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Research Article

Distribution, prevalence and intensity of *Anguillicoloides crassus* in the American eel, *Anguilla rostrata*, in the Bras d'Or Lakes, Nova Scotia

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Abstract

In 2009 to 2010, 169 American eels, *Anguilla rostrata*, from the Bras d'Or Lakes, Nova Scotia, were examined for presence of the invasive nematode *Anguillicoloides crassus*. Prevalence and intensity in eels were determined to be higher than previously reported for the Bras d'Or Lakes. Overall prevalence was determined to be 46% with mean intensity at 9 parasites/eel (±11). Higher prevalence of *A. crassus* (60 to 67%), higher mean intensities (6.8–12.6 parasites/eel), and greater number of eels with more than 20 parasites per eel were found in semi-enclosed basins with higher freshwater input and close proximity (13 to 20 km) to probable source(s). No significant differences were found between mean intensity between riverine, estuarine or coastal lagoon habitats, however, prevalence was found to be higher in riverine habitats. No significant differences were found between infected and non-infected eels for total length, total body weight, gonad weight, GSI or condition factor. The Bras d'Or Lakes form a semi-enclosed estuarine body with low flushing times, high summer water temperatures (>20°C) and an international shipping destination, that makes it an ideal environment for the establishment and spread of *A. crassus*. The need to preserve aquatic habitats and reduce environmental stressors is imperative in an *A. crassus* infected environment. Greater controls and innovative solutions are needed to prevent further introduction of aquatic invasive species.

Key words: epidemiology; swimbladder parasite; American eel; invasive nematode; habitats; estuarine; freshwater; coastal lagoon

Introduction

The American eel, *Anguilla rostrata*, is an important fish species to the local Mi'kmaq people on the east coast of Canada for food, medicinal and spiritual purposes. Widely distributed throughout Atlantic Canada, the eel was recently re-examined and designated as a threatened species by the Committee on the Status of Endangered Wildlife in Canada due to dramatic declines in abundances in Lake Ontario and the upper St. Lawrence River. Eel abundance in other areas of Atlantic Canada is highly variable (COSEWIC 2012). Recent declines in eel abundance and observations of eel mortalities in 2008 and 2009 in the Bras d'Or Lakes, Nova Scotia, are of concern to indigenous eel fishers. Invasive nematode, *Anguillicoloides crassus,* infection in eels compounds the issue challenging traditional eel management practices of the Mi'kmaq people.

Anguillicoloides crassus, a nematode native to its host, the Japanese eel, *Anguilla japonica*, was introduced to European waters in the mid-1980s from East Asia where it spread rapidly throughout the continent (Evans and Matthews 1999). The impact of *A. crassus* on European eels is well documented (Kirk 2003). In heavily infected European eels, the swimbladder was observed as inflamed, thickened, or blocked (Würtz and Taraschewski 2000) with reduction in oxygen to swimbladder gas (Würtz et al. 1996). Reduced swimming speeds (Sprengel and Lüchtenberg 1991) and resistance to environmental stressors (Kangur et al. 2002; Gollock et al. 2005) were also reported. In migrating silver eels, impacts reported include reduced migrating periods and distance covered, and alteration in migratory route to shallower depths where there is lower demand on swimbladder functionality (Sjöberg et al. 2009). Impairment in vertical migration increases chances of capture in the fishery and exposure to visual predators (Sjöberg et al. 2009).

In North America, *A. crassus* was first detected in 1994 in American eels, *Anguilla rostrata* (Johnson et al. 1995; Fries et al. 1996). In 2007, it was detected as far north as northern New Brunswick (Aieta and Oliveira 2009) and Cape Breton, Nova Scotia, including the Bras d'Or Lakes (Rockwell et al. 2009; Aieta and Oliveira 2009). Its absence along southern Nova Scotia indicates a secondary mode of transport of *A. crassus* to Atlantic Canada (Aieta and Oliveira 2009). Previous studies by Aieta and Oliveira (2009) determined prevalence to be 14.3% for the Bras d'Or Lakes. Given the semi-enclosed nature of the Bras d'Or Lakes, frequent visits from ships of international origins, and the rapidly-spreading ability of *A. crassus*, it is likely that the prevalence of *A. crassus* in Bras d'Or Lakes eels is much higher than previously documented. The aim of this study was to determine the distribution, prevalence and intensity of *A. crassus* in American eels in the Bras d'Or Lakes, Nova Scotia.

Methodology

During the summer of 2009 to the winter of 2010, yellow and silver eels of various sizes were collected from three habitat types (estuarine, coastal lagoon and river) in the Bras d'Or Lakes and watershed, Nova Scotia (Figure 1). Samples were obtained from the commercial eel fishery (fyke nets), Mi'kmaq traditional food, social and ceremonial fishery (spear) and personal sampling using un-baited small fyke nets (6 mm mesh).

The Bras d'Or Lakes (Figure 1) are approximately 1,099 km^2 (NRCAN 2009) of interconnected estuarine bodies of water situated in the centre of Cape Breton Island, Nova Scotia. The Bras d'Or Lakes boasts higher water temperatures and lower salinities than the adjacent Atlantic Ocean. Summer water temperatures exceed 16^{o}C and surface and sub-surface temperatures exceed 20°C (Petrie and Bugden 2002), especially in coves and coastal lagoons, locally referred to as barachois ponds. Average salinity is 22 psu in most open regions with salinity ranging from 30 psu in the Great Bras d'Or Channel to less than 18 psu in semi-enclosed basins. Primary salt water exchange between the Bras d'Or Lakes and the Atlantic Ocean occurs in the larger, 30 km long Great Bras d'Or Channel (Petrie and Bugden 2002). Tidal ranges are small and diminish rapidly from the Great Bras d'Or Channel inward, ranging between 16 cm near the entrance of the channel to 4 cm at the Barra Strait, the connection between the two main bodies of the lakes (Gurbutt et al. 1993; Petrie and Bugden 2002). Freshwater inflow comes from small rivers and brooks (Petrie and Bugden 2002) and coastal lagoons. The larger rivers run north to south and are found in St. Patrick's Channel, Whycocomagh Bay, Denys Basin and in East Bay. Sand bar height, tide and freshwater influence render the numerous coastal lagoons as unique habitats. Flushing times vary throughout the Lakes. Semi-enclosed basins have longer flushing times resulting in reduction in supply of oxygenated water and slower dilution (Petrie and Bugden 2002). The ports of Little Narrows and Baddeck are international shipping destinations for gypsum and tourism industries respectively. Introduction of the single celled protozoan parasite *Haplosporidium nelsoni* is responsible for MSX disease in the local American oyster, *Crassostrea virginica,* population (Cusack et al. 2011). Other established aquatic invasive species include the green crab, *Carcinus maenus*, and golden star tunicate, *Botryllus schlosseri*.

Habitats were classified as estuarine (main body of the Bras d'Or Lakes), river (larger rivers leading to the Bras d'Or) or coastal lagoon (bodies of water that are separated by the main body of the Lakes by a sandbar but may also have an open but narrow connection). Catch location, habitat classification, temperature (^{O}C), salinity and dissolved oxygen (DO_2 in mg/L) were recorded for samples collected by the authors; however, only habitat classification and catch location was provided by eel fishers.

After collection or receipt of eels from fishers, eels were processed fresh for total length (mm), total body weight (0.01g) and gonad weight (0.01g). Intact swimbladder parasites were removed from the lumen, counted, preserved in ethanol and sent for identification to Dr. David Cone, Saint Mary's University (Halifax, Nova Scotia). *Anguillicoloides crassus* found outside the swimbladder were counted and added to the total (*A. crassus* was found in the abdominal cavity of the eel on two occasions). Empty swimbladders were examined under a dissecting microscope to verify absence of *A. crassus*.

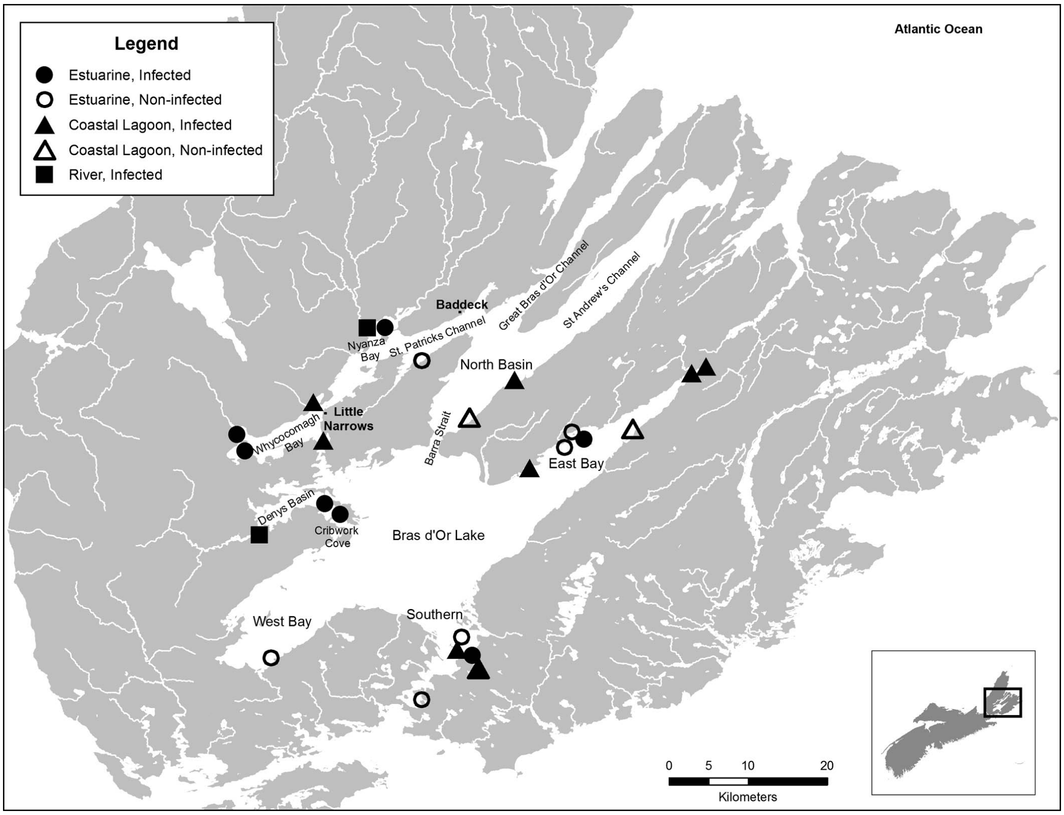

Figure 1. Infected and non-infected sites in the Bras d'Or Lakes (2009–2010).

Eels were assessed for prevalence (percent of eels infected) and mean intensity (average number of parasites per infected eel). Gonadosomatic (GSI) index was calculated as gonad weight (g)/total weight (g) *100. Fulton's condition factor (K) was calculated as weight (g)/length (mm)^3. Data was analyzed with SPSS 19.0. Outliers (defined as 5 SD ± mean) were identified and removed from analysis. Pearson correlation (2-tailed significance) was used to estimate the relationship between prevalence and length, GSI and condition factor. Data were transformed prior to Pearson correlation calculations. To transform right-skewed data, a constant of 1 was added to parasite values and the inverse was calculated. GSI values were log-transformed. ANOVA was used to test for differences between habitats using untransformed parasite values. Independent t-tests were used to test for differences between infected and non-infected eels for condition factor and gonadosomatic index (GSI). Significance was accepted for all tests at $p \leq 0.05$.

Results

Samples were collected from the commercial and food, social and ceremonial fisheries and sampling efforts of the Unama'ki Institute of Natural Resources (UINR). The Mi'kmaq food, social and ceremonial fishery traditionally takes place in the estuarine or coastal lagoon environments and accounted for approximately half of the samples collected in 2009 and 2010 (Table 1).

Anguillicoloides crassus was found in 46% of samples collected in the Bras d'Or Lakes in eels ranging in length from 165 to 928 mm and corresponding weights of 6.99 to 1503.45 g (Table 2). Mean intensity over the two year sampling period was found to be 9 parasites per eel (±11) (Table 2).

Anguillicoloides crassus was detected in the majority of length groups sampled (Figure 2). Four size classes were found to be not infected (150, 200, 700 and 900 mm) but sample sizes for these were small. Intensity differed among

Table 1. Method of collection of eel samples in 2009 and 2010.

Fishery	Eels collected (N)	
	2009	2010
Commercial	12	0
Food, social, ceremonial	58	28
UINR	38	33
Total	108	61

Table 2. Summary of number of eels sampled, infected with *A. crassus*, prevalence of infection, intensity of parasite, eel length and eel weight.

Year	Collected (N)	Infected	Prevalence (%)	Intensity ±SD (range)	Mean length (mm) ±SD (range)	Mean weight (g) ±SD (range)
2009	108	48	44%	11 ± 13 (1-75)	572 ± 104 (228-857)	353.9 ± 200.2 (14.94-1110.43)
2010	61	30	49%	6.6 ± 6.1(1-26)	555 ± 142 (165-928)	365 ± 307 (6.99-1503.45)
TOTAL	169	78	46%	9.0 ± 11(1-75)	566 ± 119 (165-928)	357 ± 243 (6.99-1503.45)

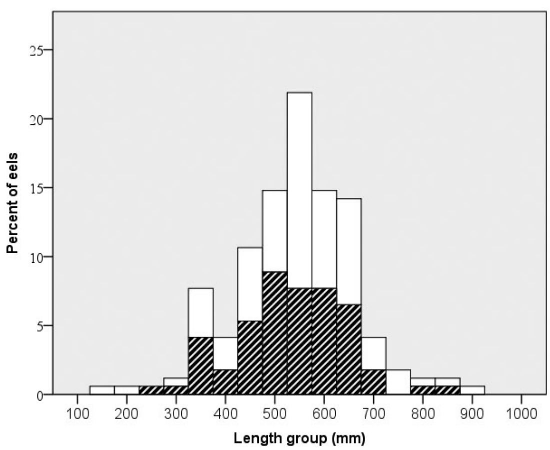

Figure 2. Proportion of infected (▨) and non-infected (☐) eels in 50 mm length increments.

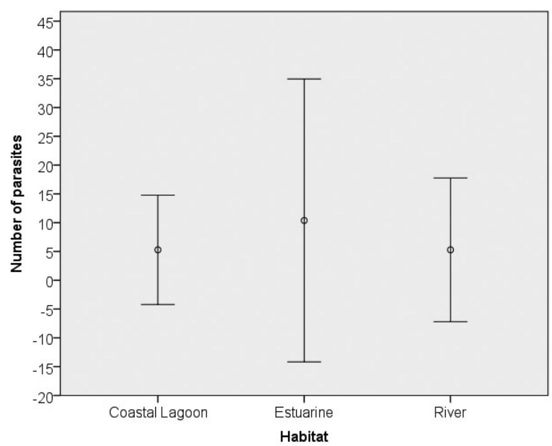

Figure 4. Mean intensity of *A. crassus* of infected eels in habitat sampled (±2 SD).

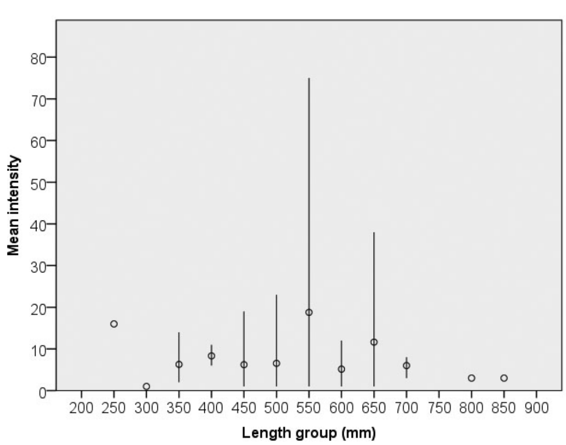

Figure 3. Mean intensity of *A. crassus* in infected eels (±2 SD).

length groups with light infections (<10 parasites/eel) occurring in the majority of length groups represented (Figure 3). No significant correlation between eel length and intensity of *A. crassus* (Pearson coefficient = 0.156, p = 0.378) was found. A statistical difference was not found between length groups and mean intensity (F = 1.106; df = 8; p = 0.392). No statistical correlation was found between *A. crassus* intensity and GSI (Pearson coefficient = -0.029, p = 0.803) or between intensity and condition factor (Pearson coefficient = -0.138, p = 0.229).

Parasite prevalence and mean intensity differed by area. The highest prevalence was 67%, in Denys Basin and Nyanza Bay, followed

Table 3. Summary of eels collected, prevalence, intensity of infected eels, range of *A. crassus*, and number of eels with >20 parasites from sample sites in the Bras d'Or Lakes (2009–2010).

Location	Number of Eels (N)		Prevalence	Mean	Range	# Eels with
	Collected	Infected	%	Intensity ±SD		>20 parasites
Cribwork Cove (2009)	12	1	8	1	1	0
Denys Basin (2010)	15	10	67	6.8 ± 5.4	1–19	0
East Bay (2009–10)	39	10	26	4.1 ± 2.9	1–11	0
North Basin (2009–10)	6	1	17	16	16	0
Nyanza Bay (2010)	18	12	67	6.8 ± 7.3	1–26	1
Southern Bras d'Or Lake (2009–10)	8	1	13	1	1	0
St. Patrick's Channel (2009)	20	12	60	8.6 ± 8.2	1–24	2
West Bay (2010)	4	0	0	0	0	0
Whycocomagh Bay (2009–10)	47	31	66	12.6 ± 15.0	1–75	7

Table 4. Statistical values for independent t-tests performed on total length, total weight, gonad weight and GSI between infected and non-infected eels.

Parameter	t	df	p
Total length	-0.742	167	0.459
Total weight	-0.392	167	0.696
Gonad weight	-0.865	163	0.388
GSI	-0.491	161	0.615
Condition factor	1.922	167	0.056

Table 5. Summary of eel length, total weight, gonad weight, GSI and condition factor for eels collected in the Bras d'Or Lakes (2009–2010).

Parameter	Infected Mean ±SD (range)	Non-Infected Mean ±SD (range)
N	89	77
Total Length (mm)	559 ± 110 (282-857)	572 ± 127 (165-928)
Total Weight (g)	349.2 ± 231.0 (41.60-1171.68)	363.82 ± 254.64 (6.99-1503.45)
Gonad Weight (g)	4.24 ± 6.56 (<0.010-45.08)	5.19 ± 7.46 (0.08-38.55)
GSI	0.87 ± 0.69 (<0.010-3.85)	1.1 ± 0.99 (<0.010-5.37)
Condition Factor	0.2 ± 0.03 (0.07-0.27)	0.16 ± 0.026 (0.11-0.24)

Table 6. Prevalence of *A. crassus* and salinity, temperature and dissolved oxygen (DO_2) ranges for habitat classifications (2009-2010).

Habitat Classification	Collected (N)	Infected	Prevalence %	Mean ± SD (Range)		
				Salinity (psu)	Temperature (^{O}C)	DO_2 (mg/L)
Coastal Lagoon	32	14	44	.0.9 ± 5.31 (3.51-19.16)	18.6 ± 3.81 (11.1-24.5)	8.2 ± 1.6 (3.8-9.9)
Estuarine	126	57	45	14 ± 8 (0.05-19.2)	18.9 ± 3.37 (12.3-23.4)	9.3 ± 0.67 (8.4-10.4)
River	11	7	64	3.4 ± 4.1 (0.13-10.21)	15.9 ±1.47 (13.6-18.1)	10 ± 0. 70 (9.1-11.3)

closely by Whycocomagh Bay at 66% and St. Patrick's Channel at 60%.Whycocomagh Bay had the highest mean intensity, largest range of number of parasites and highest number of heavily infected eels (Table 3). With the exception of the North Basin and Whycocomagh samples, mean *A. crassus* intensity was below overall mean intensity of 9 parasites (Table 3). Two occurrences of a single parasite were found in Cribwork Cove and the southern portion of the Bras d'Or Lake (Table 3). *Anguillicoloides crassus* was not detected in samples collected in West Bay, but small sample size may be a factor. No statistical difference was found between mean intensity of infected areas (ANOVA; F=0.665; df=6; p=0.679).

No significant differences in total length, total weight, gonad weight, GSI and condition factor were found between infected and non-infected eels (Table 4). Mean and standard deviation for total length, total weight, and gonad weight and GSI were higher in non-infected eels (Table 5). Condition factor was greater in infected eels (Table 5).

Prevalence of *A. crassus* was similar between estuarine and coastal lagoon habitats and higher in riverine habitats (Table 6). Mean intensity was similar between riverine and coastal lagoon habitats (Figure 4), however, statistical difference between habitat and intensity was not significant (ANOVA; F=1.668, df=2, p=0.196). Coastal lagoon and estuarine habitats were similar in temperature and salinity at the time of eel captures (Table 6).

Discussion

Results from this study found *A. crassus* infection in eels from the Bras d'Or Lakes in greater prevalence and intensities than previously reported. Studies conducted in 2007 for this area documented a prevalence of 14.3% with mean intensity of 4.0 parasites (Aieta and Oliveira 2009). Overall prevalence of *A. crassus* was determined to be 46% with mean intensity of 9 parasites/eel. Prevalence and intensity differed between locations, with prevalence as high as 67% and mean intensity of 12.6 (±15.0) (Table 2). Intensity is likely even higher than observed in this study as larvae may have been missed during examinations of the swimbladder, since they feed on epithelial tissue (Würtz et al. 1996).

Distribution of *A. crassus* infections was found throughout the Bras d'Or Lakes. Previous eel parasite research in the Humes River, located approximately 7 km northeast of Little Narrows and 19 km southwest of Baddeck Bay, did not detect *A. crassus* between 1989–1993 (Marcogliese and Cone 1996). *Anguillicoloides crassus* was not detected in the Bras d'Or Lakes in 2000 (A. McIsaac, pers. comm.). Starting in 2002, the parasite responsible for MSX oyster disease, *Haplosporidium nelsoni*, caused major declines in local oyster populations. *Anguillicoloides crassus* was found in MSX-infected areas of Denys Basin, Whycocomagh Bay, St. Patrick's Channel, East Bay and Chapel Island (found in the southern Bras d'Or Lake) (Cusack et al. 2011). This suggests the source of introduction and/or the host responsible for these infections may be more than coincidental. Further investigation is needed to determine the relationship between vector hosts of the parasites.

Distribution of *A. crassus* found in this study is consistent with theories of a secondary mode of introduction (Aieta and Oliveira 2009). Prevalence and mean intensity in the Maritime Provinces are considered low at 10.1% with mean intensity of 2.6 ± 4.1 parasites (reviewed in COSEWIC 2012), a small fraction of prevalence and intensity determined for the Bras d'Or Lakes. Introduction of *A. crassus* through an intermediate host in ballast water (Rockwell et al. 2009) is probable. Proximity of the sites with the highest prevalence and greatest number of heavily infected eels (> 20 parasites or more/eel) were found within 13 to 20 km of the international shipping destinations of Little Narrows and Baddeck. High prevalence and lower mean intensity found in the distant area of Denys Basin may be attributed to human transport of infected eels and/or vector hosts to this area.

The greatest prevalence and intensity were found in semi-enclosed basins where there was lower salinity, generally higher summer water temperatures, and longer flushing times. It is likely that these four abiotic characteristics enhanced establishment and spread of *A. crassus* once it was introduced in the Bras d'Or Lakes. Successful establishment of *A. crassus* is due to its ability to be found in a variety of vector hosts (De Charleroy et al. 1990), including copepods, snails, and fish (Moravec 1996) and its short life cycle in specific environments. Under laboratory conditions at 20°C, the life cycle can be completed in less than 2 months (De Charleroy et al. 1990). Increasing water temperatures accelerate larval migration and moulting (reviewed in Ashworth and Kennedy 1999). *Anguillicoloides crassus* is found in freshwater and brackish environments but rarely marine salinities (32–35 psu) (Kennedy and Fitch 1990; Jakob et al. 2009). Once introduced in freshwater and estuarine environments, prevalence may reach 100% within 1 year (Kennedy and Fitch 1990). Semi-enclosed basins likely offer containment of *A. crassus* and contribute to higher prevalence found in these areas. Given the lower salinity and longer resident time of water in already infected semi-enclosed bodies of water such as Whycocomagh Bay and Denys Basin, we should expect an increase in prevalence and intensity of *A. crassus* in these areas, and for the Bras d'Or Lakes in general.

Higher prevalence of *A. crassus* infections found in freshwater habitats is consistent with other studies of *A. anguilla* (Lefebvre et al. 2003), however, no significant difference in mean intensity between habitats was found. Prevalence of *A. crassus* in the Bras d'Or Lakes is comparable to estuarine environments in France (Lefebvre et al. 2003), northern Germany (Jakob et al. 2009) and Chesapeake Bay, U.S.A. (Fenske et al. 2010), but at higher intensities. Higher intensities found in estuarine environments may be attributed to greater sample size, probable movements between habitats in the Bras d'Or Lakes watershed and the abiotic characteristics of the Bras d'Or Lakes that likely enhances establishment of *A. crassus*.

Eels of various sizes in the Bras d'Or Lakes were infected with *A. crassus*. Eels as small as 250 mm and as large as 850 mm were found infected. There were no significant differences in total length, total body weight, gonad weight, GSI or condition factor between infected and non-infected eels. There were no correlations between mean intensity and GSI, condition factor and eel length. These are consistent with previous studies on *A. anguilla* (Kangur et al. 2002) and *A. rostrata* (Barse et al. 2001; Moser et al. 2001; Machut and Limburg 2008) although Moser et al. (2001) found positive correlation between mean intensity and eel size. The lack of statistical differences between infected and non-infected eels does not imply that *A. crassus* does not impede the ability of the eel to thrive. Local hypoxic conditions have been found to reduce the ability of infected eels to cope with environmental stressors (Kangur et al. 2002; Gollock et al. 2005). Urbanized watersheds may increase eel susceptibility to *A. crassus* infection by increasing stressors (Machut and Limburg 2008). Nutrient build-up in Whycocomagh Bay and many of the coastal lagoons around the Bras d'Or Lakes resulted in eutrophication of these areas (Strain and Yeats 2002). Given the high prevalence and intensity of infection in eels from Whycocomagh Bay, eel mortalities reported by eel fishers in 2008 and 2009 could be attributed to a reduced ability to cope with poor water quality.

A declining eel population infected with *A. crassus* at higher intensities than previously reported for *A. rostrata*, coupled with historical accounts of local eel mortalities, leaves traditional Mi'kmaq fishers uncertain of the future of the Bras d'Or Lakes eel population. To maintain eel fisheries, traditional or otherwise, and improve the chance of spawning recruitment for infected eels, the need to preserve aquatic habitats and reduce environmental stressors is imperative. We cannot change the characteristics of the Bras d'Or Lakes that make it an ideal environment for higher intensities of *A. crassus*. Greater controls and innovative solutions are needed to restrict and eliminate further introduction of aquatic invasive species to the Bras d'Or Lakes.

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