to both use local knowledge and to further understand motivations of charter captains in a way that benefited captains. Further, it was relayed to us that captains would use the study as a teaching moment to invest clients in conservation practices and increase awareness of water quality issues (Captain C. Mader, personal communication). Increasing stewardship among anglers can promote trust and increase the likelihood of participation in conservation initiatives (Granek et al., 2008). We incorporated key basic knowledge on visual abilities of target fish with the effects of anthropogenically altered environments in a way that is directly applicable to fisheries management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the survey respondents and members of the Lake Erie Charter Boat Association (LECBA) for participating in the project. Further, we thank T. Gabriel and Ohio Sea Grant College Program for facilitating collaboration with LECBA. We also thank L. Pintor and S. Ludsin for input and ideas throughout the experimental design process. Funding for this project was provided by the Ohio Sea Grant Large Grant Program to SMG, JTB, and EB. We would further like to thank the reviewers for helping us to improve this work.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2020.03.002.

References

Ali, M.A., Anctil, M., 1977. Retinal structure and function in the walleye (*Stizostedion vitreum vitreum*) and Sauger (*S. canadense*). J Fish. Res. Board. Can. 34, 1467–1474.

Arlinghaus, R., Mehner, T., Cowx, I.G., 2002. Reconciling traditional inland fisheries management and sustainability in industrialized countries, with emphasis on Europe. Fish Fish. 3, 261–316.

Arlinghaus, R.T., 2006. Understanding recreational angling participation in Germany: Preparing for demographic change. Hum. Dimens. Wildl. 11, 229–240.

Arlinghaus, R.T., Klefoth, T., Kobler, A., Cooke, S.J., 2008. Size selectivity, injury, handling time, and determinants of initial hooking mortality in recreational angling for Northern Pike: the influence of type and size of bait. N. Am. J. Fish. Manag. 28, 123–134.

Benfield, M.C., Minello, T.J., 1996. Relative effects of turbidity and light intensity on reactive distance and feeding of an estuarine fish. Environ. Biol. Fish. 46, 211–216.

Burkhardt, D., Hassin, G., Levine, J., MacNichol, E.F., 1980. Electrical responses and photopigments of twin cones in the retina of the Walleye. J. Physiol. 309, 215–228.

Cooke, S.J., Cowx, I.G., 2004. The role of recreational fishing in global fish crises. BioSci. 54, 857–859.

Cronin, T.W., Johnsen, S., Marshall, N.J., Warrant, E.J., 2014. Visual Ecology. Princeton University Press, Princeton, NJ.

Dickinson, J.L., Zuckerberg, B., Bonter, D.N., 2010. Citizen science and an ecological research tool: challenges and benefits. Annu. Rev. Ecol. Evol. System. 41, 149–172.

Donohue, I., García Molinos, J., 2009. Impacts of increased sediment loads on the ecology of lakes. Biol. Rev. 84, 517–531.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Leveque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163–182.

Einfalt, L.M., Grace, E.J., Wahl, D.H., 2012. Effects of simulated light intensity, habitat complexity and forage type on predator-prey interactions in walleye *Sander vitreus*. Ecol. Freshw. Fish. 21, 560–569.

Gill, D., Rowe, M., Josh, S.J., 2018. Fishing in greener waters: Understanding the impact of harmful algal blooms on Lake Erie anglers and the potential for adoption of a forecast model. J. Environ. Manag. 227, 248–255.

Granek, E.F., Madin, E.M.P., Brown, M.A., Figueira, W., Cameron, D.S., Hogan, Z., Kristianson, G., de Villiers, P., Williams, J.E., Post, J., Zahn, S., Arlinghaus, R., 2008. Engaging recreational fishers in management and conservation: global case studies. Conserv. Biol. 22, 1125–1134.

National Oceanic and Atmospheric Administration, 2018. HAB Operational Forecast System Bulletin.

NOAA Coastwatch, 2018. Great Lakes MODIS Imagery. Available at: https://coastwatch.glerl.noaa.gov/modis/ (last accessed 29 November 2018).

Great Lakes Environmental Research Laboratory, 2018. Lake Erie Archived Real-Time Data. [Unpublished raw data]. Available at: https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/rtMo nSQL.php. (last accessed 29 November 2018).

Holland, S.M., Ditton, R.B., 1992. Fishing trip satisfaction: a typology of anglers. N. Am. J. Fish. Manag. 12, 28–33.

Hushak, L.J., Winslow, J.M., Dutta, N., 1988. Economic value of great lakes sportfishing: the case of private-boat fishing in Ohio's Lake Erie. T. Am. Fish. Soc. 117, 363–373.

Kemp, P., Sear, D., Collins, A., Naden, P., Jones, I., 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. 25, 1800–1821.

Kershner, M.W., Schael, D.M., Knight, R.L., Stein, R.A., Marschall, E.A., 1999. Modeling sources of variation for growth and predatory demand of Lake Erie walleye (*Stizostedion vitreum*), 1986–1995. Can. J. Fish. Aquat. Sci. 56, 527–538.

Klefoth, T., Skov, C., Kuparinen, A., Arlinghaus, R., 2017. Toward a mechanistic understanding of vulnerability to hook-and-line fishing: boldness as the basic target of angling-induced selection. Evol. Appl. 10, 994–1006.

Lennox, R.J., Alós, J., Arlinghaus, R., Horodysky, A., Klefoth, T., Monk, C.T., Cooke, S.J., 2017. What makes fish vulnerable to capture by hooks? A conceptual framework and a review of key determinants. Fish Fish. 18, 986–1010.

Lester, N.P., Dextrase, A.J., Kushneriuk, R.S., Rawson, M.R., Ryan, P.A., 2004. Light and temperature: key factors affecting walleye abundance and production. T. Am. Fish. Soc. 133, 588–605. https://doi.org/10.1577/T02-111.1.

Levine, J.S., MacNichol, E.F., 1982. Color vision in fishes. Sci. Am. 246, 140–149.

Lichtkoppler, F., O'Keefe, D.M., Lucente, J., Gabriel, T., 2015. The great lakes charter fishing industry: 2002 to 2011. Fish. 40, 200–212.

Lick, W., Lick, J., Ziegler, C.K., 1994. The resuspension and transport of fine-grained sediments in Lake Erie. J. Great Lakes Res. 20, 599–612.

Liu, Z., Uiblein, F., 1996. Prey detectability mediates selectivity in a zooplanktivorous cyprinid (*Alburnus alburnus* (L.)). Sitzungsber. Abt. I. 203, 3–13.

Lythgoe, J.N., 1979. The Ecology of Vision. Clarendon Press, Oxford.

Matthews, W.J., 1984. Influence of turbid inflows on vertical distribution of larval shad and freshwater drum. T. Am. Fish. Soc. 113, 192–198.

Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., Chaffin, J.D., Cho, K., Confessor, R., Dalağlu, I., DePinto, J.V., Evans, M.A., Fahnenstiel, G.L., He, L., Ho, J.C., Jenkins, L., Johengen, T.H., Kuo, K.C., LaPorte, E., Liu, X., McWilliams, M.R., Moore, M.R., Posselt, D.J., Richards, R.P., Scavia, D., Steiner, A.L., Verhamme, E., Wright, D.M., Zagorski, M.A., 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proc. Natl. Acad. Sci. 110, 6448–6452.

Moeller, G.H., Engelken, H.H., 1972. What fishermen look for in a fishing experience. J. Wildl. Manag. 36, 1253–1257.

Moraga, A.D., Wilson, A.D.M., Cooke, S.J., 2015. Does lure colour influence catch per unit effort, fish capture size and hooking injury in angled largemouth bass? Fish. Res. 172, 1–6.

Nieman, C.L., Oppliger, A., McElwain, C., Gray, S.M., 2018. Visual detection thresholds in two trophically distinct fishes are compromised in algal compared to sedimentary turbidity. Conserv. Physiol. 6. https://doi.org/10.1093/conphys/coy044.

Nieman, C.L., Gray, S.M., 2019. Visual performance impaired by elevated sedimentary and algal turbidity in walleye *Sander vitreus* and emerald shiner *Notropis atherinoides*. J. Fish Biol. 95, 186–199. https://doi.org/10.1111/jfb.13878.

Ohio Division of Natural Resources (ODNR), 2017. Ohio's Lake Erie Fisheries, 2016. Annual Status Report. Federal Aid in Fish Restoration Project F-69-P. Ohio Department of Natural Resources, Division of Wildlife, Lake Erie Fisheries Units, Fairport and Sandusky.

Payer, R.D., Pierce, R.B., Pereira, D.L., 1989. Hooking mortality of walleyes caught on live and artificial baits. N. Am. J. Fish. Manag. 9, 188–192.

Pearl, H.W., Otten, T.G., 2013. Harmful cyanobacterial blooms: causes, consequences, and controls. Microb. Ecol. 65, 995–1010.

R Development Core Team. 2018. R: A language and environment for statistical computing. Vienna, Austria.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2018. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873.

Ryder, R.A., 1977. Effects of ambient light variation on behavior of yearling, subadult, and adult Walleyes (*Stizostedion vitreium vitreum*). J. Fish. Res. Board Can. 34, 1481–1491.

Shoup, D.E., Wahl, D.L., 2009. The effects of turbidity on prey selection by piscivorous largemouth bass. Trans. Am. Fish. Soc. 138, 1018–1027.

Sibeaux, A., Cole, G.L., Endler, J.A., 2019. The relative importance of local and global visual contrast in mate choice. Anim. Behav. 154, 143–159.

Silvertown, J., 2009. A new dawn for citizen science. Trends Ecol. Evol. 24, 467–471.

Slagle, K., Bruskotter, J.T., Toman, E., 2014. Retention of Ohio Anglers. The Ohio State University, School of Environment and Natural Resources, and the Ohio Department of Natural Resources, Division of Wildlife.

Sohngen, B., Zhang, W., Bruskotter, J., Sheldon, B., 2015. Results from a 2014 survey of Lake Erie anglers. Final report submitted to the Lake Erie Protection Fund.

Storlazzi, C.D., Norris, B.N., Rosenberger, K.J., 2015. The influence of grain size, grain color, and suspended-sediment concentration on light attenuation: why fine-grained terrestrial sediment is bad for coral reef ecosystems. Coral Reefs. 34, 967–975.

Sridhar, B.B.M., Vincent, R.K., 2007. Spectral reflectance measurements of a Microcystis bloom in Upper Klamath Lake. Oregon. J. Great Lakes Res. 33, 279–284.

Sutherland, A.B., Meyer, J.L., 2007. Effects of increased suspended sediment on growth rate and gill condition of two southern Appalachian minnows. Environ. Biol. Fish. 80, 389–403.

Sutter, D.A., Suski, C.D., Philipp, D.P., Klefoth, T., Wahl, D.H., Kersten, P., Cooke, S.J., Arlinghaus, R., 2012. Recreational fishing selectivity captures individuals with the highest fitness potential. Proc. Natl. Acad. Sci. 109, 20960–20965. https://doi.org/10.1073/pnas.1212536109.

U.S. Department of the Interior, U.S. Fish and Wildlife Service, U.S. Department of Commerce, U.S. Census Bureau, 2011. National Survey of Fishing, Hunting, and Wildlife-Associated Recreation.

Utne-Palm, A.C., 2002. Visual feeding of fish in a turbid environment: Physical and behavioural aspects. Mar. Freshw. Behav. Physiol. 35, 111–128.

Urbanek, S. 2015. Package 'png'. R package version 0.1-7.