Water Air Soil Pollut (2014) 225:1869
DOI 10.1007/s11270-014-1869-1

Exploring the Potential Effects of Lost or Discarded Soft Plastic Fishing Lures on Fish and the Environment

T. Raison · A. Nagrodski · C. D. Suski · S. J. Cooke

Received: 18 September 2013 / Accepted: 9 January 2014

Abstract As the popularity and use of soft plastic lures (SPLs) by recreational anglers have increased in recent years, so does the number of anecdotal reports of SPLs being found in aquatic environments and in the digestive tract of a variety of fish species. We used a multistep approach to determine the possible consequences of SPLs on fish and aquatic environments. Field work focussed on lake trout (*Salvelinus namaycush*) and smallmouth bass (*Micropterus dolomeiu*) in Charleston Lake in eastern Ontario, a system identified by resource managers and the lake association as potentially having an SPL problem based on numerous anecdotal reports from anglers. Snorkel surveys revealed that the deposition rate of SPLs was potentially as high as ~80 per km of shoreline per year. In the laboratory, eight different types of SPLs were immersed in water at two temperatures (4 and 21 °C) for a 2-year period to evaluate change in SPL size (both swelling and decomposition). Despite SPLs varying by manufacturer and in composition, there was little evidence of decomposition. Indeed, most SPLs swelled and remained that way throughout the study. In cold water, SPLs increased an average of 61 % in weight and 19 % in length, while warm water treatments experienced an increase of 205 % in weight and 39 % in length. A summer creel survey conducted on Charleston Lake revealed that 17.9 % of anglers interviewed reported finding at least one ingested SPL when cleaning lake trout. However, when we sampled lake trout (using gill nets) and smallmouth bass (by rod and reel), we found few ingested SPLs (2.2 and 3.4 %, respectively). Based on the examination of fish that contained SPLs and the near-shore surveys, the most common SPLs were soft stick baits/wacky worms. The most promising approach to address the SPL problem is to educate anglers about the need to rig SPLs in a manner such that they are less likely to be lost during fishing and to always discard SPLs appropriately. Moreover, the tackle industry should continue to investigate SPLs that are less likely to be pulled off by fish and/or that degrade rapidly.

Keywords Fishing · Discarded gear · Lakes · Water pollution · Freshwater

1 Introduction

Recreational fishing is a popular activity around the globe (Cooke and Cowx 2004) and particularly in regions such as North America (Arlinghaus and Cooke 2009). In Canada alone, over 3.3 million residents participated in recreational fishing in 2010 and collectively spent over 39 million angler days (DFO 2012). In 2006, in the USA, over 33.9 million residents went fishing at

---

T. Raison · A. Nagrodski · S. J. Cooke (✉)
Fish Ecology and Conservation Physiology Laboratory,
Department of Biology and Institute of Environmental
Science, Carleton University,
1125 Colonel By Dr., Ottawa, ON, Canada K1S 5B6
e-mail: Steven_Cooke@carleton.ca

C. D. Suski
Department of Natural Resources and Environmental
Sciences, University of Illinois,
Urbana, IL 61801, USA

least once during that period (USFWS 2007). Recreational fishing provides immense socio-economic benefits, and consequently, many water bodies in North America are managed to maximize benefits for anglers and society (Arlinghaus and Cooke 2009; UN 2012). In recent years, there has been a growing recognition that recreational fishing, despite the use of modern fisheries management strategies, can have a variety of negative consequences that extend beyond exploitation (McPhee et al. 2002). In particular, there are a growing number of reports of environmental pollution and degradation attributed to angling activities (Cooke and Cowx 2006; Lewin et al. 2006).

Recreational angling can generate pollution through a variety of sources including the use of combustion boat motors (noise, production of hydrocarbons, fuel spills) and the deposition of fishing tackle (e.g. fishing line, lead sinkers, lures) and associated litter (e.g. packaging from fishing materials). Fishing gear is discarded haphazardly by irresponsible anglers (i.e. littering) and, more commonly, as unintentional loss by responsible anglers (e.g. when line breaks during a failed cast, when gear becomes entangled in debris). To emphasize the potential magnitude of gear loss, a study in Minnesota (Radomski et al. 2006) interviewed 8,068 boat anglers for five walleye (*Sander vitreus*) fisheries and found 80 % of anglers reported tackle loss, translating to a loss rate of 0.0127 pieces per hour. Relating this to angler numbers and hours spent fishing, this equated to over 100,000 lead-based items lost in the summer of 2004 alone. O'Toole et al. (2009) surveyed bank fishing sites in Ontario and found a variety of litter, including fishing line, lures and packaging from fishing gear (e.g. worm containers, tackle packaging). Bird ingestion of lead sinkers has been well studied (Scheuhammer and Norris 1996; Franson et al. 2003), and there are a variety of efforts underway by governments, anglers and the fishing industry to 'get the lead out' through education programs and development of non-toxic alternatives (Goddard et al. 2008). Hooks can be ingested by a variety of organisms (reviewed in Cooke and Cowx 2006) and lost line can become entangled in animals (Derraik 2002) and has also contributed to degradation of coral habitats (Yoshikawa and Asoh 2004). Tackle loss has the potential to create problems for a variety of wildlife, but birds have been the focus of most studies.

Soft plastic fishing lures (SPLs) have been commonly used in the angling community since the early 1970s. Soft plastic lures closely resemble natural forage and provide an alternative to cumbersome live bait. With growing concern for biosecurity and bait transfer, there is additional recent interest in the use of SPLs for a variety of fisheries. Another advantage to the use of SPLs is that they are much more durable than live bait, allowing one to catch multiple fish per bait. This durability and subsequent longevity is presumably a result of their being composed of inert non-biodegradable synthetic polymers. Currently, there are hundreds of types and brands of soft plastic lures, and for the most part, they are the same general composition, softened plastic which contains phthalates added to polyvinyl chloride or other similar products. Similar to lead sinkers/tackle, SPLs have the potential to be lost or discarded in terrestrial and aquatic ecosystems. Soft plastic lures (depending on rigging) can be easily ripped off angler's hooks by fish and can be either ingested immediately, or settle on the bottom (note—some SPLs float) where other fishes may be foraging. Indeed, given that most SPLs are fished very slowly and that fish often pick SPLs up when they are still, it is not unrealistic to assume that some of these lost SPLs are ingested after being lost. Others are not eaten and simply remain in the environment as a form of pollution. One of the potential problems with SPLs is that they may not biodegrade and therefore cannot be broken down and digested. This problem can be further amplified as some brands of SPLs contain a porous plastic that has the ability to absorb water and swell to very large sizes. When ingested, these SPLs can serve as a 'bezoar'—a veterinary term for a non-digestible/non-degradable foreign object that obstructs the gastrointestinal tract of an animal. To our knowledge, there are no comparative studies that evaluate the relative swelling or shrinking of SPLs through time which is relevant to considering their potential role as bezoars as well as their long-term persistence in the environment. Moreover, there is nothing known about how swelling or decomposition of SPLs varies with water temperature which is necessary to better understand the fate and potential impacts of such lures in different types of water bodies.

In recent years, there has been an increasing number of anecdotal and government reports of fish being captured with SPLs in their stomachs. In the only scientific paper to explore the effects of SPLs on fish, Danner et al. (2009) reported that adult brook trout (*Salvelinus fontinalis*) voluntarily ingested SPLs that were offered during regular feeding events. In fact, 63 % of test fish (n=37) ingested at least one SPL over a 90-day test period; of those fish, 12.5 % consumed more than 10 % of their body mass in SPLs. More importantly, brook trout that consumed soft plastic lures lost significant weight during the study, had a significant decrease in body condition factor (*K*) and began displaying anorexic behaviour. In general, however, little is known about the occurrence, fate or consumption rates of SPLs in a natural setting.

Based on this background, the objective of the current study was to gain further insight on the fate of plastic lures in the wild and determine their potential impact on wild fish. More specifically, we coupled field and laboratory observations in an effort to (1) quantify the density and deposition rate of SPLs in the littoral zone of Charleston Lake, (2) quantify the swelling of commonly used SPLs at different water temperatures in a laboratory environment, (3) document the frequency of SPLs in the stomachs of wild smallmouth bass and lake trout caught by anglers and (4) conduct surveys of anglers to gain insight into the frequency that SPLs are discovered within wild fishes. For this, we adopted a case study approach and focussed our efforts on Charleston Lake in eastern Ontario. Charleston Lake has been identified as potentially having an SPL issue by the Ontario Ministry of Natural Resources (OMNR) and the local cottagers association. Numerous anecdotal reports have surfaced regarding SPLs being found in the digestive track of lake trout and smallmouth bass, often with anglers delivering bags of SPLs retrieved from fish guts (Anne Bendig, OMNR, personal communication). Interestingly, SPLs are not typically used to capture lake trout, and SPLs are mainly associated with shallow water black bass (*Micropterus* spp.) fishing. Lake trout may come into contact with SPLs when they move into the shallow littoral zone at night to feed (Martin 1952). Their use of littoral zones may also vary seasonably, particularly during cooler periods (e.g. winter) when they are not restricted to hypolimnetic waters (Morbey et al. 2006). Charleston Lake is a popular fishing destination and is not unlike many other water bodies in south-central Ontario and indeed north temperate North America.

2 Methods

2.1 Study Site and SPL Field Survey

Charleston Lake (44°32′ N, 75°59′ W) is in southeastern Ontario, Canada and covers an area of approximately 2,517 ha with 152 km of shoreline. It is a clear, oligotrophic lake, with an average depth of 17 m, and is dominated by rocky shorelines and hard bottom structure. There is relatively little shoreline fishing (aside from some cottage docks) so most fishing activity occurs via boat (or through the ice in the winter). Lake trout fishing occurs in more offshore waters, while black bass and northern pike (*Esox luscius*) fishing tends to be focussed on littoral regions. Aside from sparse cottage development, the lake is rather undeveloped so there is high quality black bass littoral habitat throughout the lake.

To quantify the density and deposition rate of SPL in littoral areas, the shoreline of the southern portion of Charleston Lake was first divided into 100 m transects, and five of these transects were identified using a random number generator. Snorkel surveys were conducted on two different occasions in each of these five transects, occurring 3 months apart (May and August, 2010). During surveys, two snorkelers swam parallel to the shore with one snorkeler covering a zone of 0 to 3 m from shore and the other 3.1 to 6 m from shore, and the substrate was inspected for the presence of soft plastic lures; these two zones covered a depth of approximately 3 m. All soft plastic lures found during these surveys were removed from the site and subsequently categorized as follows: grubs, stick baits, ribbon tail worms, jerkbaits, creature baits or tube jigs. During the second visit 3 months later, the same sites were surveyed using identical techniques. By visiting sites on two occasions, it was possible to calculate an estimate of SPL deposition rate over time that could be extrapolated to the entire shoreline of Charleston Lake. We recognize a number of potential biases with doing such extrapolations, but this serves as a useful approach for characterizing the potential scale of the issue.

2.2 SPL Swelling

To quantify the swelling rate of SPLs over time, 8 replicates of 10 popular, commercially available SPLs were marked with a plastic tie to identify individual lures. Next, all SPLs were placed in 3 L jars filled with water from a nearby river adjacent to Carleton University where experiments were conducted (rather than driving 2 h to Charleston Lake for water changes) to replicate natural aquatic conditions and to avoid effects of chemically treated municipal water if we were to use tap water (see Table 1 for information on lure types).

To define the effects of temperature on SPL swelling, both cold water and room temperature water treatments were used. For the cold water treatment, four replicates of each SPL were placed in a refrigerator at approximately 4 °C, while warm water replicates were kept at room temperature (approximately 21 °C). Because the refrigerator was dark, SPLs at room temperature were covered with a dark plastic sheet. At~monthly intervals, all SPLs were removed from their respective jars, measured for length, width and weight, then returned to jars containing refreshed water from the nearby river. Length (millimeters) was measured between the farthest edges of the SPL, except in the case of ribbon tail worms when body alone was measured excluding the tail. Width (millimeters) was measured with a set of digital calipers across the widest section of lure, which was either one third of the way down the lure, at the simulated 'egg sac', or at the fourth ringed segment depending on the shape and style of the lure. Weight (grams) was measured to the nearest ten thousandth of a gram after the worms were patted dry. Initially, we intended to monitor the SPLs for 6 months; however, they were still continuing to swell at that time and there was little evidence of decomposition so the monitoring extended across two full years.

2.3 Fish Sampling

To quantify the occurrence of SPLs in the stomachs of wild fish, both wild lake trout and wild smallmouth bass were captured from Charleston Lake and examined. Lake trout were captured using gill nets that were 50 m long with mesh sizes ranging from 25.4 to 76.4 mm (i.e. panels of various sizes). Nets were set in a way to maximize capture rates and were therefore placed at depths ranging from 9 to 30 m in areas known to have high densities of lake trout. Once set, nets were checked every 2 to 3 h to reduce the possibility of lethal bycatch. Set duration ranged from 2 to 3 h, and all captured lake trout were euthanized with cerebral percussion (using a preacher) and placed on ice in a cooler until they could be processed in accordance with our animal care protocol. During processing and necropsy, the entire gastrointestinal tract was inspected for ingested SPLs. All lake trout had stomach contents identified and enumerated for further analysis.

Smallmouth bass were not captured in sufficient quantity using gill nets, so we relied on conventional hook-and-line angling gear on rocky near-shore habitat and reefs during the months of July and August to obtain fish for sampling. To determine the presence of ingested SPLs, a gastric lavage was performed (Light et al. 1983). Gastric lavage involves flushing the gut of fish by pumping water into their stomachs using a modified bilge pump and then applying pressure to the ventral side of the fish starting at the pelvic fins and moving towards the pectoral fins after the hose has been removed. Previous work has shown this technique to be non-lethal, minimally invasive and highly effective at flushing the stomach contents of fishes (Hakala and Johnson 2004). We acknowledge that any SPLs in the lower intestinal tract would not be collected via gastric lavage, although we observed no evidence to support that. Following gastric lavage, the lengths and weights of smallmouth bass were measured using the same methods as described for lake trout, and fish were released alive back into the lake.

2.4 Creel Survey

To quantify the occurrence of SPLs found by anglers in the stomachs of harvested fish, a summer-long creel survey of Charleston Lake anglers was performed from May 25 to September 1, 2011. The roving creel survey was conducted by OMNR staff as part of routine monitoring. During the creel survey, two questions related to the discovery of ingested SPLs in lake trout from Charleston Lake were asked of anglers based on requests from our research team. First, anglers were asked whether they harvested lake trout from Charleston Lake. If anglers responded that they did harvest lake trout from Charleston Lake, they were then asked to categorize the proportion of harvested fish that contained SPLs in their stomachs: 0, <10, 10–50 or >50 %. Also during the survey, the viscera of any harvested lake trout were collected, labeled and placed on ice for subsequent dissection in an effort to locate ingested SPLs.

2.5 Statistical Analysis

Swelling of all SPLs combined during the 2-year observation period was analysed using a two-way, repeated measures analysis of variance (ANOVA), with temperature treatment (cold vs. warm), lure code (Table 1) and measurement date entered as categorical, fixed effects and individual lure number entered as a random effect; the interaction between measurement date and temperature treatment was also entered into the ANOVA

Table 1 Brands and types of soft plastic lures (SPLs) used in the swelling component of the study. Four lures of each type were left in 21 °C water for 2 years, while an additional four replicates remained in 4 °C water for 2 years. Lures were sampled regularly for length, width and weight during holding

Abbreviation	Name	Colour
PW	PowerBait Heavy Weight SinkWorm	Black/Blue Fleck
GY	Gary Yamamoto Custom Baits Senko	Black/Red Flake
Y	Yum Dinger (LPT)	Black Blue Lam
BSM	Berkley Gulp! Sinking Minnow	Black
L	Le Baron Paul's Premium Pro Selection	Black
BPS	Bass Pro Shops Tournament Series Stik-o-worm	Texas Smoke
S	Strike King Perfect Plastics with coffee scent and salt	Ocho Okeechobee Craw
GL	Gambler Lures Ace	Blue Grass
CB	Culprit Brand Ribbon Tail Plastic Worm (no salt)	Blue/Black
BAW	Berkley Gulp! ALIVE! Super worm	Black

model. The use of a random effect (essentially a repeated measures design) was necessary because multiple measurements were taken from each SPL meaning that each measurement was not independent and potentially correlated within a lure (Laird and Ware 1982; Lindstrom and Bates 1990). Where appropriate, a Tukey-Kramer post hoc test was used to separate means. Swelling of individual SPLs, defined as the difference between the initial and final measurements, was compared across brands using a paired *t* test, and a *t* test was used in this instance as there were only two categories being compared. All data are shown as means±standard errors (SE) where appropriate, and α was set at 0.05.

3 Results

The snorkel surveys performed in May 2010 yielded a total of 16 SPLs discovered in littoral areas across all five of the 100-m transects (Fig. 1). When these same five transects were subsequently surveyed by snorkelers in August 2010, a total of 10 SPLs were discovered (Fig. 1). Deposition rate was therefore calculated at 20 SPLs per km shoreline in these transects over this period of time. The shoreline perimeter of Charleston Lake is approximately 152 km, which equates to approximately 12,160 soft plastic lures deposited in near-shore littoral zones every year (assuming a constant deposition rate in all lake areas during all months of the year). Assuming an average SPL mass of 8.75 g (based on measurements of initial weights shown in Fig. 2), this translates to approximately 106 kg of SPLs deposited into the lake per year (assuming a constant deposition rate into all areas of the lake during all months of the year—or 53 kg over the 6-month season that bass fishing is legal). Soft plastic stick baits (also known as wacky worms or senko-style baits) accounted for 76.9 % (20 out of 26) of the total SPLs found in all transects (Table 2).

When considered as a group, soft plastic lures increased in their length, weight and width during a 2-year period being immersed in water (Fig. 2a, Table 3). More specifically, soft plastic lures held at 21 °C were significantly longer than initial measurements after 3 months and grew in length by approximately 10 % after 4 months (Fig. 2a, Table 3). After 2 years of holding, soft plastic lures held at 21 °C were 50 % longer than initial

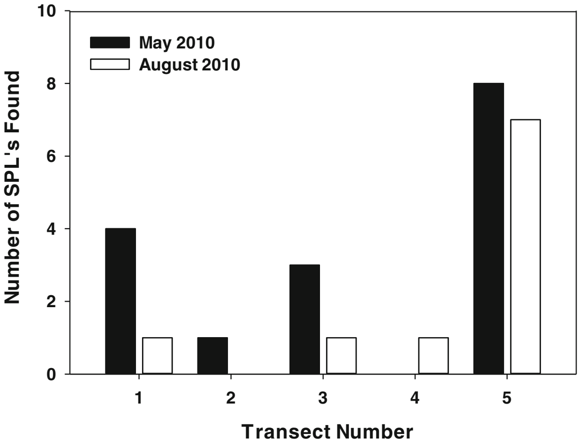

Fig. 1 Numbers of soft plastic lures (SPLs) found during snorkel surveys of littoral areas of Charleston Lake, Ontario, Canada. Two snorkelers swam five transects of 100 m and searched for discarded soft plastic lures in May and in August of 2010

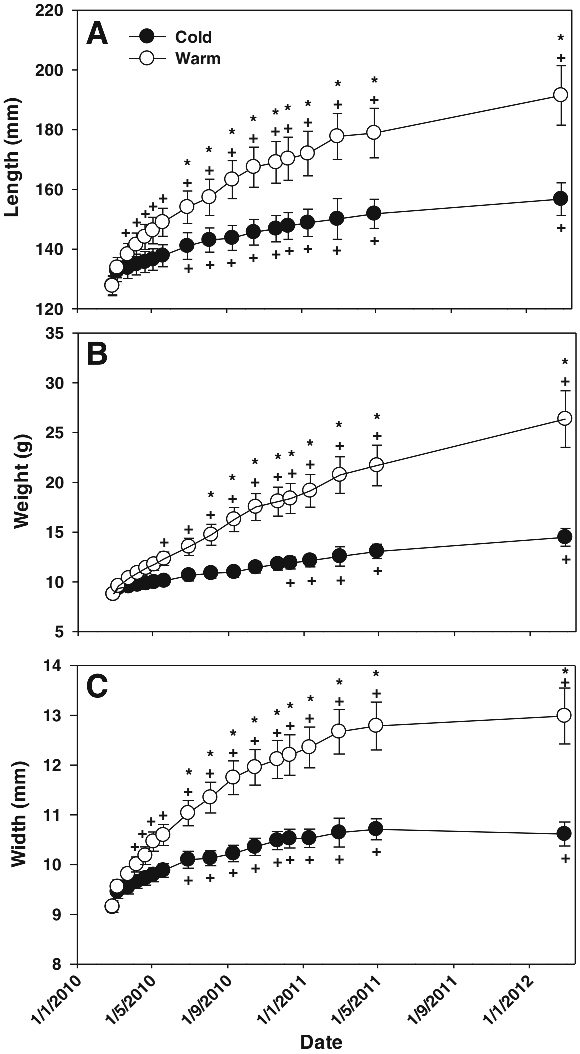

Fig. 2 Change in the **a** length, **b** weight and **c** width of all soft plastic lures held at either 4 °C (cold) or 21 °C (warm) for 2 years. Lure brands are shown in Table 2. At each sampling point, two to four replicates of 10 different lure types were measured. Lure brands are shown in Table 1. An *asterisk* (*) denotes a significant difference between temperature treatments at a sampling point, and a *plus sign* (+) denotes a significant difference between a data point and the initial measurement within a thermal treatment. Results from statistical tests are given in Table 3

measurements, and soft plastic lures in cold water were 25 % longer, with significant differences noted across lure types (Fig. 2, Table 3). Similarly, the weight of soft plastic lures tended to double after 7 months in water at 21 °C (Fig. 2b, Table 3). After 6 months of holding, soft plastic lures in the warm treatment were significantly heavier than those in the cold treatment, and changes in weight varied across the lure types examined (Fig. 2b, Table 3). After 5 weeks at 21 °C, soft plastic lures were significantly wider than their initial width, and widths increased significantly for cold water after 4 months. Warmer holding conditions resulted in a 30 % greater increase in width relative to soft plastic lures held in cooler water, and changes in width varied across lure type (Fig. 2c, Table 3).

When the different lure brands were considered separately, 9 of the 10 brands examined experienced increases in length relative to initial measurements, with increases in length ranging from 10 to 120 % (Fig. 3). For seven lure brands, holding in warm water resulted in an increase in length relative to cool water, while for two lure brands, cold water holding resulted in increased length (Fig. 3a; paired *t* tests, p values<0.05). Similarly, changes in weight during holding ranged from negligible to almost 800 % across the different brands, and in all but one case, warmer water resulted in more weight gain than lures of the same brand held at cooler temperatures (Fig. 3b; paired *t* tests, p values<0.05). Seven of the 10 brands experienced an increase in width in both cold and warm treatments, with width increases ranging from 5 to 130 %. For all lure types but one, water at 21 °C resulted in greater increases in width than water at 4 °C (Fig. 3c).

A total of two lake trout and three smallmouth bass with ingested SPLs were captured during sampling efforts, out of 90 lake trout and 88 smallmouth bass. We were able to add to our sample size of lake trout with ingested SPLs by incorporating fish captured by local anglers and those caught during 2009 spring netting efforts by the Ontario Ministry of Natural Resources. The most common SPL found in lake trout gastrointestinal tracts were stick baits. Of the lake trout with ingested soft plastics, 75 % (9 out of 12) contained at least one stick bait (Table 2). Stick bait frequencies were followed by ribbon tail worms, soft plastic jerkbaits and creature baits, each of which accounted for 8.3 % of SPLs found within lake trout. SPLs found in lake trout stomachs varied in condition (Fig. 4).

During the summer of 2011, the Ontario Ministry of Natural Resources conducted a creel survey where anglers were interviewed on Charleston Lake. In total, 140 anglers were interviewed. Of these, 98 (70 %) indicated that they have not kept lake trout from Charleston Lake. Of the 42 anglers (30 %) that indicated that they had retained lake trout from Charleston Lake, 17 (40.5 %) indicated not finding any SPLs in lake trout, 12 (28.6 %) indicated finding SPLs in less than 10 % of lake trout, 3

Table 2 Frequency of occurrence of soft plastic fishing lures (SPLs) found in the stomachs of wild-caught lake trout, as well as the number of SPL discovered by snorkelers during surveys of the littoral areas. Quantities of SPLs found in lake trout came from a number of sources including our sampling, OMNR spring netting on Charleston Lake and those provided by local anglers. A total of 10 snorkel surveys were performed over approximately 1 km (linear distance) of littoral areas in August and May. All data were collected from Charleston Lake, Ontario, Canada

Soft plastic lure type	Number in stomach	Percent found in stomachs	Number found in snorkel survey	Percent found in snorkel survey	Total	Total percent
Stick bait	9	75.0	20	76.9	29	76.3
Creature bait	1	8.3	2	7.7	3	7.9
Ribbon tail	1	8.3	1	3.9	2	5.3
Soft plastic jerkbait	1	8.3	1	3.9	2	5.3
Tube jig	0	0.0	1	3.9	1	2.3
Grub	0	0.0	1	3.9	1	2.6
Total	12	100.0	26	100.0	38	100.0

(7.1 %) indicated finding SPLs in 10–50 % of lake trout and 10 (23.8 %) indicated finding SPLs in greater than 50 % of the lake trout. Unfortunately, we were unable to determine how much effort was required for anglers to actually capture a fish with an SPL, such that these values only represent crude approximations of angler SPL encounters.

4 Discussion

A variety of anecdotal reports both regionally (e.g. local OMNR office based on reports from the public, cottage association) and more broadly (online message boards, fishing magazines) have indicated concern regarding discarded SPLs in the environment, as well as on fish and fish populations. Indeed, some jurisdictions are considering the ban of soft plastic lures (e.g. bill introduced in Maine, USA in 2013; see http://www.mainelegislature.org/legis/bills/getPDF.asp?paper=HP0037&item=1&snum=126) which received national (BassMaster Magazine; http://www.bassmaster.com/news/soft-plastics-banned) and international (Australian Fishing World Website: http://www.fishingworld.com.au/news/us-state-moves-to-ban-soft-plastics) media attention. Despite the apparent timeliness of this issue, there is currently only a single study related to SPLs. Danner et al. (2009) used an experimental approach in a laboratory setting where they fed SPLs to brook trout and evaluated the consequences of SPL ingestion on growth and survival. While this study unequivocally demonstrated the *potential* for wild brook trout to ingest SPLs, performing this study in a laboratory setting does not reveal if SPL ingestion is indeed occurring in the wild, or the actual ingestion rates of wild fish. We therefore designed a study to quantify the extent to which SPLs are a potential problem by using a combination of field studies (snorkel, fish and creel surveys) and laboratory experiments.

Our work revealed that SPLs are indeed present in the littoral zone of Charleston Lake. Based on the estimates of discarded soft plastic lures in Charleston Lake,

Table 3 Results of two-way repeated measures analysis of variance (ANOVA) assessing the effects of temperature treatments (4 vs. 21 °C), sampling date and lure type on swelling metrics of soft plastic lures held in water for almost 2 years. Lure code refers to the different brands of SPLs used as shown in Table 1, *df* refers to degrees of freedom, while Prob>*F* refers to the *p* value of each of the main effects of the ANOVA model

	Source	*df*	*F* ratio	Prob>*F*
Length	Date	16	93.4	<0.0001
	Treatment	1	66.9	<0.0001
	Treatment × date	16	13.9	<0.0001
	Lure code	9	106.0	<0.0001
Weight	Date	16	62.0	<0.0001
	Treatment	1	59.7	<0.0001
	Treatment × date	16	17.5	<0.0001
	Lure code	9	30.1	<0.0001
Width	Date	16	74.0	<0.0001
	Treatment	1	69.2	<0.0001
	Treatment × date	16	14.8	<0.0001
	Lure code	9	37.0	<0.0001

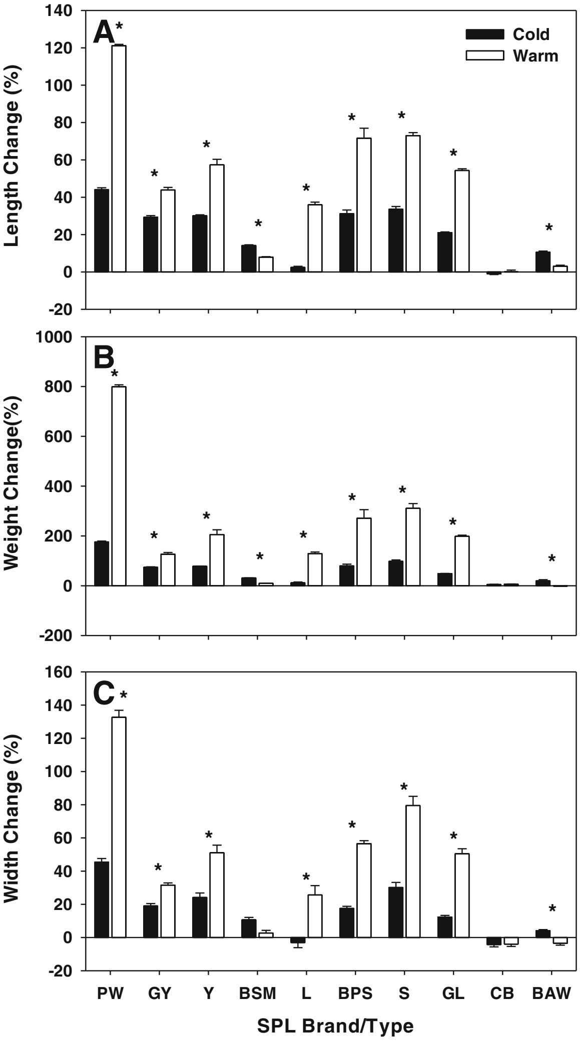

Fig. 3 Percent change in **a** length, **b** weight and **c** width for each of the 10 different soft plastic lure types, comparing the initial and final measurements taken over a 2-year monitoring period. Lures were held at either 4 ° C (cold) or 21 ° C (warm), and lure brands are shown in Table 1. An *asterisk* (*) denotes a significant difference between warm and cold treatments within a lure type for a specific swelling metric. Sample sizes are four lures of each type, except for the cold treatment for CB width where sample sizes were 3. Lure names and brands and types are shown in Table 1

Fig. 4 Soft plastic lures (SPLs) removed from the stomachs of wild lake trout collected during field sampling on Charleston Lake, Ontario, Canada

roughly ~12,000 SPLs may be deposited in near-shore littoral habitats annually. This estimate assumes a constant rate of deposition (or fishing effort) throughout the year. As such, the estimate of ~6,000 SPLs being deposited over the course of the bass season when SPLs are presumably most commonly used would seem to be a more reasonable estimate. Most bass fishing is restricted to the ice-free periods, but SPLs are used to target northern pike through the ice so likely the most appropriate estimate is intermediate between the two estimates. Indeed, this number is likely an underestimate as there are many hectares of fish habitat that were not surveyed by snorkelers including large flats, shoals and deep water habitats that were inaccessible due to the limitations of snorkeling gear and not included as 'shoreline' for analytical purposes. Interestingly, in the first snorkeling transect of the year (May), there were relatively few SPLs found despite a lengthy period during which they could accumulate. It is unclear whether SPLs that were presumably deposited before that time had been degraded (which is inconsistent with laboratory findings) or consumed (by fish or perhaps other vertebrates like birds or turtles). Future studies that use video cameras or potentially telemetry tags to study SPL fate in natural systems would help to address uncertainty regarding SPL pollution.

Despite a modest rate of SPL accumulation, the number of fish sampled with ingested SPLs was much lower than anticipated. Of the 90 lake trout captured in the current study, only two were found to have ingested single SPLs, and of the 88 smallmouth bass sampled, only three were found to have ingested SPLs. This rate of occurrence was much lower than previous gill netting surveys performed by the Ontario Ministry of Natural Resources (OMNR) staff in 2009, who showed that 25 % of lake trout captured had at least one ingested SPL (Anne Bendig, OMNR, personal communication). Additionally, anecdotal reports by the Charleston Lake Association to OMNR indicated that anglers were finding high numbers of SPLs in lake trout. We did observe some regurgitation of both species sampled. It is possible that lake trout and bass regurgitated stomach contents (including SPLs) at depth although similar mechanisms would have been likely in the OMNR study. The gill netting conducted by OMNR in 2009 occurred earlier in the year when water temperatures were lower, which may have been less stressful to the fish and thus resulted in less regurgitation. Alternatively, the behaviour of fish and anglers may have been such that the fish encounter rates of SPLs vary seasonally with more SPLs evident during earlier sampling periods. One of the hypotheses of ingested SPLs is that the presence of the plastic in their stomach effectively works to make the fish feel full. Also there is less room in the stomach for food, which would result in a decline in the condition of the fish. Both of these possibilities could lead to a behaviour change and smallmouth being less active or simply slower at getting to the bait, than stronger, healthier fish, which would be able to get to the bait quicker. This scenario seems to contradict the results found in this study, especially that of the creel survey. As previously mentioned, 17.9 % of anglers interviewed claimed to have found SPLs in lake trout, which suggests that, even though lake trout has a plastic lure in its belly, it is still sufficiently active to strike an anglers lure.

Prior to this study, it was not known the extent to which different types of SPLs (from different manufacturers) would swell, shrink or decompose. This is relevant given that one of the concerns with SPLs is that they have the potential to swell in stomachs if ingested, not to mention understanding the fate of SPLs in the environment (Danner et al. 2009). We used a laboratory approach where SPLs were held in a cool or warm environment for ~2 years. We acknowledge that the laboratory environments were dark and the role of solar radiation in SPL swelling and decomposition dynamics is unknown. Similarly, the holding vessels used lacked regular agitation (e.g. as one might expect from currents or wave action in the field) aside from when water changes occurred. We did refresh water in the holding vessels at roughly monthly intervals using water from a nearby river so there was potential for microbial activity. The SPLs were removed from the water at~monthly intervals and it is unclear whether aerial exposure influenced our findings. Further, SPLs were held together in the same vessels (four replicates of the vessels at each temperature) and it is conceivable that the properties of one SPL could influence the swelling or decomposition dynamics of others (e.g. if there were preservatives that leached into the water). Despite these potential challenges, however, swelling of SPLs over time was both striking and substantial, with several lure brands increasing in weight by 200 % and increasing in weight over 50 %; there were very few instances of shrinkage during the experiment. Swelling rate was not consistent throughout the study and it appeared that the rate of change of SPLs was slowing near the end of the experiment, in both warm and cold water treatments, which could suggest either a transition to decomposition if left for a longer period, or that the SPLs have a maximal swelling potential that had been reached. Interestingly, the Berkley Gulp! ALIVE! worm, which is advertised as a biodegradable bait (http://www.berkley-fishing.com/products/soft-bait/gulp), only reduced slightly in size during the experiments. As noted above, this may be related to a lack of solar radiation given that worms were held in darkness. Without further information on the characteristics used by manufacturers to label an SPL as ‘biodegradable’ (e.g. over what time period, under what conditions), it is impossible to provide further insight. Anecdotally, there was pronounced variation in shape change among the different brands/materials during the holding period. Unfortunately, without information on the proprietary composition of various types of worms, it is not possible to draw conclusions on the drivers of shape change, aside from the fact that all of the worms grew to some extent during the experiment, and there was little evidence that decomposition was occurring even after 2 years. Clearly this points to the need for more innovation in SPL materials such that they are either less prone to being lost (assumes that intentional discarding is not the primary mechanism of bait SPL loss) or that if lost that they decompose rapidly, ideally without swelling in size.

The high rate of swelling of SPLs could have detrimental effects on a fish if ingested, depending on whether it continued to swell in the fish’s stomach. Although there was no test for determining how SPL size would change in conditions such as a fish’s stomach, in every case where SPLs were found in fish, the SPLs appeared bloated and, in some cases, were extremely stiff. It is unknown whether this inflation occurred prior to ingestion. Also relevant to fish is the fact that SPL swelling was influenced by water temperature (i.e. SPLs swell more rapidly in warm water than cold water). An ingested SPL in a shallow warm water fish, such as a largemouth bass, may swell more rapidly and have more adverse health effects than an ingested SPL in a deep cold water fish, such as a lake trout, that would presumably swell more slowly. However, this is somewhat speculative given that the only experimental study to be done was on brook trout in a laboratory setting at stable water temperatures (Danner et al. 2009). Future studies that vary water temperature during experimental holding would seem necessary to determine if the consequences on individual fish arising from bezoars are temperature specific.

Both snorkel survey and stomach analyses revealed that stick baits were the most commonly encountered SPL. Stick baits have become extremely popular with anglers in recent years due to their effectiveness at catching bass. The preferred rigging method is referred to as 'wacky rigging' in which a small hook is used directly in the midpoint of the SPL. That method of rigging is one of the least effective at retaining the SPL because smaller or non-target fish pull the SPL from the hook as they are unable to fit the entire bait in their mouths. These baits may also be lost during the fight once fish are hooked (e.g. head shaking). Another way that SPLs could enter aquatic systems is through littering where 'used' SPLs are discarded by anglers.

Soft plastic lures are a common part of modern recreational angling, especially for shallow, warm water species. Unfortunately, due to the nature of their composition, they are also a source of plastic litter in aquatic systems such as Charleston Lake, where thousands of soft plastic lures may be deposited every year. Although the focus of the current study was not to quantify possible health effects of ingested SPLs on different fish species, it is clear that SPLs are a source of pollution and that some SPLs are indeed ingested by fish, but apparently at a much lower rate than what it reported by anglers. Reports of fish with ingested SPLs have recently come to light in a variety of media outlets (e.g. BassMaster, InFisherman, Ontario Out-of-Doors), which has increased angler awareness on the issue, and may result in anglers over-exaggerating the frequencies of ingested SPLs in their catches. Our sampling for each of two species focussed on a single gear type (gill net for lake trout and rod and reel for smallmouth bass) and season, so it is possible that ingestion varies spatiotemporally, and thus, we failed to detect much in the way of ingested SPLs. Nonetheless, strategies for reducing the deposition of SPLs in aquatic systems is a prudent measure. Anglers need to be further educated on alternative SPL-rigging methods, such as using an o-ring on stick baits for better hook retention, as well as information on how to properly dispose spent SPLs. Some grassroots initiatives have emerged from the recreational fishing community that encourage anglers to deposit 'used' SPLs in the trash which is a promising development (http://www.bassmaster.com/news/dont-discard-soft-plastics-they-can-kill; Love and Sewell 2012). There have also been efforts to develop recycling programs for SPLs (Love and Sewell 2012). For example, the Bass Anglers Sportsmen Society has been involved with the Re-Bait program (http://www.bassmaster.com/news/re-baits-reduce-soft-plastic-dumping), which was launched in 2012. It may also be possible to design SPLs that are more robust and thus less likely to tear (e.g. through use of novel materials such as fibers; see http://www.sciencedaily.com/videos/2008/0701-better_bait.htm) and thus reduce the loss of such lures. Additional efforts to develop biodegradable SPLs would also be desirable. The effects of SPL ingestion by fish or other taxa such as birds, turtles and snakes remain unknown. The evidence generated here points to educating anglers and engaging industry rather than regulatory actions (e.g. introduction of a bill to ban use of 'rubber' lures in Maine; http://www.mainelegislature.org/legis/bills/getPDF.asp?paper = HP0037&item=1&snum=126), a strategy that is generally regarded as effective for addressing recreational fisheries issues (Cooke et al. 2013).

Acknowledgments We are indebted to Dwayne Struthers and the Charleston Lake Cottagers Association for providing financial support for this research. We also thank Anne Bendig with OMNR for allowing us to incorporate questions on SPLs into their creel surveys. OMNR also provided gill nets for lake trout netting. Cooke is supported by the Canada Research Chairs Program. Scientific Collection Permits were provided by the OMNR and animal care clearances from the Carleton University Animal Care Committee.

References

Arlinghaus, R., & Cooke, S. J. (2009). Recreational fishing: socio-economic importance, conservation issues and management challenge. In B. Dickson, J. Hutton, & B. Adams (Eds.), *Recreational hunting, conservation and rural livelihoods: science and practice* (pp. 39–58). Oxford: Blackwell Publishing.

Cooke, S. J., & Cowx, I. G. (2004). The role of recreational fishing in global fish crises. *BioScience, 54*, 857–859.

Cooke, S. J., & Cowx, I. G. (2006). Contrasting recreational and commercial fishing: searching for common issues to promote unified conservation of fisheries resources and aquatic environments. *Biological Conservation, 128*, 93–108.

Cooke, S. J., Suski, C. D., Arlinghaus, R., & Danylchuk, A. J. (2013). Voluntary institutions and behaviours as alternatives to formal regulations in recreational fisheries management. *Fish and Fisheries, 14*, 439–457.

Danner, G. R., Chacko, J., & Brautigam, F. (2009). Voluntary ingestion of soft plastic fishing lures affects brook trout growth in the laboratory. *North American Journal of Fisheries Management, 29*, 352–360.

Department of Fisheries and Oceans Canada (DFO) (2012). 2010 survey or recreational fishing in Canada. http://www.dfo-mpo.gc.ca/.

Derraik, J. G. (2002). The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin, 44*, 842–852.

Franson, J. C., Hansen, S. P., Creekmore, T. E., Brand, C. J., Evers, D. C., Duerr, A. E., et al. (2003). Lead fishing weights and other fishing tackle in selected waterbirds. *Waterbirds, 26*, 345–352.

Goddard, C. I., Leonard, N. J., Stang, D. L., Wingate, P. J., Rattner, B. A., Franson, J. C., et al. (2008). Management concerns about known and potential impacts of lead use in shooting and in fishing activities. *Fisheries, 33*, 228–236.

Hakala, J. P., & Johnson, F. D. (2004). Evaluation of a gastric lavage method for use on largemouth bass. *North American Journal of Fisheries Management, 24*, 1398–1403.

Laird, N. M., & Ware, J. H. (1982). Random-effects models for longitudinal data. *Biometrics, 38*, 963–974.

Lewin, W. C., Arlinghaus, R., & Mehner, T. (2006). Documented and potential biological impacts of recreational fishing: insights for management and conservation. *Reviews in Fisheries Science, 14*, 305–367.

Light, R. W., Adler, P. H., & Arnold, D. E. (1983). Evaluation of gastric lavage for stomach analyses. *North American Journal of Fisheries Management, 3*, 81–85.

Lindstrom, M. J., & Bates, D. M. (1990). Nonlinear mixed effects models for repeated measures data. *Biometrics, 46*, 673–687.

Love, J.W., Sewell, S., (2012). Bass and stewardship: the effects of soft plastics. The Maryland Natural Resource, 10–11. Available at: http://www.dnr.state.md.us/fisheries/bass/docs/The_Effects_of_Soft_Plastic_Lures.pdf.

Martin, N. V. (1952). A study of the lake trout, *Salvelinus namaycush*, in two Algonquin Park, Ontario, lakes. *Transactions of the American Fisheries Society, 81*, 111–137.

McPhee, D. P., Leadbitter, D., & Skilleter, G. A. (2002). Swallowing the bait: is recreational fishing ecologically sustainable? *Pacific Conservation Biology, 8*, 40–51.

Morbey, Y. E., Addison, P., Shuter, B. J., & Vascotto, K. (2006). Within-population heterogeneity of habitat use by lake trout *Salvelinus namaycush. Journal of Fish Biology, 69*, 1675–1696.

O'Toole, A. C., Hanson, K. C., & Cooke, S. J. (2009). The effect of shoreline recreational angling activities on aquatic and riparian habitat within an urban environment: implications for conservation and management. *Environmental Management, 44*, 324–334.

Radomski, P., Heinrich, T., Jones, T. S., Rivers, P., & Talmage, P. (2006). Estimates of tackle loss for five Minnesota walleye fisheries. *North American Journal of Fisheries Management, 26*, 206–212.

Scheuhammer, A. M., & Norris, S. L. (1996). The ecotoxicology of lead shot and lead fishing weights. *Ecotoxicology, 5*, 279–295.

U.S. Fish and Wildlife Service (USFWS). (2007). *National survey of fishing, hunting and wildlife associated recreation*. Washington, DC: U.S. Fish and Wildlife Service.

UN FAO. (2012). Recreational fisheries. FAO Technical Guidelines for Responsible Fisheries. No. 13. Rome, FAO 2012. 176 pp.

Yoshikawa, T., & Asoh, K. (2004). Entanglement of monofilament fishing lines and coral death. *Biological Conservation, 117*, 557–560.