FACETS
a multidisciplinary open access science journal

REVIEW ARTICLE

The biology and ecology of slimy sculpin: A recipe for effective environmental monitoring

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Abstract

Recently, the use of small-bodied fish in environmental monitoring has increased, particularly within the Canadian environmental effects monitoring (EEM) and other adaptive programs. Although it is possible to measure changes with many small-bodied species, interpretation is often complicated by the absence of information on the biology and ecology of fish not of commercial, recreational, or traditional interest. Knowing and understanding the basic biology of these fishes aids in the sensitivity of study designs (i.e., ability to detect change) and the interpretation of all biological levels of responses (e.g., cellular to community). The increased use of slimy sculpin (*Cottus cognatus* Richardson, 1836) in impact assessment studies in North America provides a considerable amount of information on life history aspects. The slimy sculpin has the most ubiquitous North American distribution among cottids but yet has a very small home range, thus integrating environmental conditions of localized areas. This paper describes aspects of slimy sculpin life cycle that affect collection efficiency and timing, and describes and provides data collected over more than 10 years of studies at more than 20 reference study sites. This overview provides a functional and informative compilation to support adaptive environmental monitoring and provide a baseline for comparative ecological study.

Key words: slimy sculpin, environmental effects monitoring, sentinel species, freshwater monitoring, small-bodied fish

Citation: Gray MA, Curry RA, Arciszewski TJ, Munkittrick KR, and Brasfield SM. 2018. The biology and ecology of slimy sculpin: A recipe for effective environmental monitoring. FACETS 3: 103–127. doi:10.1139/facets-2017-0069

Handling Editor: Brett Favaro

Received: June 20, 2017

Accepted: September 26, 2017

Published: February 5, 2018

Published by: Canadian Science Publishing

Introduction

Federal regulations governing the pulp and paper (Walker et al. 2002) and metal mining (Ribey et al. 2002) industries in Canada require cyclical environmental effects monitoring (EEM; ec.gc.ca/esee-eem) studies to assess the potential impact of their effluents on the aquatic receiving environments when in compliance with discharge guidelines. When it was initiated, EEM was a novel, hypothesis-driven monitoring program designed as a check on the protection afforded by existing regulations: are they sufficiently protective or are there remaining concerns in the receiving environment (Ribey et al. 2002; Walker et al. 2002)? The cyclical and adaptive nature of EEM aims to provide the information required by all parties to protect the environment, provide convincing evidence that any changes observed are meaningful, and to evaluate whether they should be addressed. Recent developments have also emphasized the advantages of adaptive monitoring (Lindenmayer and Likens 2010), and the design philosophy is being more widely adapted (Arciszewski and Munkittrick 2015). Lindenmayer and Likens (2010) promoted the concept of an iterative adaptive monitoring approach that relies on the collection and analysis of long-term data, focused questions, and a rigorous statistical design a priori to resolve problems associated with contemporary monitoring programs.

Utility of an adaptive approach to environmental management in aquatic environments depends on the collection of interpretable, reliable, and relevant information on changes in the receiving environment. In addition to studies on benthic invertebrates to provide information on habitat health, information on fish growth, reproduction, condition, and age structure are required to assess the overall health of exposed fish (Environment Canada 2005). Ideally, the benthic and fish components are mutually reinforcing and provide a more complete picture than either alone. The use of both benthic invertebrates and fish endpoints is meant to enhance the probability of detecting complex ecological changes that may not always be expressed or may be transient (Wu et al. 2005). However, not all studies include each level of biological organization exposed to a stressor or found in a "stressful" environment; instead, studies focus on indicators (Munkittrick et al. 2002). In some instances, fish are preferred over benthic invertebrates, for example, due to beneficial mobility and life spans, whereas in others the opposite is true. A sentinel species is one that can be used as an early, or advanced, warning of some environmental danger or hazard, much like canaries were used in coal mines. Where fish are used in an adaptive framework, such as EEM, an approach using sentinel species can signify change and provide focus for follow-up studies to evaluate the significance of change.

Sentinel species approach

Studies of fish usually focus on life history and parameters indicating the performance of populations. The characteristics of growth, survival, and reproduction are estimated by measurements, such as size-at-age, relative gonad and liver mass, condition (body mass relative to length), and age. Changes in these attributes, relative to some reference range, are then combined to inform a hypothesis for more detailed follow-up work (Gibbons and Munkittrick 1994). Gibbons and Munkittrick (1994) described multiple response patterns including eutrophication (increased liver size, condition, gonad size, and faster growth) and metabolic disruption (increased condition and liver size, smaller gonads). Subsequently, these two patterns in particular are commonly found downstream of pulp mills in Canada. Patterns of metabolic disruption led to the initiation of an "investigation of cause" for pulp mill effluents involving several partners (Hewitt et al. 2008). Eventually, this work led to the development of effluent management practices to reduce and eliminate the occurrence of reproductive abnormalities in fish (Martel et al. 2011).

The utility of informing adaptive monitoring using the sentinel species approach requires several key assumptions, as follows.

- The sentinel species is representative of the receiving environment,
- does not move between the reference and exposure areas, and
- there are minimal physical habitat differences between the reference and exposed areas.

To maximize the probability of fulfilling these assumptions, the sentinel selected requires suitable characteristics: (1) high abundance, (2) high site fidelity, and (3) measurable life history characteristics relevant for the assessment. These initial characteristics are necessary for a robust analysis, whereas other characteristics simplify interpretation and further increase the likelihood of detecting ecologically relevant changes, (4) a short generation time, (5) single-event spawning, (6) large reproductive effort, and (7) benthic feeding. Using large-bodied species, these assumptions can be difficult to support. Large-bodied species can be effective sentinels where natural or artificial barriers are found (Arciszewski et al. 2015b) but are less successfully used where movement is unrestricted, migration of organisms between sites is possible, and exposure regimes are uncertain (Galloway et al. 2003). Although large body size is generally associated with a large home range, there can be exceptions. In the white sucker (*Catostomus commersonii* (Lacepède, 1803)), spawning migrations can cover a large distance, but during non-spawning periods this species forages within a more restricted range (Doherty et al. 2010).

In most cases comprehensive databases are not required to consider species selection, and choices of abundant species may be limited. However some life history characteristics may improve the utility of potential monitoring species and the interpretation of biological and physiological data collected including fish growth rate, longevity, food preference, and spawning time (**Table 1**). The ideal characteristics vary for studies looking at point-source discharges, non-point discharges, and for understanding risks to human health, and can be both site- and issue-specific. Selection of the monitoring species should evaluate the relative benefits and disadvantages of the species for the specific purpose of the study (**Table 1**). For example, although longevity influences the lag time for detecting responses, in the case of studies concerned with lipophilic contaminants and food chain biomagnification, a species with a prolonged life span may inherently maximize bioaccumulation. However some compounds have been shown to accumulate at higher rates in freshwater slimy sculpin (*Cottus cognatus* Richardson, 1836) compared with lake trout (*Salvelinus namaycush* (Walbaum in Artedi, 1792)) as top fish predator, and all other fish sampled, due to their close association with bottom sediments (Asher et al. 2012). Additionally, maternal transfer of lipophilic compounds can sometimes occur during egg maturation and spawning (Fisk and Johnston 1998). In the absence of other elimination mechanisms, low reproductive rates may also increase the body burdens of lipophilic compounds. Similarly, predatory fish would be preferred for biomagnification concerns but would be a disadvantage for point-source discharges because of their higher mobility and associated uncertainty of exposure (Munkittrick et al. 2002). A commonly desired outcome, and one necessary for an adaptive approach, is a signal to intensify monitoring or sampling effort based on data that fall outside of the range of estimated site, local, or regional variability. For example, a signal could be liver sizes of fish that are consistently larger than range of means expected based on measurements at multiple reference locations (Arciszewski et al. 2017). The more easily, quickly, precisely, and accurately these signals can be identified, the better the monitoring program will perform.

Table 1. Characteristics to consider when choosing fish species for monitoring.

Life history trait	Ecological risk	Human health risk
Longevity	–	+
Piscivorous	–	+
High reproductive output	+	–
Early maturity	+	–
Fast growth rate	+	+
Small size	+	–
Migrates to spawn[a]	–	–
Abundance	+	0

Note: Characteristics and species suitability may be more advantageous depending on whether there is an ecological or human health (consumption) risk. +, advantage; –, disadvantage; 0, not a concern.
[a]Migration is less of a concern for non-point sources of contamination.

In the past 15 years in Canada, much work has been done following the sentinel species approach using small-bodied species (Gibbons et al. 1998; Gray et al. 2005a, 2005b; Barrett et al. 2015). This is in contrast to much of the initial monitoring under EEM, which focused on large-bodied species (Munkittrick et al. 2002). This was likely related to familiarity with large-bodied species and their distributions and unfamiliarity with required characteristics of ideal sentinels. As the EEM program matured, interest in small-bodied species increased but was hindered by the lack of detailed information of life history attributes of many species (see **Table 1** for attributes; Munkittrick et al. 2002). Although many characteristics were suspected and generally true (Minns 1995), specifics were unknown. These barriers have been gradually addressed and monitoring programs using small-bodied fish have become common (Barrett et al. 2015). Several characteristics inherent to many small-bodied fish make them particularly useful for monitoring studies. Small-bodied fish are generally found at high enough densities for collection of adequate sample sizes, many species show high site fidelity that aids in establishing exposure to environmental stressors, their short life spans relate to rapid responses to environmental changes, confounding factors such as fishing pressure are usually absent, and life history characteristics can still be easily measured, e.g., age and (or) size distributions, energy storage (liver size, condition), and energy expenditure (gonad size, reproductive output) (Minns 1995; Environment Canada 1997; Gibbons et al. 1998; Gray et al. 2002; Brasfield et al. 2013; Arciszewski et al. 2015a; Barrett et al. 2015). Furthermore, there is generally less public concern about taking small-bodied "forage" fish for monitoring than charismatic sport fishes.

"Fish of the future": the slimy sculpin (*Cottus cognatus*)

Of the small-bodied freshwater fish species used in monitoring (Barrett and Munkittrick 2010; Barrett et al. 2015), the slimy sculpin is the leading choice for a sentinel species program in most of Canada and northern parts of the United States. They closely match the profile for an ideal sentinel species in areas where they are present in sufficient numbers. The slimy sculpin is a small coolwater fish, with an average length of 76 mm (Scott and Crossman 1973), exhibiting limited home ranges within stream systems (e.g., Brown and Downhower 1982; Hill and Grossman 1987; Gray et al. 2004), and has easy to measure life history characters (e.g., length, weight, and somatic indices). Studies have ranged from impacts of timber harvest (Edwards 2001), potato farming (Gray et al. 2002; Gray and Munkittrick 2005; Gray et al. 2005a; Brasfield et al. 2015), diamond mining (Gray et al. 2005b), oil sands (Tetreault et al. 2003), metal mining (Dubé et al. 2005; Allert et al. 2009) and coal mining (Miller et al. 2015), pulp and paper mills (Galloway et al. 2003), and sewage (Arciszewski et al. 2011). Due to the lack of general background information available for slimy sculpin, it has been necessary to compile unique basic reference data, or baseline data, for almost each study project conducted. With the collection of large data sets over multiple seasons and years, it may be possible to establish reference conditions for some parameters (e.g., condition, growth, size-at-age, and somatic indices) or predictive models of varying degrees of complexity (e.g., relationships with environmental factors), at least for particular regions, if not across a broader range. Establishing standard relationships or trends for slimy sculpin collected in reference areas may aid in the interpretation of data from suspected impacted sites or populations. This paper consolidates much of the basic and applied slimy sculpin research conducted in Canada over the past two decades. Much of that work was in the east, but studies in western Canada are becoming more common (Tetreault et al. 2003; Farwell et al. 2009; Miller et al. 2015). Compiling these results will form a better perspective for the use and utility of the slimy sculpin in applied research and environmental monitoring. Aspects related to slimy sculpin biology that will be discussed include capture efficiencies, reference conditions, and collection timing with special respect to physiological parameters, mobility and ability to reflect local conditions, and finally some examples of environmental monitoring studies that have successfully used the slimy sculpin as the main study species.

Many of these aspects can be easily adapted to other sculpin species, such as the mottled sculpin (*Cottus bairdii* Girard, 1850), a commonly studied species in the United States (Adams et al. 2015).

Characteristics of slimy sculpin as a sentinel species: Local and regional distribution and habitat preferences

Although sculpins are often abundant in a local environment, the slimy sculpin has the most ubiquitous North American distribution among the cottids, ranging as far south as Virginia, north to Alaska, and from one coast to the other, with few exceptions (Scott and Crossman 1973). Slimy sculpin were more recently discovered in select western Prince Edward Island streams (Gormley et al. 2005). Where the multiple species of cottids are found in a given stream, they can be difficult to discriminate, but not impossible. Where several species of sculpin occur, they may segregate based on habitat preferences with slimy sculpin occupying colder tributaries and cold-water refugia compared with mottled sculpin found in more intermediate mixing zones (Adams et al. 2015). These two most similar cottids overlap in their distribution in the centre of the continent with discontinuous distribution to the west of Manitoba (Scott and Crossman 1973; updates on fishbase.ca). When there is co-occurrence McAllister (1964) described optimal distinguishing characters, being the number of pelvic fin rays (94% separation; mottled 4, slimy 3), the final ray of the dorsal fin (95% separation; mottled double, slimy single), and the ratio of the length of the caudal peduncle to the postorbital distance (100% separation; mottled <60, slimy >70). Failure to properly identify to the species level could introduce variability into morphometric data; however it is not expected to skew data significantly, as the ontogenic sizes are very similar (Scott and Crossman 1973). Ultimately, where there is suspected species distribution overlap, techniques like DNA barcoding would help to resolve species identification (e.g., Hubert et al. 2008).

Like other cottids, slimy sculpin lack a swim bladder and are benthic cryptic species. Slimy sculpin generally dwell in lake and stream habitats with cobble substrate. More specifically, habitat selection by slimy sculpins may be age related. Adult slimy sculpin preferentially select boulders, whereas young-of-the-year (YOY) tend to select gravel and rubble (Mundahl et al. 2012a). The fish is also capable of squeezing through openings 19% smaller than their head width (Marsden and Tobi 2014). Furthermore, sculpins tend to prefer cold water, but like other stream fishes would also be affected by interactions of chemical and physical environment (e.g., pH and habitat; Warren et al. 2010). They have an upper lethal water temperature estimated between 23 and 25 °C (Symons et al. 1976; Otto and Rice 1977), and slimy sculpin are rarely found in habitats with sustained water temperatures >19 °C (Gray et al. 2005a; Edwards and Cunjak 2007).

Residency and mobility

The spatial and temporal residency of a fish species is a crucial component and major challenge of designing a successful monitoring program when assessing fish responses associated with anthropogenic stressors (Environment Canada 1997). The reliability of the results depends on the ability of the sentinel species to accurately indicate relevant changes between sampling areas. The mobility of the species in question will affect the potential for choosing and using reference sites adjacent to or upstream of the impact area when no natural barriers are present. Seasonal mobility (e.g., migrations, spawning movements) may also affect the use of fish collected at both exposed and unexposed sites.

With no swim bladder and observations of territorial behaviours, the slimy sculpin is often generally characterized as a species with low mobility and strong site fidelity (Keeler et al. 2007). Although studies on movements have not been done in every habitat, there has been much effort to rectify these sometimes imprecise expectations. There have been various tagging and recapture studies performed on freshwater sculpin, all concluding that the majority of sculpin movements were <100 m, with median sculpin movements of approximately 1–30 m (McCleave 1964; Brown and Downhower 1982; Hill and Grossman 1987; Morgan and Ringler 1992; Gray 2003; Gray et al. 2004; Petty and Grossman 2004; Schmetterling and Adams 2004; Cunjak et al. 2005; Keeler et al. 2007).

Recapture or resighting of marked individuals has been a major limiting factor in all previous movement studies. Keeler et al. (2007) overcame this limitation using antenna to search for slimy sculpin implanted with PIT tags at six sites in five tributaries of the Kennebecasis River, New Brunswick (n = 337 tagged sculpin). Of the 337 sculpin PIT-tagged, 283 (84.5%) were detected at least once over the course of the study. Annual movement of PIT-tagged sculpin was extremely low, with 50% moving <10 m, and a median home range of 9 m. An additional study using PIT tags to track the closely related mottled sculpin found 84% of tagged fish moved <100 m (median displacement 7.97 and 8.76 m, summer and winter, respectively, total n = 92; Breen et al. 2009), which matches closely with work on slimy sculpin which suggested a maximum linear home range of 150 m (Keeler 2006). The remaining individuals of mottled sculpin (16%) moved a maximum of 511 m and were biased upstream (Breen et al. 2009). Other work suggests that some movements may be larger than expected and inversely correlated with age (Clarke et al. 2015), supporting the relevance of adult sculpin surveys for monitoring programs.

Further evidence for reduced mobility and residency has also been obtained through stable isotope analysis. Gray et al. (2004) found site-specific isotope signatures (δ^{13}C, δ^{15}N) in slimy sculpin collected at 10 sites over a 30 km stretch of a river. There was very little temporal variation in site-specific isotopic signatures over a period of 18 months (δ^{13}C: 0.3‰–0.9‰; δ^{15}N: 0.3‰–0.5‰), suggesting that the sculpin were resident within a small spatial scale and displayed high site fidelity. Such spatial scale resolution is possible where there are conditions for distinct isotopic signatures (e.g., sewage effluent, lakes, and unique geological conditions). Galloway et al. (2003) showed significant differences in isotopic signatures in sculpin collected only 200 m apart that were exposed to pulp mill effluent and paper mill effluent hugging opposite shores in a large river. More recent work has also found that δ^{13}C signatures are distinct among sampling locations in many tributaries of the Athabasca River in the oil sands region (Farwell et al. 2009).

Collection efficiency and abundance estimates

Sculpin can be elusive to capture due to their cryptic colouration and their benthic habitats. There are many ways to capture sculpin including by hand, dip net, minnow trap, other modified traps, with electrofishing being the most efficient collection method. There are limitations, however, as sculpin do not respond to the electric pulses in the same manner as many other fishes. Sculpin often do not experience the classic galvanotaxic response (i.e., swim towards the anode). The response is strongly dependent on temperature and velocity of the water, but many stunned sculpin may tumble downstream in higher velocities or under low stream flow conditions will flip and become immobilized in an inaccessible interstitial space until recovery from the pulse. Injury rates of sculpin subject to repeated electrofishing events are low (Clément and Cunjak 2010), but these findings may be more relevant in multi-pass or repeated surveys.

Population abundance and density estimates with sculpin are complicated by the non-classic response to electrofishing described above and substrate composition, water temperature, electrofishing effort (number of sweeps), and overall capture efficiency. Clément (1998) investigated the electrofishing capture efficiency and the accuracy of the removal method (Zippin 1956, 1958) to estimate slimy sculpin and juvenile Atlantic salmon (*Salmo salar* Linnaeus, 1758) population sizes. Electrofishing (4–6 sweeps) was conducted at intermediate (15 °C) and cold (6 °C) water temperatures in run and riffle habitat types until approximately 90%–95% of the fish were captured. After the electrofishing removal, the actual population size of fish in the study sites was determined through an intensive search for any fish which had evaded capture; water was diverted to reduce the water level within the sites, and rocks were manually flipped to disturb any fish remaining in the sites. Capture efficiency for slimy sculpin was 31% in the first sweep, and higher capture efficiencies were observed at cold water temperatures (Clément 1998). The observed lower capture efficiency at intermediate water temperature may be attributed to a higher fright response of fish to electricity than at lower water temperatures (Vibert 1963; Hofstede 1967; Karlstrom 1976; Libosvárský 1990; Reynolds 1996). The removal method (based on three sweeps) produced accurate population size estimates of slimy sculpin at intermediate water temperatures (mean relative error (absolute value) ± SE = 9% ± 2.0%)), but the accuracy of estimates decreased at low water temperatures (23% ± 7.2%; Clément 1998). At cold water temperatures, increasing the number of electrofishing sweeps (effort) beyond the regular three sweeps improved accuracy of the sculpin population size estimates by almost fourfold (Clément 1998).

Combining all sculpin catch data from Clément (1998) with archived fish catch data (R.A. Curry, K.R. Munkittrick, and M.A. Gray, personal observation, 2002; sample sites >10 total fish, variable water temperatures), 41% (±2.5 standard error (SE)) of sample sculpin populations were captured in the first sweep (n = 18 collections; **Fig. 1**). The second and third sweeps increased the cumulative catch to 61% (±3.0 SE) and 77% (±3.2 SE), respectively. Electrofishing tends to be more efficient for salmonids; average cumulative catches for brook trout (n = 18 collections) and Atlantic salmon (n = 14 collections) were between 80% and 90% after three sweeps. Constant capture probability is a main assumption in population estimation using Zippin, and although there was no significant statistical difference in capture probability across the first three sweeps, the variability increased steadily by the third sweep (CV = 26%, 42%, 52%; sweeps 1–3, respectively n = 18). The higher relative error of the slimy sculpin population size estimates compared with salmon was likely due to the increasing departure from constant capture probability between sweeps for sculpin (Clément 1998). This suggests that the sculpin population estimates were probably underestimated.

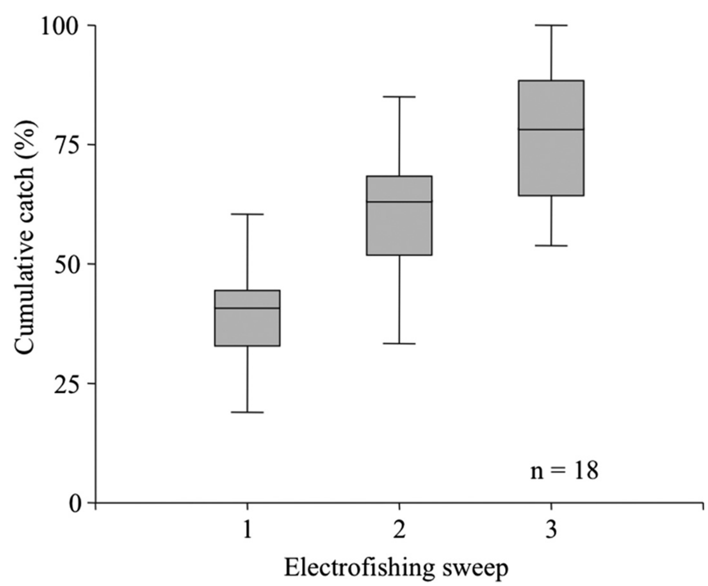

Fig. 1. Percentage of total slimy sculpin catch collected in each of the first three electrofishing sweeps from extinction/depletion studies (Clément 1998; R.A. Curry, K.R. Munkittrick, and M.A. Gray, personal observation, 2002). Box plots indicate 25th and 75th percentiles (box length) ± 1.5 times the interquartile range (whiskers), and median values (middle line).

Although electrofishing is a preferred method to capture these cryptic fish, it may not be effective in all instances and habitat types. Recent work suggests that detection rates for sculpin were highest using a beach seine (Haynes et al. 2013). Other work suggests that lucite traps (Hanson et al. 1992; McDonald and Hershey 1992; O'Brien et al. 2004) or trawling (Madenjian et al. 2005) may be useful in deep lakes. A more detailed review of capture techniques is available (Arciszewski et al. 2010).

Energy storage and seasonal demand

Energy reserves housed in the liver, muscle, and body cavity are partitioned to provide requirements for both reproduction and overwinter maintenance and survival. Energy storage in fish can be evaluated by condition factor and liver size (Environment Canada 1997). The condition factor for both male and female sculpin across an entire year is relatively stable (males and female reference slimy sculpin sampled over 12 months; Brasfield et al. 2013). Liver size is lowest for both male and female sculpin in the fall (September–October), and increases steadily for both sexes, with liver size peaking in March and declines as they prepare for spring spawning (Brasfield et al. 2013; **Fig. 2B**).

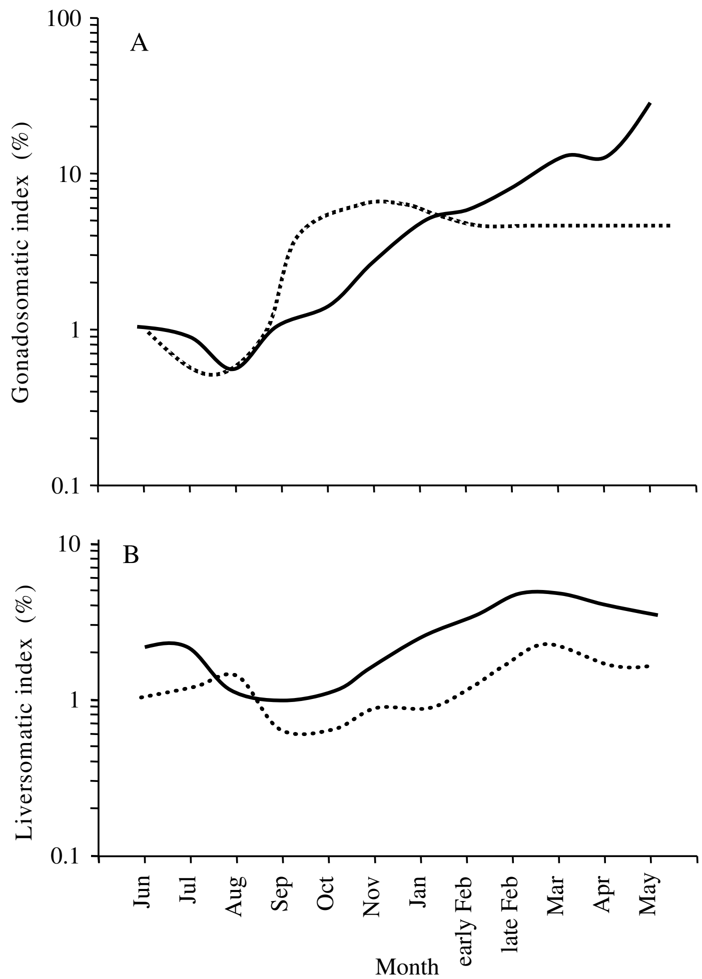

Fig. 2. Generalized female (solid line) and male (dashed line) slimy sculpin (A) gonadosomatic and (B) liversomatic index over one full year (modified with permission from Brasfield et al. 2013). Lines represent median values.

Maintenance of energy homeostasis is important for regulating body mass and requires a balance between food consumption and energy expenditure. In other studies, we found that as liver size was declining, there was an increase in ^{15}N of liver tissue relative to muscle tissue, possibly a sign of food deprivation (Doucett et al. 1999) or severe loss of mass (Jardine et al. 2005). This supports the observations made by Van Vliet (1964) that during nest-guarding periods, male sculpin may reduce their feeding to prepare, maintain, defend, and guard their breeding territories and subsequent offspring. Keeler et al. (2007) found that PIT-tagged male sculpin stayed at the nest site for approximately six weeks (mid-May until late June) during the egg incubation period. In contrast to the males, the female sculpin do not appear to be depleting liver stores as the gonad tissue accretes significantly over the winter (**Fig. 2**); both liver and gonad mass increases during the winter months. This pattern may be indicative of female sculpin actively feeding over the winter to help supply energy for gonadal growth. Correspondingly, there is no change in the stable nitrogen isotope in livers of female sculpin relative to muscle tissues in the spring (Jardine et al. 2005). The liver begins to decrease in relative size just before the spawning event and is likely related to the final mobilization of vitellogenin (yolk protein) from the liver to the developing eggs (Gray and Munkittrick 2005).

Optimized sampling times

The timing of collection is always a relevant consideration when designing a study but depends on the research question(s). To avoid confounding factors in the interpretation of biological responses in monitoring studies, one should have a basic understanding of how the fish develop during different periods throughout the year. Based on the seasonal investigation of energy storage, energy use, and hormonal profiles, Brasfield et al. (2013) recommended optimal sculpin sampling periods for various parameters of interest (**Table 2**). Recommended sampling times for a typical lethal EEM study for adult sculpin are pre-spawning (spring; Barrett and Munkittrick 2010).

Survival and growth

Slimy sculpin have a maximum age of about five years (Van Vliet 1964; Galloway 2006), though they may reach seven years at higher latitudes (Craig and Wells 1976). Ageing sculpin using otoliths is,

Table 2. Optimal sampling periods for sampling sculpin when a particular parameter of interest is important.

Parameter	Optimal sampling period
Male sculpin[a]	
Energy storage (liver)	Recrudescence or maturation (August or March)
Energy use (gonad)	Recrudescence (September–October)
Hormones	Recrudescence (August)
Female sculpin	
Energy storage (liver)	Pre-spawning (March)
Energy use (gonad)	Pre-spawning (March)
Hormones	Pre-spawning (March)

Note: Months given in brackets correspond with the optimal period found in Atlantic Canadian systems.

[a]For male characteristics that are optimal in the fall, differences can still be detected pre-spawning (spring); most sampling related to energy use should be done when female characteristics are optimal, unless sampling can be justified in both seasons.

similar to other fish, a challenge. Sculpin otoliths are generally quite opaque and if one expects a very proficient otolith reader might get estimates of ± 1 year, which means a three-year-old fish could be interpreted as 2, 3, or 4 years old. For a fish that lives to a maximum age of seven years, this is half of its actual life span. Consequently, detecting differences in size-at-age or age-at-maturity is difficult without perfect year class resolution due to short life spans of this species. Nevertheless, examining otoliths can provide crucial information as longitudinal gradients in slimy sculpin growth were successfully detected with otoliths (Bond et al. 2016; Kelly et al. 2016).

Growth is dependent upon many factors including water temperature regimes and duration of suitable growing seasons. For example, in August collections in the Little River, New Brunswick, Canada (latitude 47°N), YOY (age 0) slimy sculpin may reach lengths of 35 mm (Fig. 3), whereas age 1 slimy sculpin collected in Lac de Gras, Northwest Territories, Canada (latitude 64°N) were 25–40 mm (Fig. 4; Gray et al. 2005b). Growth can also be inferred from sequential length–frequency distributions by following modal lengths of any clearly defined age classes (Gray et al. 2002). In temperate regions like Atlantic Canada, it is mainly the YOY age class (age 0), and sometimes age 1, that can be clearly distinguished (Fig. 3). In far northern regions, early age classes are more easily distinguished due to the truncated growing seasons (Fig. 4).

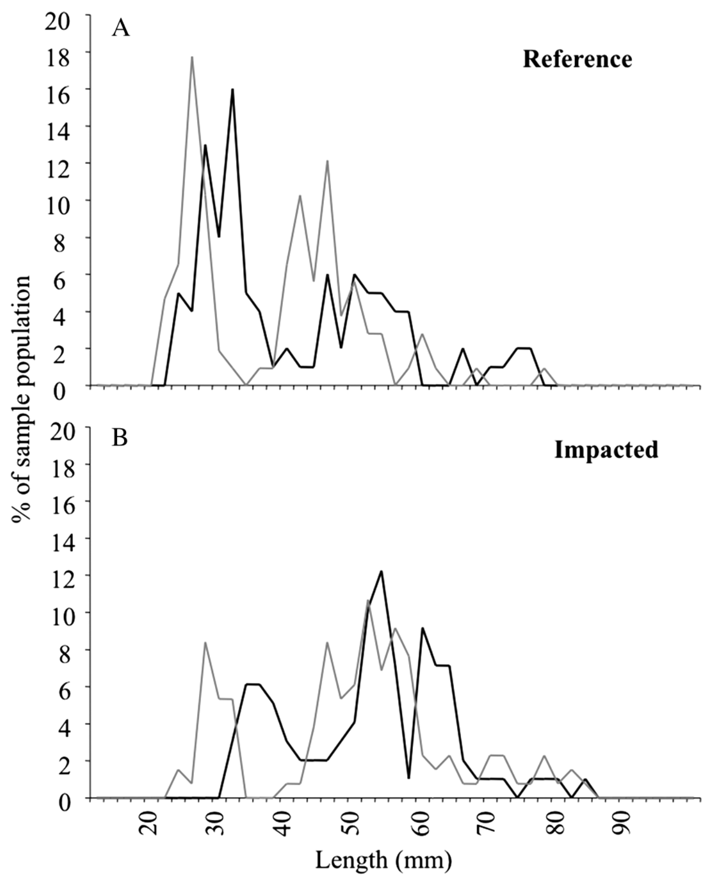

Fig. 3. Example length–frequency distributions for a reference (A) and impacted (B) sample population. Sequential collections were taken at each site in August (grey line) and November (black line) of the same year (1999) in the Little River, New Brunswick, Canada.

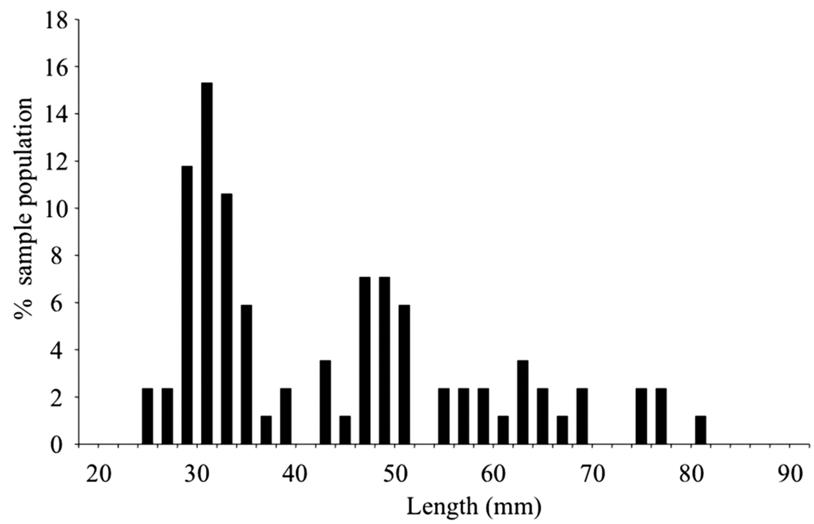

Fig. 4. Length–frequency distribution for slimy sculpin collected from Lac de Gras, Northwest Territories, Canada in August 2004 (Gray et al. 2005b). Age 0 sculpin are not represented, as they were too small for capture at that time.

Reproduction

Energy use and spawning timing

Depending on environmental factors, slimy sculpin may reach sexual maturity at age 1 (males) and age 2 (females) (Van Vliet 1964), and although not easy to do, the sex of mature slimy sculpin can be assessed non-lethally by visual inspection of the presence of the urogenital papilla in males and its absence in females (Arciszewski et al. 2010).

Slimy sculpin spawn following the spring freshet with the onset of spawning observed at water temperatures of approximately 8–10 °C (Van Vliet 1964; Keeler 2006); in New Brunswick this occurs in mid to late May, with egg incubation lasting until mid to late June (Keeler and Cunjak 2007). Slimy sculpin studied in Minnesota streams spawned when water temperature reached 10 °C in late March and early April (Majeski and Cochran 2009). Spring and early summer spawning species commonly use a reproductive strategy where gonadal tissue develops in the fall, with little development over the winter, and final gonadal growth and maturation as water temperatures rise in the spring, as with white sucker (Scott et al. 1984) or gonadal development occurs quickly in the spring, as with several species of dace (Galloway 2006). Freshwater sculpin appear to follow the second strategy (rapid gonadal development near spawning), although the bulk of female ovarian development takes place over winter (Brasfield et al. 2013).

Physiologically, male slimy sculpin begin to prepare for spawning about mid-summer with a significant increase in testosterone levels (Brasfield et al. 2013). Gonadal recrudescence follows in the early fall, with a peak gonadosomatic index in September–October (**Fig. 2A**). Both testosterone and testis size stabilize approximately 2–3 months before spawning, indicating an early readiness compared with females. Female sculpin experience an apparent hormonal "shut-down" during the summer (June–August), with a significant increase in estradiol production followed by significant ovarian development beginning in early fall (Brasfield et al. 2013). Within 1–2 months of spawning, estradiol levels drop as testosterone levels increase, and gonad size continues to increase until spawning time (**Fig. 2A**).

Reproductive strategy

Slimy sculpin have polygynous mating system where males prepare and defend nest sites, attract female to lay eggs in their nests, and guard nests through incubation and for a few days post-hatching (Van Vliet 1964). Movements of male sculpin increased in frequency, and distance in some cases, in early spring when they looked for appropriate nest sites (Keeler and Cunjak 2007). Although most males moved <10 m during this period, some males captured in the Kennebecasis River NB migrated up to 120 m just prior to spawning. Slimy sculpin appeared to move most during the spring pre-spawning period, based on the examination of the displacement of males and females at this time. Males appear to be responsible for this increase because females show minimal shifts in movement throughout the year (Keeler et al. 2007). In the Kennebecasis River, it appeared that males were moving into areas with specific nest site characteristics or increased access to females (Keeler et al. 2007).

Male slimy sculpin showed a strong preference for moderate-sized cobble (median axis >64 mm) when selecting nest sites from the available habitat (Keeler and Cunjak 2007). Other work found a nest preference for rocks >35 cm (Majeski and Cochran 2009). Past research has also shown the importance of substrate availability in other sculpin populations (Mousseau and Collins 1987; Natsumeda 2001). Mousseau et al. (1988) also suggested that substrate availability may influence the degree of polygyny in lake-dwelling populations of slimy sculpin.

Fecundity and reproductive output

The fecundity of female slimy sculpin increases through to early spring and then declines as eggs mature and some are reabsorbed immediately before spawning (Gray and Munkittrick 2005). As with many other fish, fecundity is positively related to body size in slimy sculpin ($r^2 = 0.89$), with a fecundity range of 39–194 for sculpin measuring 41–76 mm in length ($n = 40$; Brasfield 2007).

Numbers of eggs found in the streams in slimy sculpin nests post-spawning are higher than individual fecundities due to the attraction of multiple females to lay eggs in each nest. Keeler and Cunjak (2007) tracked PIT-tagged slimy sculpin and predicted that on average at least 2–3 females were laying eggs in each male's nest. Other research indicated that nests of individual males contained clutches from as many as nine females, but these eggs were not counted (Majeski and Cochran 2009). In New Brunswick, the average number of eggs deposited per female was 105 ± 52 (SD; $n = 21$; Keeler and Cunjak 2007), and the average sum of eggs per nest was 239 eggs from 40 nests in tributaries of the Kennebecasis River NB (Keeler and Cunjak 2007). A second study in New Brunswick found a median of 281 eggs from 11 nests (Gray and Munkittrick 2005). In multiple systems in Saskatchewan, the mean number of eggs in slimy sculpin nests ranged from 151 to 630 eggs per nest (Van Vliet 1964).

The size of eggs from slimy sculpin captured in the Kennebecasis River NB ranged from 2.3 to 2.8 mm ($n = 90$; Keeler and Cunjak 2007). As a surrogate for egg size, the fecundity per gram gonad mass can be used as a tool to look for differences in sample populations. Gray and Munkittrick (2005) demonstrated that the number of eggs, expressed per gram gonad mass, was significantly reduced in female slimy sculpin living downstream and adjacent to relatively intense agricultural activities during one spring collection.

Reproductive success and recruitment

Length–frequency distributions are easily constructed (recommended size interval = 2 mm when measuring length to the nearest millimetre), and with sufficient sample population sizes can provide data not only on growth but also on reproductive potential (proportion of mature fish), reproductive success and recruitment combined (proportion of YOY fish), and size-at-age for small-bodied fish. To gather meaningful non-lethal information, we suggest the collection of minimum of 100 individuals (Gray et al. 2002), though 100 mature fish plus any YOY collected is preferable to better resolve the older age classes that may be distorted by strong YOY age classes (Brasfield et al. 2015).

The best time to conduct a collection to assess the population composition is late summer through to the end of the initial growing season (August–November in eastern Canada) to ensure that the YOY slimy sculpin are large enough to be collected with standard electrofishing dip nets (mesh size ~0.5 cm). In late summer in reference systems, the proportion of YOY in the sample population can range from approximately 40% to 80% (**Fig. 3A**). In contrast, the proportion of YOY in a sample population can be reduced when there are stressors impacting the population (**Fig. 3B**). For example, in agricultural regions of northwestern New Brunswick, YOY proportions ranged from 0% to 30% at impacted sites (Gray and Munkittrick 2005; Gray et al. 2005a).

Contaminant loads

Organisms at high trophic levels are often ideal choices for studies of contaminant loading. Although non-lethal techniques are becoming more common, there may be factors that limit their use. Sculpin have been used in studies of contaminant loads (see Dubé et al. (2005) applied example below). Slimy sculpin accumulated (and retained) the lowest radionuclide load of collected fish species in lakes of the Experimental Lakes Area (Bird et al. 1998). In Lake Ontario, medium chain chlorinated paraffins predominated in most species with the highest levels detected in slimy sculpin (108 ng/g ww) and rainbow smelt (*Osmerus mordax* (Mitchill, 1814), 109 ng/g ww; Houde et al. 2008). These results suggest that in certain situations, top predators may not be the best candidates for estimating a contaminant load. Which species to sample will depend on whether the question of measuring contaminant loading is related to human health or to measuring environmental loadings, especially those associated with sediments where the slimy sculpin is more intimately connected.

Comparison with other indicators

Resources for monitoring studies are necessarily limited and inevitably lead to choices. Techniques, species, measurements, frequency, power, sensitivity, and timing are a few examples of choices. In instances where long-term programs are operating or likely to occur, initial studies can specifically evaluate questions of the adequacy, practicality, and relationship to other ecosystem components. Although an initial program scoping cannot be done, other available studies must be consulted to estimate the general applicability of a chosen approach. In several studies, consistent patterns have been observed between slimy sculpin and other environmental indicators (Culp et al. 2003; Galloway et al. 2003; Bowman et al. 2010; Arciszewski et al. 2011; Beauchene et al. 2014). Other studies have also shown similar results between slimy sculpin site occupancy and diatom acid-tolerance index (Burns et al. 2008). In yet other instances, the utility of slimy sculpin has been used as a benchmark to evaluate the usefulness of alternative approaches (mesocosms Bowman et al. 2010; benthic macroinvertebrates Arciszewski et al. 2011). These results are most useful for sampling areas where even slimy sculpin may not be abundant (Spencer et al. 2008a).

The relevance of a given indicator can also be evaluated through established linkages in a food web. For instance, biomass of lake trout declined after extirpation of prey species, including slimy sculpin (Kidd et al. 2014). Conversely, slimy sculpins have been observed predating on eggs of large-bodied species, such as lake trout (Bunnell et al. 2014; Marsden and Tobi 2014) and sockeye salmon (*Oncorhynchus nerka* (Walbaum in Artedi, 1792); Dittman et al. 1998). The position and relationships of slimy sculpins in local and regional food webs is an important area for expanded research. A more detailed review of the feeding and diet of slimy sculpin is found in Arciszewski et al. (2015a).

Applied examples

The value of the slimy sculpin as an environmental monitoring tool is becoming more widely recognized with each successful study. Below are some brief summaries of applied studies to illustrate the wide-ranging utility of the slimy sculpin for assessing biological effects of environmental stressors. Among much of the recent literature, several key themes of the deployment of slimy sculpin as sentinel species occur. Sculpin are sensitive to acidity (and consequently, alkalinity; Baker et al. 1996; Burns et al. 2008; Warren et al. 2008), show clear temperature preferences (Kaeser and Sharpe 2001; Lessard and Hayes 2003; Adams et al. 2015), and sensitivity to physical instream disturbance, both small (Edwards and Cunjak 2007; Maitland et al. 2016) and large scale (Magilligan et al. 2016), and to landscape development (Scrimgeour et al. 2008; Smedley et al. 2011). However, a notable response to changing habitats is not always observed in fish (Baldigo et al. 2008) and is more likely related to the impact of any habitat changes on the preferences of slimy sculpin (Mundahl et al. 2012b).

Row crop agriculture

The slimy sculpin was chosen as a sentinel species to investigate the non-point source impacts of agriculture on stream fish (Gray et al. 2002; Gray and Munkittrick 2005; Gray et al. 2005a; Brasfield et al. 2015). The slimy sculpin was particularly well suited for assessing non-point source inputs due to low mobility and high site fidelity. Major findings from these studies include the ability to detect population-level changes using non-lethal collection methods and assessing length–frequency distributions (Gray et al. 2002); lethal collection methods found larger sculpin with smaller livers and gonads, reduced fecundity, and smaller nest sizes were found in agricultural reaches compared with upstream forested reaches of the same river (Gray and Munkittrick 2005).

To confirm the responses seen in the single river agricultural study, we collected slimy sculpin in multiple watersheds ($n = 19$ systems) to examine the influence of environmental factors like water temperature, sediment deposition, and precipitation on sculpin populations in forested (reference) and agricultural streams (Gray et al. 2005a). In the reference systems, there was a strong positive relationship with YOY sculpin size ($r^2 = 0.84$) and strong negative relationship with sculpin density ($r^2 = 0.78$), related to water temperature. There was no relationship found between sculpin size or density and the amount of sediment deposited in either the forested or, unexpectedly, in the agricultural regions. As expected, precipitation was not a significant factor for sculpin populations in reference areas, with no relationship between the percent YOY sculpin comprising sample populations and the total rainfall in forested systems ($r^2 = 0.0006$). In contrast, there was a strong negative relationship between precipitation and YOY sculpin size in the agricultural systems ($r^2 = 0.77$), suggesting that inputs from surrounding land use activities introduced via variable rainfall amounts during the early cropping season (June–August) may affect resident slimy sculpin populations.

Forest harvesting

Edwards (2001) monitored slimy sculpin populations in Catamaran Brook, New Brunswick to investigate their responses to forestry activities. Population abundance of slimy sculpin at sites downstream of the forestry activities was not different during pre-harvest years (1990–1996) compared with harvest years (1996–1998). With 8% of the total catchment harvested, more intense forest removal practices may still have the potential for impacts. In one tributary, however, that experienced increased peak flows after harvesting (Caissie et al. 2002) and one high-suspended sediment event during harvesting (autumn of 1996), there were no associated population-level changes in slimy sculpin observed in the two years following timber harvest (Edwards 2001). There was a significant decline in abundance in the summer of 1996 (immediately before timber harvest was initiated that autumn), presumably as a result of a mid-winter ice breakup and consequent disturbance to the streambed and fish population in Catamaran Brook (Cunjak et al. 1998).

Edwards (2001) also showed that the longitudinal distribution and abundance of slimy sculpin in an 18 km length of stream was strongly correlated with the maximum summer water temperatures; in stream reaches where temperature maxima exceeded 23 °C, slimy sculpin were scarce or absent. This may partly explain the scarcity of sculpin from mainstem, high-order river reaches such as in the Miramichi River and Saint John River where substrate habitat is suitable but summer water temperatures can exceed 25 °C several times each year (Cunjak and Newbury 2005), which is the lethal temperature threshold for slimy sculpin (Symons et al. 1976). First- and second-order streams and headwater tributaries are often cold-water brooks inhabited by fishes like brook trout and slimy sculpin in northeastern North America. As land use activity such as forestry and agriculture encroach on these sub-basins, the small brooks are experiencing increases in summer water temperatures (and fine sediment loading) that may influence their suitability for cold-water fishes such as slimy sculpin. For example, Cunjak et al. (2005) measured a warming of small streams (sub-basin sizes $<2\ km^2$) in response to forestry activity such that maximum temperatures were substantially greater in the reaches downstream of road crossings and harvest blocks. Abundance of slimy sculpin (and brook trout) has generally declined in those streams where water temperatures have increased most.

Oil sands

Tetreault et al. (2003) examined health parameters of slimy sculpin in the Steepbank River, Alberta, to determine whether there were differences among sites with naturally occurring oil sands deposits (natural), adjacent to active oil sands mining activity (developed), and a reference area. Slimy sculpin showed increased hepatic 7-ethoxyresorufin-*O*-deethylase (EROD) levels at the natural (twofold increase) and developed sites (10-fold increase) relative to the reference location. Steroid hormone production was reduced for both female and male slimy sculpin collected within the oil sands deposit. Although there were inconsistencies between years, at least one collection indicated that males had larger livers and gonads at exposed sites, whereas females had larger livers, smaller gonads, and reduced fecundity relative to the reference site.

Metal mining

Dubé et al. (2005) examined the multitrophic level biological effects of effluent from a Zn–Pb–Cu mine in northeastern New Brunswick. Using small, modular mesocosms (seeded with algae and benthic invertebrates), YOY slimy sculpin were exposed for 26 d to reference water, 20% effluent, and 80% effluent to examine growth and survival. Over the study, average YOY sculpin survival in the reference mesocosms was 69%, with a reduction to 56% and 25% in the 20% and 80% effluent exposure units, respectively. Percent mass gain was also reduced from 80% in the reference treatment, to 67% and 21% in the 20% and 80% exposure treatments, respectively. The slimy sculpin was identified as a useful indicator to ammonia in mine effluent (Spencer et al. 2008b) and sensitive to aluminum toxicity (Van Sickle et al. 1996). This study also successfully demonstrated that small-bodied fish could be added to small, modular benthic invertebrate mesocosm exposure systems, adding a trophic level and also demonstrating effects from both waterborne exposure and exposure through the diet. The slimy sculpin was also identified as a useful indicator to ammonia in mine effluent (Spencer et al. 2008b) and sensitive to aluminum toxicity (Van Sickle et al. 1996).

Conclusion

The objective of this paper was to provide a compilation of slimy sculpin research to environmental monitoring applications as well as future ecological studies. Characteristics of the slimy sculpin that

Table 3. Summary of sentinel species characteristics for the slimy sculpin observed in research studies conducted in New Brunswick, Canada.

Characteristic	Slimy sculpin information
Residency	Average <30 m
Abundance	Varies with temperature and habitat 0–20+/m^2
Longevity	Age 4–5; 95% of population <4
Food preference	Benthic invertebrates, fish eggs, YOY young sculpin (i.e., cannibalistic)
Energy use in reproduction	GSI as much as 40% in females in spring
Growth	Grows continuously throughout year
	Average 10–15 mm/year (mature sculpin)
Age to maturation	Age 1 (males), age 1–2 (females)
Spawning	Spring synchronous spawner
	Water temperature ~8–10 °C
Food chain involvement	Key component of food web; benthic position

Note: YOY, young-of-the-year; GSI, gonadosomatic index.

make it an ideal sentinel species include its low mobility and high site fidelity, ubiquitous distribution through northern regions of North America (Scott and Crossman 1973; Magilligan et al. 2016), relatively high abundance in cool-water systems (Edwards and Cunjak 2007), short life span, high reproductive output (Brasfield et al. 2015), easy to measure biological and physiological parameters, and benthivory (**Table 3**). The efficiency and timing of collection need to be considered for abundance estimates as well as for changes in population structure and physiological parameters that occur during the year. The use of slimy sculpin to investigate environmental contaminant loadings in aquatic systems should be expanded, as they are important and complex links between benthic and pelagic food webs (Kidd et al. 2014). Increasing basic research and monitoring of slimy sculpin at site and regional scales will help to improve and develop long-term data sets to detect change when biological and ecologically important.

Other future research and data gaps include general information on variability in characteristics across their range of distribution, capture techniques at very low conductivities, effects of warmer temperatures on energy use and storage, comparisons of normal ranges of life history characters with other cottid species, modeling studies on sculpin populations for predictive purposes, and improved aging techniques and understanding of growth rates. Understanding basic biological information of a given species aids the interpretation of responses in environmental monitoring studies.

Acknowledgements

We acknowledge the support and input from colleagues who reviewed early versions of this paper: R. Keller, M. Clément, and R. Cunjak.

Author contributions

MAG and KRM conceived and designed the study. MAG, RAC, TJA, KRM, and SMB performed the experiments/collected the data. MAG, RAC, TJA, KRM, and SMB analyzed and interpreted the data. MAG, RAC, TJA, KRM, and SMB contributed resources. MAG, RAC, TJA, KRM, and SMB drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data accessibility statement

All relevant data are within the paper.

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