

Silver shiner, *Notropis photogenis*, fecundity and parasite infections during the reproductive period

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Abstract

The reproductive period is a critical part of a species' life history. Estimating species-specific fecundity can improve demographic models aimed at developing recovery targets for imperilled species. We provide egg diameter and fecundity estimates and develop a length–fecundity relationship for silver shiner, *Notropis photogenis* (Cope, 1865), a small-bodied freshwater species listed as Threatened under Canada's *Species at Risk Act*. Furthermore, we document the incidence of an acanthocephalan parasite, the thorny-headed worm, *Leptorhynchoides thecatus* (Linton, 1891), in the gastrointestinal tract of silver shiner, which is the first published record of the parasite in this species. Silver shiner egg diameters (mean $\pm$ standard deviation) were 0.61 ± 0.15 mm and ranged from 0.13 to 0.92 mm. Fecundity ranged from 311 to 2768 eggs and was significantly higher in age 2–3+ fish (1475 ± 570 eggs) compared with age 1+ fish (576 ± 270 eggs). We highlight that parasite infection negatively impacted the body condition of individuals and that additional work is needed to determine the impact of parasite infestation on reproductive output, recruitment, susceptibility to predation, and survival of silver shiner in Canada. The fecundity and egg diameter estimates for Canadian silver shiner provided here can be incorporated into future populations modelling for this threatened species.

Key words: spawning, imperilled species, minnows, egg diameter, fecundity length relationship, silver shiner, *Notropis photogenis*

Résumé

La saison de reproduction est un élément clé du cycle biologique d'une espèce. L'estimation de la fécondité propre à l'espèce peut améliorer les modèles démographiques utilisés pour établir des cibles de rétablissement pour des espèces en péril. Nous présentons des estimations du diamètre des œufs et de la fécondité et établissons une relation entre la longueur et la fécondité pour le méné-miroir, *Notropis photogenis* (Cope, 1865), une espèce de petit poisson d'eau douce qui figure sur la liste des espèces menacées de la *Loi sur les espèces en péril* du Canada. Nous documentons en outre l'incidence d'un ver acanthocéphale parasite, *Leptorhynchoides thecatus* (Linton, 1891), dans le tube gastrointestinal de ménés-miroirs, ce qui constitue la première observation publiée du parasite chez cette espèce. Le diamètre moyen ($\pm$ écart-type) des œufs de ménés-miroirs est de $0,61 \pm 0,15$ mm et la fourchette des valeurs va de 0,13 à 0,92 mm. La fécondité va de 311 à 2768 œufs et est significativement plus grande chez les poissons de 2–3 ans et plus (1475 ± 570 œufs) que chez les poissons d'un an et plus (576 ± 270 œufs). Nous soulignons le fait que l'infection par le parasite a un impact négatif sur l'embonpoint des individus et que d'autres travaux sont nécessaires pour déterminer l'impact de l'infestation de parasites sur l'efficacité de la reproduction, le recrutement, la susceptibilité à la prédation et la survie chez le méné-miroir au Canada. Les estimations présentées de la fécondité et du diamètre des œufs pour des ménés-miroirs canadiens peuvent être intégrées à la modélisation démographique future pour cette espèce menacée. [Traduit par la Rédaction]

Mots-clés : frai, espèce en péril, ménés, diamètre des œufs, relation entre fécondité et longueur, méné-miroir, *Notropis photogenis*

Introduction

Reproduction is a critical component of life history (Winemiller and Rose 1992). Fecundity, in particular, has implications for population dynamics, species persistence, and estimates of minimum viable population size (MVP) (Power

2007; Wang et al. 2019). Fecundity can be influenced by a multitude of factors, including climate (Mills 1988; Power et al. 2005), fish size (Schemske 1974; Lauer et al. 2005), and environmental stressors (Power 1997; Miller and Ankley 2004). Therefore, obtaining contemporary, population-specific esti-

mates of fecundity can improve the predictive ability of demographic models aimed at estimating MVPs and assessing the recovery potential of imperilled species. Failure to utilize suitable fecundity estimates can lead to erroneous conclusions regarding the recovery potential of a species and may lead to unrealistic recovery targets due to the importance of fecundity as an input in population models (Beissinger and Westphal 1998; Beissinger and McCullough 2002).

Silver shiner, *Notropis photogenis* (Cope, 1865), is a small-bodied freshwater fish listed as threatened under Canada's *Species at Risk Act*. Currently no fecundity estimates exist for silver shiner within Canada and current estimates of recovery potential incorporate fecundity from a surrogate species, the emerald shiner, *Notropis atherinoides* (Rafinesque, 1818) (Schapp 1989; DFO 2013; Young and Koops 2013). The use of surrogate species for conservation can be problematic as surrogates may provide a poor representation of the species of interest, possibly leading to erroneous conclusions regarding species survival and recovery potential (Lindenmayer et al. 2002; Wiens et al. 2008). Furthermore, previous fecundity studies for silver shiner in Alabama, USA, (Hodgskins et al. 2016) did not directly relate fecundity to fish size and may not reflect fecundity of the species in Canada owing to different thermal conditions, growth, spawn timing, and the number of spawning events (Burbank et al. 2021a). Thus, estimation of contemporary, population-specific fecundity information for silver shiner can improve estimates of recovery potential by avoiding the use of surrogate species (Caro and O'Doherty 1999; Cooke et al. 2017) and fecundity estimated from individuals occupying different climatic conditions.

Furthermore, the presence and impact of parasites during the reproductive season is poorly understood for many small-bodied freshwater fishes, including silver shiner. The infestation of parasites during the reproductive period can have population-level impacts for the host species (Thomas et al. 1996; Marcogliese and Pietrock 2011; Krkošek et al. 2013). Parasite infestation can also alter the behavior of the host, resulting in increased susceptibility to predation (Barber et al. 2000; Latham and Poulin 2002). Therefore, it is important to examine and identify the presence of parasites during spawning, particularly for imperilled species.

To address the absence of relevant Canadian data, we examined silver shiner from an Ontario population to examine (i) egg diameter, (ii) the fish length–egg diameter relationship, (iii) fecundity (egg count), and (iv) fish age–fecundity, fish length–fecundity, and fish weight–fecundity relationships to improve the ability to inform recovery strategies for silver shiner in Canada. Additionally, we identified an acanthocephalan parasite, the thorny-headed worm, *Leptorhynchoides thecatus* (Linton, 1891), within the gastrointestinal tract of silver shiner and examined (v) the timing of parasite infection, (vi) the relationship between parasite load and length, and (vii) the impact of parasite load on fish condition.

Materials and methods

Silver Shiner were captured during the spring (April–June) of 2018 and 2019 in Sixteen Mile Creek, Oakville, Ontario, Canada (43.49908°N, 79.77673°W). Fishes were captured us-

ing repeat hauls of a 9.14 m bag seine (see Burbank et al. (2021a) for details regarding fish collections), with a subsample of silver shiner ($n = 367$ and $n = 178$ in spring 2018 and 2019, respectively) retained for study. Fish handling and lethal sampling for this project were approved by the Great Lakes Laboratory for Fisheries and Aquatic Science (Fisheries and Oceans Canada) – Water Science and Technology Directorate (Environment and Climate Change Canada) Animal Care Committee (AUP 1846) and conformed to Canadian Council on Animal Care guidelines. Retained silver shiner were euthanized and frozen following approved Fisheries and Oceans Canada protocols.

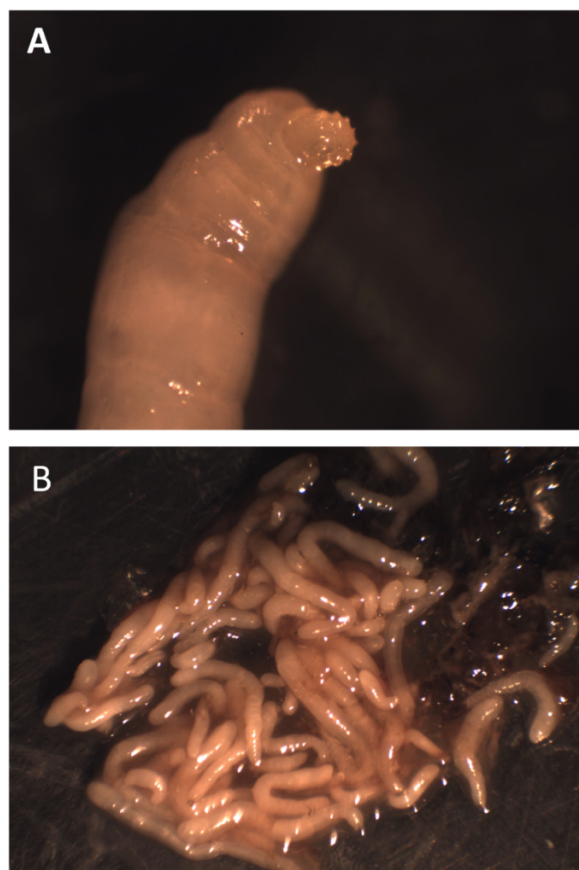
In the laboratory, silver shiner were thawed and measured for total length (mm) and mass (g). Individuals were dissected and their gonads and gastrointestinal tract were thoroughly examined under a dissection microscope (SZN-2; Optika, Italy). Sex was determined based on gonad examinations. Of the silver shiner kept, $n = 160$ (2018) and $n = 81$ (2019) were identified as adult females.

The gonadosomatic index (GSI), which is an indication of reproductive status, was calculated as gonad mass expressed as the percentage of somatic mass for all females following Hodgskins et al. (2016) and Burbank et al. (2021a). Body condition (Fulton's K) and body condition calculated net of gonad weight were also estimated (Ricker 1975). Body condition calculated net of gonad weight was estimated in addition to Fulton's K to control for gonad weight when estimating body condition. For a random subset of mature reproductive females captured in spring 2018 ($n = 40$), the gonads were placed in Gilson's fluid (Bagenal and Braum 1978) prior to being separated in a Petri dish split into nine equal-area sections. All eggs from mature females were included in the analysis, with egg stages that ranged from early maturing to ripe (Hodgskins et al. 2016). The eggs were photographed, and egg diameter and fecundity were assessed using a Nikon DS-Fi3 camera mounted on a Nikon SMZ800 stereo microscope. To estimate the average egg diameter per fish, the diameters of the longest axis of $n = 20$ randomly selected eggs from each female were measured (mm) using the measurement function on the Nikon DS-L4 tablet interface and the mean was calculated. The relationship between fish length and average egg diameter was evaluated using simple linear regression. To estimate fecundity, the total number of eggs in each fish were counted three times and the average of the three estimates was taken. We evaluated the relationship between fish length (mm) and fecundity (measured as the number of eggs) using a power function model following Bagenal and Braum (1978) and Power et al. (2005) as

$$F = aL^b$$

where F is the fecundity (number of eggs), L is the total fish length (mm), a is the estimated constant, and b is the estimated exponential coefficient. The relationship between fish weight (g) and fecundity was estimated using the same approach. Furthermore, we evaluated whether older individuals (ages 2–3+; generally second- or third-time spawners) had significantly higher average fecundity than younger individuals (age 1+; generally first-time spawners), using a

Fig. 1. Photographs of the acanthocephalan thorny-headed worm, *Leptorhynchoides thecatus*, from the gastrointestinal tract of a silver shiner, *Notropis photogenis*, taken through a microscope at 4× magnification (A) and 1.5× magnification (B).



two-sample one-tailed t test. Age was estimated using the age-length key and length-frequency histogram for spring-captured fish provided in Burbank et al. (2021b).

Parasites within the gastrointestinal tract of silver shiner were discovered during fish dissections. Subsequently, each tract was thoroughly examined for the presence of parasites. The parasitic species *L. thecatus* was identified (Fig. 1), distinguished by the number of hooks per longitudinal row of the proboscis following Steinauer and Nickol (2014). Taxonomic confirmation of the parasite was made by parasitology experts. The number of *L. thecatus* in each gastrointestinal tract was counted to estimate the parasite load (the total number of parasites found in an individual fish) for each fish. Additionally, the frequency of occurrence of parasites in individual fish retained at each sampling event was calculated and the correlation between frequency of occurrence of parasites and GSI of females was examined in each year using Pearson's correlation coefficient. The relationship between fish length and the parasite load was investigated with nonlinear regression using a power function similar to the length-weight relationship. The correlations between the parasite load of females and body condition and body condition calculated net of gonad weight were examined using Pearson's correlation coefficient. Grubbs' test (Sokal and Rohlf 2012) was used

to examine the ordered datasets for outliers, both high and low. We also used a two-sample two-tailed t test to determine whether the parasite load differed significantly between all younger (age 1+; generally, first-time spawners) and older (ages 2–3+; generally second- or third-time spawners) fish. For the t tests conducted, assumptions of normality and homogeneity of variance were assessed using the Shapiro-Wilk W test and Bartlett's homogeneity of variance test, respectively (Zar 2010). If assumptions were not met, the nonparametric Mann-Whitney U test was used instead. Assumptions of linear regression including normality and homoscedasticity were evaluated for each regression with the Shapiro-Wilk W test and graphs of residual versus fitted values, respectively (Zar 2010). For all nonlinear regressions, residuals were examined for statistical adequacy following Bates and Watts (1988). All analyses were conducted in R version 4.0.2 (R Development Core Team 2020).

Results

The diameter of eggs averaged 0.61 ± 0.15 mm (mean $\pm$ standard deviation) and ranged from 0.13 to 0.92 mm (Supplementary Table S1). The fish with the smallest egg diameter was an outlier (Grubbs' test, $p = 0.03$) and was excluded from further analysis. For the remaining fish, there was a significant positive linear relationship between fish length (mm; L) and average egg diameter (mm; ED) as follows:

$$ED = 0.00387L + 0.281$$

(linear regression, $F_{1,37} = 12.14$, $p = 0.001$, $R^2 = 0.23$).

Fecundity estimates for silver shiner ranged from 311 to 2768 eggs (Supplementary Table S1). The fish with the smallest egg diameter also had the highest fecundity and within the fecundity data similarly tested as an outlier (Grubbs' test, $p = 0.03$). Fecundity was positively related to fish total length (Fig. 2) as follows:

$$F = 0.0168L^{2.39}$$

(nonlinear regression, $p < 0.001$, $n = 39$, $R^2 = 0.52$).

Fecundity was also positively related to fish weight (g; W) as follows:

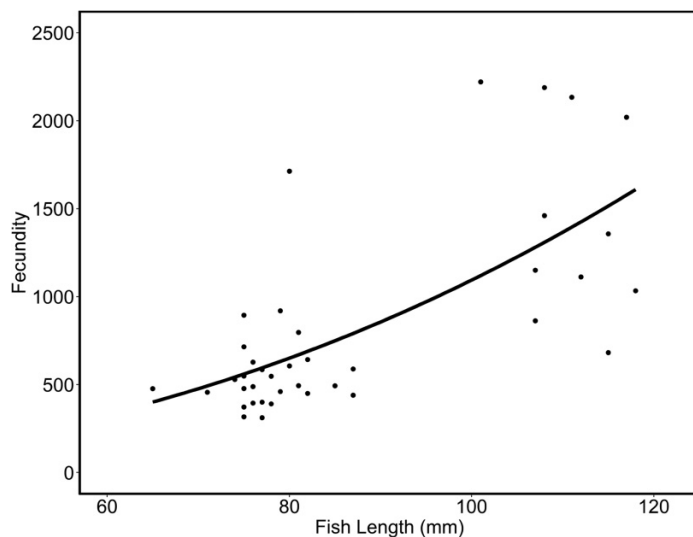
$$F = 217.3W^{5.38}$$

(nonlinear regression, $p < 0.001$, $n = 39$, $R^2 = 0.52$).

The average fecundity of ages 2–3+ individuals (1475 ± 570 eggs) was significantly higher than the average fecundity of age 1+ individuals (576 ± 270 eggs; t test, $t_{11.8} = 5.01$, $p < 0.001$).

Leptorhynchoides thecatus was found within the gastrointestinal tracts of silver shiner in 2018 and 2019 but no other parasitic species were discovered. There was a significant positive correlation between the frequency of occurrence of parasites and GSI (Fig. 3) in 2018 (Pearson's $r = 0.83$, $p = 0.001$) and 2019 (Pearson's $r = 0.60$, $p = 0.03$). The relationship between GSI and parasite frequency of occurrence (PF) was described

Fig. 2. The relationship between fish length (mm) and fecundity (measured as total number of eggs) described by the equation $F = 0.0168L^{2.39}$ ($R^2 = 0.52$, $n = 39$, $p < 0.001$) for silver shiner, *Notropis photogenis*, captured in Sixteen Mile Creek in spring 2018.



by the equation

$$PF = 0.0474GSI + 0.355$$

(linear regression, $F_{[1,16]} = 13.66$, $p = 0.002$, $R^2 = 0.43$).

The frequency of occurrence of parasites followed the temporal pattern of GSI in both years (Fig. 3), indicating parasite infections were highest during the spawning period and declined in the weeks following spawning. Parasite load averaged ~ 6 parasites per fish (range 0–56 per fish) during the spawning period. When considering individuals infected with parasites, there was a significant nonlinear relationship between fish length (mm) and parasite load (number of parasites in gastrointestinal tract; PL) described by the equation

$$PL = 9.02 \times 10^{-9}L^{4.44}$$

(nonlinear regression, $p < 0.001$, $n = 296$, $R^2 = 0.22$).

The average parasite load was significantly higher in age 2–3+ individuals (8.31 ± 11.62) compared with age 1+ individuals (2.24 ± 3.81 ; Mann–Whitney U test, $W = 15\,100$, $p < 0.001$). Furthermore, for females, parasite load was significantly negatively correlated with body condition (Pearson's $r = -0.15$, $p = 0.02$) and body condition calculated net of gonad weight (Pearson's $r = -0.31$, $p < 0.001$).

Discussion

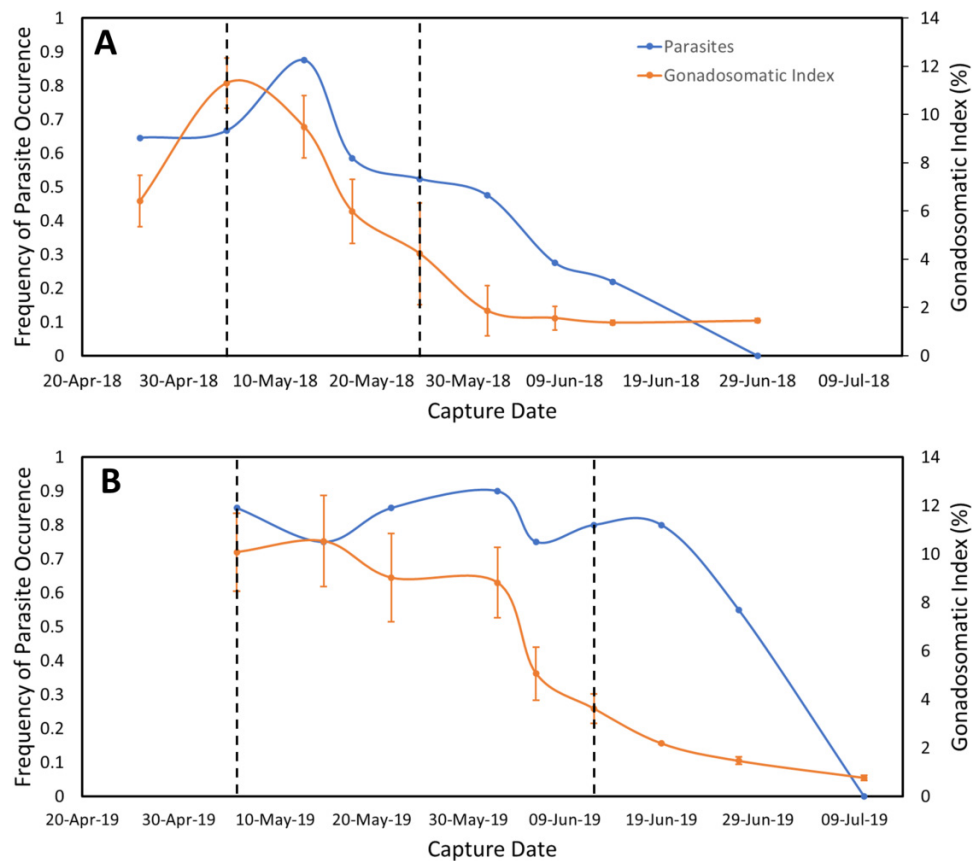
Here we provide fecundity estimates for the threatened silver shiner at the northern edge of its geographic range and identify a high frequency of occurrence of *L. thecatus* during the reproductive period. To our knowledge, there are no previous published records of acanthocephalan parasites including *L. thecatus* in silver shiner. Our results indicate parasite

load is negatively correlated with body condition; therefore, further research is required to understand the ecological implications of parasite infection for silver shiner.

Based on our data, previous recovery potential modelling for silver shiner overestimated the reproductive potential for the species as a result of using higher than actual fecundity estimates from surrogate emerald shiner. Fecundity estimates from emerald shiner ranged from 2452 to 2630 eggs (Young and Koops 2013), whereas we found silver shiner fecundity was generally below 1000 eggs, with some older individuals (ages 2–3+) exhibiting fecundity of up to a maximum of 2768 eggs. Previously studied silver shiner captured in Alabama, USA, were estimated to have average fecundity of 5115 eggs, with a range of 2499–9115 (Hodgskins et al. 2016), suggesting southern populations display substantially higher fecundity, possibly as a result of the thermal factors on growth and reproduction (Kirk et al. 2022) or differences in productivity (Power et al. 2005) in northern habitats. Comparatively, silver shiner within Canada display fecundity that is generally less than half of that estimated for southern USA populations. Latitudinal variation in life-history traits, including reproductive traits, is common in fish species (Winemiller and Rose 1992; Blanck and Lamouroux 2007), and has been demonstrated for walleye, *Sander vitreus* (Mitchill, 1818) (Johnston and Leggett 2002), Arctic char, *Salvelinus alpinus* (Linnaeus, 1758) (Power et al. 2005), American shad, *Alosa sapidissima* (Wilson, 1811) (Leggett and Carscadden 1978), and roach, *Rutilus rutilus* (Linnaeus, 1758) (Lappalainen et al. 2008). Such findings suggest it would be misleading to utilize fecundity estimates from populations of the species in other climates, as they would lead to positively biased estimates of individual fecundity, population-wide reproductive potential and estimated MVP sizes. The lower estimates for reproductive output based on our fecundity estimates have significant conservation implications. Populations with lower fecundity will (ceteris paribus) have lower intrinsic rates of population increase and with lower abundance will have consequent increased risk of extirpation (e.g., Pimm et al. 1988). Together such effects may suggest poorer prospects for the recovery of this imperilled species within Canada than previously assumed.

The discovery of parasites during the reproductive season raises several questions about the potential ecological consequences of infestation for silver shiner. In fishes, parasitic infection has been repeatedly shown to markedly increase susceptibility to predation (e.g., Lafferty and Morris 1996; Seppälä et al. 2004; Lafferty 2008; Krause et al. 2010). Acanthocephalan parasites, in particular, commonly alter the behaviour of their host in a manner that increases susceptibility to predation, thereby facilitating parasite transmission to the final host (Moore 1984). For instance, acanthocephalan parasites have been observed to reduce the burrowing and hiding behaviour of three species of shore crabs in New Zealand, with consequent increases in their susceptibility to predation (Latham and Poulin 2002). Although the occurrence and impacts of acanthocephalan parasites on the population ecology of fishes in Canada has often been overlooked, the parasite is known in some Canadian fish and bird species (MacLulich 1943; Sanford 1978; Song and Proctor 2020). For

Fig. 3. The mean gonadosomatic index $\pm$ standard error (orange) and frequency of occurrence (blue) of the acanthocephalan thorny-headed worm, *Leptorhynchoides thecatus*, within the gastrointestinal tract of silver shiner, *Notropis photogenis*, by capture date from sampling conducted in Sixteen Mile Creek during spring 2018 (A) and spring 2019 (B). The observed spawn window identified in Burbank et al. (2021a) is shown by the broken vertical black lines.



example, *L. thecatus* are common in smallmouth bass, *Micropterus salmoides* (Lacepède, 1802) (Richardson and Richardson 2009), where damage to the intestinal wall by the parasite can cause extensive tissue damage and death (Nickol and Crompton 1985). Smallmouth bass are known to prey upon silver shiner (McKee and Parker 1982; Bunt 2016), thus predation of infected silver shiner may facilitate transmission of the parasite to smallmouth bass, which is a preferred definitive host for the parasite (Muzzall and Gilliland 2004).

Previous studies have identified parasites within silver shiner including small numbers of black-spot trematode, *Uvulifer Yamaguti*, 1934, cysts and infestations of the trematode *Neodactylogyrus* Price, 1938 (currently known as *Dactylogyrus* Diesing, 1850) (Baldwin 1987, 1988; Hoffman 1999). The identification of *L. thecatus* within silver shiner is a novel finding but not surprising given that *L. thecatus* has been identified in approximately 50 fish species (Richardson and Richardson 2009) and displays a preference for smallmouth bass as a definitive host (Muzzall and Gilliland 2004). Nevertheless, it is important to document *L. thecatus* infection in silver shiner, particularly since the infestation is concentrated during the reproductive period. Parasite infections during the reproductive period generally have population-level impacts for the host species, reducing reproductive

potential (Thomas et al. 1996; Barber et al. 2000), recruitment (Krkošek et al. 2013), survival (Marcogliese and Pietrock 2011), and leading to consequent reductions in the intrinsic rates of population increase (Nisbet et al. 1989; Manly 1990; Burgman et al. 1993; Power 2007). Infestation during the reproductive period may be an adaptive advantage for parasites as it can increase the energy available to the parasite, with the host fish disproportionately allocating energy to gonad development and reproduction as opposed to immune response function (Barber et al. 2000; Šimková et al. 2005). In the studied population of silver shiner, larger and older individuals tended to have higher parasite loads and parasite infection had a significant negative impact on body condition as observed in other species (Pennycuik 1971). As larger individuals may be proportionally more susceptible to predation due to their higher parasite loads and reduced body condition, they may be less likely to survive and successfully reproduce, potentially negatively impacting overall population reproductive output. Larger females can contribute disproportionately to population replenishment (Barneche et al. 2018), demonstrated by the positive relationship between fish size and both fecundity and egg diameter observed here for silver shiner. Thus, the overall threat to silver shiner populations posed by the parasite may

be substantial. However, currently we have limited knowledge of how parasite infections affect life history traits and whether the observed parasite infection is an inherent life history risk or a new, environmentally driven threat to silver shiner.

Silver shiner exists in only five drainages within Canada; Bronte Creek, Grand River, Thames River, Sixteen Mile Creek, and Saugeen River (Glass et al. 2016; Burbank et al. 2020, 2021b; Gáspárdy et al. 2021), but is found throughout the Ohio and Tennessee river drainages in the east-central and southeastern United States. Due to its limited distribution in Canada, caution is warranted about the use of vital rate data from surrogate species. Differences between studied Canadian and American populations point to the importance of environmental factors for determining fecundity and suggest that management of the species will require the population-specific information provided here. Furthermore, because of the potential consequences of parasitic infections for net reproductive output, it is necessary to develop a more thorough understanding of the prevalence and ecological consequences of acanthocephalan parasites in Canadian populations of silver shiner to ensure their continued survival.

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Data availability

Data can be found in the supplementary material and can be provided by the corresponding author upon reasonable request.

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Competing interests

The authors have no competing interests.

Supplementary material

Supplementary table is available with the article at <https://doi.org/10.1139/cjz-2022-0031>.

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