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PRIMARY RESEARCH PAPER

Fouling of fishing line by the waterflea *Cercopagis pengoi*: a mechanism of human-mediated dispersal of zooplankton?

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Abstract The fishhook waterflea *Cercopagis pengoi* was first reported in Lake Ontario in 1998, but subsequently spread to Lakes Michigan and Erie as well as some inland lakes. One possible mechanism of dispersal to inland lakes occurs via fouling of and subsequent transfer on sport fishing lines. Here we explore fouling of *Cercopagis* on different commercial brands of fishing lines while trolling on Lake Ontario. Accumulation of animals varied significantly across brands, and was lowest on Flea Flicker brand. Fouling was more intense with line set at 20 than at 10 m, and was directly related to the distance trolled. Different pound-tests of Flea Flicker did not vary significantly in *Cercopagis* accumulation rates. The maximum number of *Cercopagis* and diapausing stages on a fishing line was 1024 individuals and 106 diapausing eggs. Because diapausing eggs may remain viable for weeks or longer, their transfer on fouled fishing line to non-invaded lakes poses a risk of invasion and supports previous studies that suggested sport fishermen as possible vectors of dispersal of invasive waterfleas.

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Introduction

The recent invasion history of the Laurentian Great Lakes includes a disproportionate number of Ponto-Caspian species, among them the zooplankter *Cercopagis pengoi* (Ostroumov) (MacIsaac et al., 1999; Ricciardi, 2006). Some of these species, including *Cercopagis*, have dispersed within and adjacent to the Great Lakes system. *Cercopagis pengoi* and *Bythotrephes longimanus* Leydig are unique among introduced Great Lakes' zooplankton in possessing an extremely long caudal appendage, which is often two or more times longer than the body length. The appendage may serve an anti-predatory function against gape-limited fish predators. Both species are reported to accumulate in tangled masses on fishing lines trolled through epilimnetic waters during summer and early autumn periods (Krylov et al., 1999). Indeed, initial discovery of *Cercopagis* in Lake Ontario in July 1998 was attributed to sport fishermen who had experienced difficulty retrieving fishing lines owing to animal accumulations too large to fit through eyelets on fishing rods (MacIsaac et al., 1999). This problem is not new to invaded regions, as fishing artisans in the native region of the Black Sea refer to the species as 'frost' owing to its tendency to accumulate on gill nets (H. MacIsaac, pers. observ.).

A key life-history characteristic of both *C. pengoi* and *B. longimanus* that potentially facilitates their dispersal to new lakes is the ability to produce diapausing eggs that remain viable after periods of dormancy. Diapausing eggs are resistant to adverse environmental conditions, including desiccation and passage through fish digestive tracts and exposure to salt water (Jarnagin et al., 2004; Branstrator et al., 2005). Diapausing stages are produced by these species when reproduction switches from the typical parthenogenetic mode to sexual generation, usually but not exclusively in mid- to late-summer (MacIsaac et al., 1998). For example, timing of the appearance of females carrying diapausing eggs was similar in Lake Michigan and the Caspian Sea, in both cases occurring in autumn as water temperature declined (Charlebois et al., 2001). Some workers have suggested that invasive waterfleas alter their reproductive behavior during the initial years of an invasion, leading to prolonged production of diapausing eggs, thereby enhancing the probability of establishment (Ketelaars et al., 1995).

Both *Cercopagis* and *Bythotrephes* were probably introduced to the Great Lakes via ballast water transfer, a principal vector that has transferred a variety of species to the system (e.g., Ricciardi, 2006). *Cercopagis* possesses moderate salinity tolerance (up to ~8 ppt), and thus could potentially survive alive in ballast tanks flushed with salt water, although entry as diapausing eggs would seem more likely. Once established in Lake Ontario, inter-lake transfer of ballast water almost certainly was responsible for its introduction to Lake Michigan. MacIsaac et al. (2004) stated that *Bythotrephes* diapausing eggs fouled on fishing gear or other submerged materials could subsequently detach and hatch in previously non-invaded lakes if the same contaminated equipment were used, and Drake (2004) suggested that *Bythotrephes* invasions could occur with as few as 1–8 transferred individuals. Owing to similarities in life histories between the species, the same dispersal mechanisms may be available to *Cercopagis*. To date, however, no experimental tests have been conducted to examine the fouling characteristics of either of these species on fishing lines used by sport fishermen.

In this study, we experimentally examined the propensity for *Cercopagis* to foul fishing lines in Lake Ontario. First, we investigated fouling on four different commercial brands of fishing lines trolled at each of two depths. We also explored the relationship between distance trolled and number of waterfleas accumulated on one brand of monofilament (Flea Flicker). Finally, we examined whether fouling intensity was related to characteristics (e.g., thickness) of the line by using different tests of the same commercial brand of microfilament braided line (Spectra PowerPro Line).

Materials and methods

Experiments were designed to explore *Cercopagis* fouling of fishing line in relation to distance and depth trolled, and whether fouling differed for four different brands and different tests of a single brand of line in western Lake Ontario, approximately 1–2 km from Burlington, Ontario. Lines were set out four at a time as the boat moved at a speed of ~5 km/h. Trolling distance and boat speed were estimated using a hand-held GPS unit (GlobalMap 10). The lines were evenly spaced about the rear of the boat using fishing rods to minimize the chance of line entanglement and were rotated every trial to avoid possible bias from the lines being too close to the motor. To ensure the lines stayed relatively deep in the water, a single 5 ounce (141 g) weight was attached to the end of each line prior to trolling. After a trolling distance of 1 km, the boat was stopped and all lines were reeled in by hand, with fouled sections carefully excised and preserved in 95% ethanol until samples were processed. At the end of each trial, a vertical plankton haul was taken using a 50-cm mouth, 50-μm mesh size plankton net to measure the density of *Cercopagis* in the water column; depth of hauls were 10 or 20 m, corresponding to the depth lines had been set in the experiment. Zooplankton was preserved as per fishing line samples. In the laboratory, all zooplankton were counted in total, and identified at 120× magnification using a Leica dissection microscope where all individuals and their diapausing eggs were counted. All *Cercopagis* and diapausing eggs carried by adult females were identified and counted. No *Bythotrephes* were encountered fouled on fishing lines.

In the first experiment, we tested fouling on four of the most preferred and easily obtained brands available at tackle outlet stores. The lines had different characteristics, but all were the same weight and single textured lines. The brands were Berkley Trilene Big Game™ ("Trilene Big Game"), Berkley Trilene XL Smooth Casting™ ("Berkley Trilene XL Smooth Casting"), Red Wolf™ ("Red Wolf"), and Flea Flicker™ ("Flea Flicker"). Berkley Trilene Big Game is 0.457 mm in diameter and identified by its manufacturer as a premium fishing line that is super strong. Berkley Trilene XL Smooth Casting is described by its manufacturer as easy-casting and strong; this line has a diameter of 0.406 mm. The Red Wolf monofilament fishing line, with a diameter of 0.330 mm, is identified by its manufacturer as a value leader for cost-conscious anglers. Flea Flicker by Cortland is described by its manufacturer as a premium monofilament line specifically designed to reduce fouling by waterfleas owing to its oval (as opposed to round) shape (major and minor axis of 0.58 and 0.42 mm, respectively) and a proprietary slip additive.

The effect of trolling depth on accumulation rates on the four brands of fishing line were tested on September 7th with lines set at 10 and 20 m depth. Trolling distance was 1 km, as identified by GPS, following which lines with fouled animals were retrieved and preserved. The experiment was repeated three times. The number of *Cercopagis* fouled on different brands of lines set at different depths was ln(x + 1) transformed before statistical analysis with 2-way Analysis of Variance. The number of diapausing eggs per female for animals fouled on fishing lines was likewise analyzed with 2-way ANOVA.

The effect of distance trolled on *Cercopagis* accumulation rate was tested using only 20-lb test Flea Flicker line. Four lines were placed in the lake water at 20 m depth on September 7th and 8th. Lines were retrieved approximately every 200 m trolling distance (200, 400, 600, 800 m). The experiment was conducted three times in total, but one trial was removed for analysis because there was no accumulation. Accumulation rate (ln(x + 1)) was tested using Analysis of Covariance with distance trolled as a continuous variable (including zero fouling at the origin) and trial date a categorical variable.

The effect of line thickness on accumulation rate was tested using four different thicknesses of a single braided line on September 27th. The Spectra PowerPro Line™ ("Spectra PowerPro") is reported by the manufacturer to be the roundest and easiest-to-use fishing line on the market. This braided microfilament line has thicknesses of 0.15, 0.23, 0.28, and 0.36 mm for the 10, 20, 30, and 50 lb lines, respectively. For each trial, a 10, 20, 30 and 50 lb test line were set out at 20 m depth. Trolling continued for 1 km, after which fouled lines and animals were recovered and preserved. Accumulation rate of *Cercopagis* (ln(x + 1)) and their diapausing eggs (ln(x + 1)) on each thickness were each tested using a 2-way ANOVA.

Results

Every brand of fishing line was fouled by *Cercopagis pengoi*, though accumulation rates varied significantly in relation to trolling depth (ANOVA, $P < 0.001$). For example, mean *Cercopagis* accumulation rates were much higher for 20 than for 10 m set lines for each of the XL Smooth Casting (393 vs. 76 individuals), Flea Flicker (31 vs. 9 individuals), Big Game (143 vs. 55 individuals) and Red Wolf (266 vs. 49 individuals) (Fig. 1a). In addition, fouling rate differences among brands of fishing line were also significant (ANOVA, $P < 0.005$). The Flea Flicker brand accumulated, on average 4-, 8-, and 13-fold less *Cercopagis* than did Big Game, Red Wolf and XL Smooth Casting lines, respectively, set out at the same time. Because diapausing eggs produced by *Cercopagis* are retained in the female brood chamber, the degree of fouling by female adult animals directly influences the number of diapausing eggs on each line, as does the depth lines are set. For example, mean diapausing eggs fouled on 10 and 20 m lines of XL Smooth

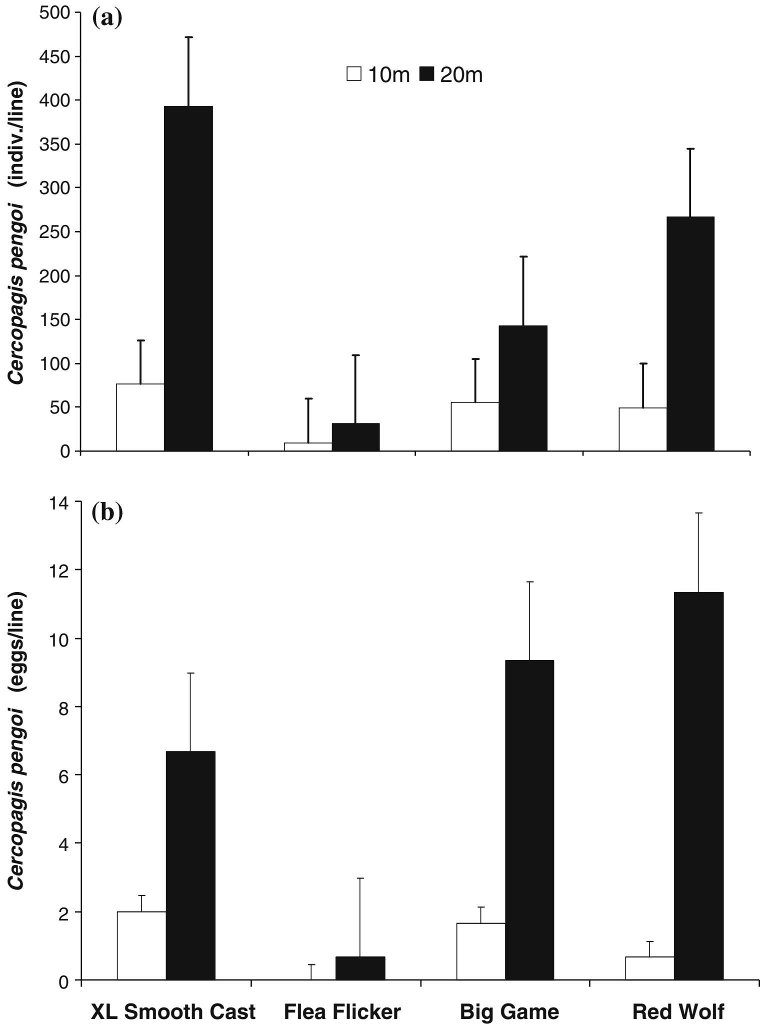

Fig. 1 Mean (+1 SE) number of *Cercopagis* individuals (**a**) and diapausing eggs (**b**) per line fouled on four commercial brands of fishing lines trolled at 10 and 20 m depths over a 1 km distance. Differences between fishing line types and across depths were significant

Casting (2.00 vs. 6.67), Flea Flicker (0.00 vs. 0.67), Big Game (1.66 vs. 9.33) and Red Wolf (0.66 vs. 11.33) were related both to brand type (ANOVA, $P < 0.005$) and depth of line (ANOVA, $P < 0.0005$)(Fig. 1b). Effects of both brand and depth remained significant when diapausing eggs were expressed per female (ANOVA, $P < 0.05$). There was no significant interaction between line brand and depth for either number of *Cercopagis* or diapausing egg number (ANOVA, $P > 0.05$).

Two trials were conducted on different days to assess the effect of trolling distance on *Cercopagis* accumulation rate on fishing lines. Both trial day and distance trolled affected accumulation rate of *Cercopagis* on fishing line (ANCOVA, $P < 0.005$; Fig. 2). Indeed, large differences were observed in accumulation rates for the two days, even though sampling was conducted at the same location on adjacent days.

The density of *Cercopagis* in Lake Ontario was high on the date we tested for differences in accumulation rates on different tests of the Spectra PowerPro (Table 1). Ten, 20, 30 and 50 lb lines averaged 806, 490, 604 and 278

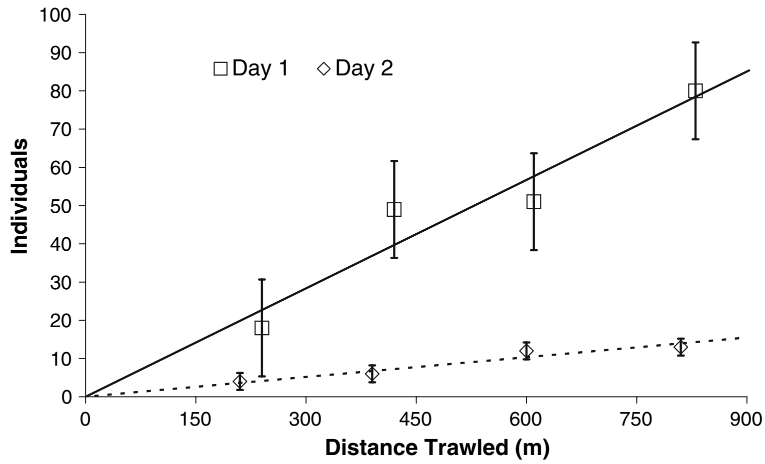

Fig. 2 Mean (±1 SE) number of *Cercopagis* fouled on 20 lb test of Flea Flicker line in relation to trolling distance (m) in trials 1 (squares) and 2 (diamonds). Trials were conducted over two days. Trials 1 and 2 had R^2 values of 0.92 and 0.93, respectively

Table 1 Mean (±1 SE) density of *Cercopagis* in Lake Ontario at the terminal location of each fishing line test. Samples were collected as 10 and 20 m-surface vertical tows with a 50-cm diameter, 50-µm mesh, Wisconsin-style plankton net. Tests on the effect of trolling depth and distance trolled tests were completed at the same GPS coordinates

Date	Test	Brands tested	Number of tows, depth	Mean density of *C. pengoi* (ind/m^3 ± 1 SE)
9/7/2005	Trolling depth	Trilene Big Game, Red Wolf, Flea Flicker, Trilene XL Smooth Casting	3, 10 m	57 ± 24
9/7/2005 9/8/2005	Distance trolled	Flea Flicker	3, 20 m	81 ± 29
9/27/2005	Line thickness	Spectra PowerPro	3, 20 m	262 ± 143

Cercopagis, respectively (Fig. 3). These accumulation rates did not, however, differ statistically (ANOVA, $P > 0.05$). Similarly, the mean number of diapausing eggs on these lines (82, 69, 59 and 24, respectively) did not differ significantly (Fig. 3).

Discussion

Diapausing stages have been hypothesized as a major dispersal mechanism for zooplankton in general (e.g., Green & Figuerola, 2005 and references therein) and *Bythotrephes* waterfleas in particular (e.g., Charalambidou et al., 2003; MacIsaac et al., 2004; Muirhead & MacIsaac, 2005). While less is currently known about *Cercopagis* than *Bythotrrephes*, their similar life histories suggest that mechanisms important to dispersal of one species are likely of importance to the other. Accumulation rates for *Cercopagis* varied widely in relation to trolling depth and distance and brand of line used, but were unrelated to thickness of test used (Figs. 1–3). It is not surprising that lines trolled farther through a water column or placed in deeper water accumulated more individuals, as contact opportunities would be proportionally higher than for lines exposed over shorter distances or lesser depths. Considering that anglers commonly troll over much greater distances than those used here, accumulation rates experienced by these individ-

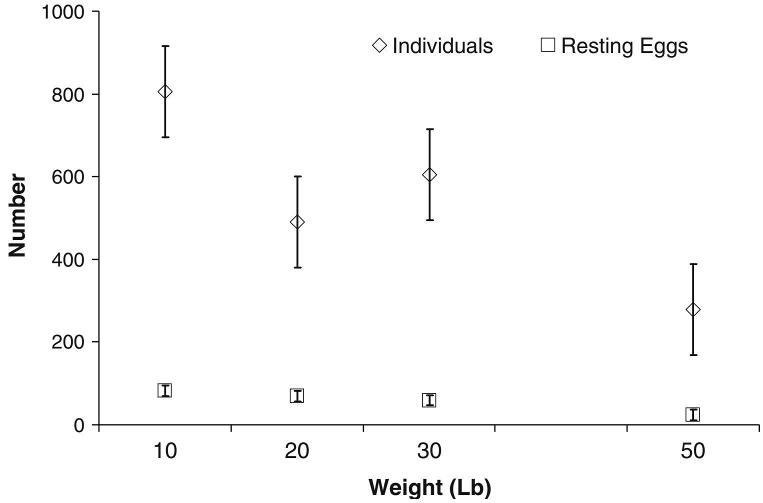

Fig. 3 Mean (±1 SE) number of *Cercopagis* individuals and diapausing eggs per line fouled on different tests (lb) of PowerPro line. Differences in thickness were not significant. Individual and diapausing egg trend lines had R^2 values of 0.78 and 0.98, respectively

uals may be correspondingly higher. In addition, lake density of *Cercopagis* ranged from 36 to 77 ind. m^3 during our trials. These values are considerably lower than mean values (281, 295 ind. m^3) reported elsewhere in Lake Ontario (Makarewicz et al., 2001; Ojaveer et al., 2001; Benoit et al., 2002) and maximum values (305, 420 ind. m^3) reported in the Baltic Sea (Krylov et al., 1999; Ojaveer et al., 2004). Consequently, trolling during periods of enhanced *Cercopagis* abundance should result in greater fouling of fishing tackle. Because the species' phenology is characterized by mid- to late-summer population maxima (Benoit et al., 2002; Laxon et al., 2003; Ojaveer et al., 2004), the severity of fouling should be highest during this period.

We observed higher fouling rates on lines trolled at 20 m than at 10 m. This finding is consistent with reports that *Cercopagis* achieves highest abundances in the top 20 m or at the bottom of the epilimnion or top of the metalimnion (Ojaveer et al., 2001; Laxon et al., 2003), with Benoit et al. (2002), suggesting that the species accumulates of Lake Ontario. This pattern suggests that all fishing lines trolled through anything except perhaps surface waters are prone to fouling if the species is present in the lake.

The Flea Flicker brand of fishing line experienced much lower fouling (and reduced abundance of diapausing eggs) relative to the other brands tested. Indeed, the extent of fouling on Flea Flicker line was only ~12% of that of the most heavily fouled brand, XL Smooth Casting. Consequently, the Flea Flicker line holds promise for reducing the likelihood of transmission of *Cercopagis* from invaded to noninvaded lakes. Even though fouled Flea Flicker line would pose a risk if used on noninvaded lakes, the 'propagule pressure' associated with this line should be substantially lower than that associated with the other tested brands. Recent research has clearly implicated the importance of 'propagule pressure' as a determinant of invasion success (see Lockwood et al., 2005), thus any factors that reduce the number of transferred diapausing eggs is of potential management value.

It is not clear how many diapausing eggs of *Cercopagis* or *Bythotrephes* would be needed to initiate an invasion. Demographic collapse and invasion failure may occur when population (e.g., inoculum) sizes are very small, owing to Allee effects (Drake, 2004). This effect may be less important for species like *Cercopagis* and *Bythotrephes*, diapausing eggs of which hatch into parthenogenetic females. Drake (2004) argued that *Bythotrephes* invasions could succeed with high probability (~1.0) with as few as ~10 parthenogenetic females introduced, or with a lower probability (~0.45) with as few as 1 parthenogenetic female introduced. This model considered only demographic stochasticity, and assumed that the introduction event occurred early enough in the season that multiple generations could be produced by the time sexual reproduction and the quest for mates occurred in autumn. If introduction events occurred later in the year—as would be the case with *Cercopagis*—the inoculum required to achieve the same probability of establishment would be correspondingly higher (Drake, 2004). Assuming that the same conditions apply to *Cercopagis*, transfer of contaminated fishing lines from invaded to noninvaded lakes clearly poses a risk to the latter systems, as we observed up to 106 diapausing eggs per line surveyed. One factor that could reduce this risk is reduced viability of desiccated diapausing eggs. Branstrator et al. (2005) found that viability of *Bythotrephes* diapausing eggs was sharply lower following a desiccation periods of <1 day exposure. Thus, risk associated with fishing line highly fouled with invasive waterfleas carrying diapausing eggs might be expected to diminish with prolonged aerial exposure. Nevertheless, results of this study support the hypothesis that invertebrate diapausing stages can be present in sufficient quantities on fouled fishing line as to pose a significant risk of invasion if the uncleaned equipment is subsequently used on a noninvaded lake. These finding indicate that public education campaigns may be required to ensure that anglers do not unwittingly introduce fouled masses of *Cercopagis* from invaded to noninvaded lakes.

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