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Secondary invasion of the round goby into high diversity Great Lakes tributaries and species at risk hotspots: potential new concerns for endangered freshwater species

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Abstract The round goby (*Neogobius melanostomus*) first invaded North America in 1990 when it was discovered in the St. Clair River. Despite more than 15 years of potential invasion, many Great Lakes' lotic systems remained uninvaded. Recently, we captured the round goby from several Great Lakes tributaries known as species-at-risk hotspots. With a combination of field sampling of round gobies and literature review of the impact of round gobies on native taxa, we assess the potential impacts of the secondary invasion to native species using three mechanisms: competition; predation; and indirect impacts from the loss of obligate mussel hosts. We estimate that 89% (17/19) of benthic fishes and 17% (6/36) of mussels that occur in these systems are either known or suspected to be impacted by the secondary invasion of round goby. In particular, we note that the distribution of potential impacts of round goby invasion was largely associated with species with a conservation designation, including seven endangered species (1 fish, 6 mussels). As these recent captures of round goby represent novel occurrences in high diversity watersheds, understanding the potential impacts of secondary invasion to native biota is fundamental to prevent species declines and to allow early mitigation.

Keywords Endangered species · *Neogobius melanostomus* · Round goby · Secondary invasion · Great Lakes · Ecological impact · Species at risk · Invasive species

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Introduction

The round goby *Neogobius melanostomus* is a freshwater benthivorous gobiid that was first found in North America in the St. Clair River in 1990 (Jude et al. 1992), a major tributary that connects Lake Huron and Lake St. Clair. The round goby spread to and impacted all five Laurentian Great Lakes within 5 years, where they are now abundant (Charlebois et al. 2001). Surprisingly, despite over 15 years of potential invasion (e.g., through natural dispersal) from the Great Lakes into secondary waterways (i.e. tributaries), the round goby has not been captured in high diversity lotic systems (Phillips et al. 2003;

Carman et al. 2006; Dunning et al. 2006; Irons et al. 2006). The lack of round goby expansion into species-rich communities supports conventional community assembly theory in which speciose communities are thought to provide biotic resistance to invasions (Elton 1958; Lodge 1993; Ricciardi 2001).

Recently, we captured the round goby in several high diversity Great Lakes tributaries known as a species-at-risk hotspots; which are systems known for having the highest diversity of aquatic species at risk of extinction in Canada (Staton and Mandrak 2006; Hutchings and Festa-Bianchet 2009). Hotspots include the Ausable, Grand, Sydenham and Thames rivers (Staton and Mandrak 2006). These are, to our knowledge, the first records of the round goby in lotic areas with high species richness and in particular, species-at-risk hotspots, which include eight species that occur solely within this region in Canada, as well as four species that are globally imperiled (Staton and Mandrak 2006; Nature Serve 2008). The secondary invasion of round goby into these areas may pose potential threats of species declines that have not been identified previously, and therefore must be quantified (Charlebois et al. 2001).

The risk associated with the spread of round goby to tributaries of the Great Lakes and into species-at-risk hotspots is not well understood. Round goby typically out-compete native benthivorous fish species such as logperch (*Percina caprodes*) and mottled sculpin (*Cottus bairdii*), and similar consequences can be expected for other small benthic species (Dubs and Corkum 1996; French and Jude 2001; Balshine et al. 2005). Gobies also may have direct impacts through predation on juvenile fish and fish eggs (Chotkowski and Marsden 1999; French and Jude 2001). Dreissenid mussels are the most important prey item for large round goby (Barton et al. 2005; Walsh et al. 2007), which suggests that native mussel species may also be at risk due to predation. Lastly, the impacts on benthic fishes, including species-at-risk, may pose additional complications for unionid mussels (i.e. indirect effects), which require fish hosts to transform and disperse their glochidia larvae (Fig. 1; Kat 1984; McMahon 1991; Barnhart et al. 2008; Newton et al. 2008).

The several recent first occurrences of round goby within the tributaries of the lower Great Lakes (and species-at-risk hotspots), suggests that threat factors need to be identified so vulnerable communities which may be impacted can be mitigated. Accordingly, the purposes of our paper is to: (1) identify areas undergoing secondary invasion from the round goby; and (2) identify the potential direct and indirect impacts of the secondary invasion of round goby using literature accounts of documented impacts from round goby on native biota. From these, we seek to identify whether freshwater species-at-risk are more vulnerable to round goby invasion than other co-occurring freshwater species.

Methods

Field surveys

We conducted fish surveys in the Ausable, Grand, Sydenham, and Thames rivers, which contain the largest diversity of aquatic species-at-risk in Canada (Dextrase and Mandrak 2006). Initially field sampling was not intended to document the spread of round goby, and as such, there are some inconsistencies with sampling methodology and gear.

In the Ausable, Grand, and Thames Rivers all fish sampling was conducted using a 9.2 m long, 3.2 mm bag seine at 10 × 10 m sites in randomly selected reaches as part of habitat modeling project for the eastern sand darter (*Ammocrypta pellucida*) (Ausable River $n = 32$ sites, Grand River $n = 151$, Thames River $n = 151$). Sampling was conducted between mid-May and mid-September in 2006 and 2007. Sites were seined in a downstream direction, with three consecutive hauls conducted at each site. Fish were enumerated and released, except for specimens of round goby, which were euthanized.

In September, 2007 we conducted field surveys at a lone site in the Sydenham River for a project on identifying indirect impacts on mussel species at risk. This site was known as one of the most diverse mussel and fish communities in Canada, with a high diversity of species at risk (Metcalfe-Smith et al. 2005; Poos et al. 2008). We sampled fish using single pass backpack electrofishing (pulsed DC current at 200–225 V, hertz = 60, pulse length = 3 ms) with two netters. Fish were enumerated and released, except for 3 specimens of round goby, which were euthanized. We repeated sampling at this site in August, 2008 and sampled 15 other sites to determine the extent of the round goby distribution

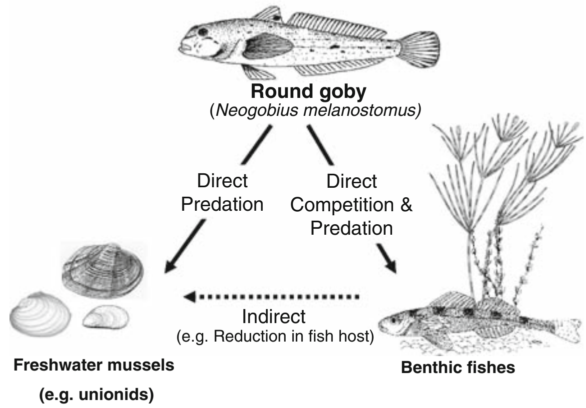

Fig. 1 Potential mechanisms of impact from the secondary invasion of round goby to tributaries of the Laurentian Great Lakes and to species at risk of extinction

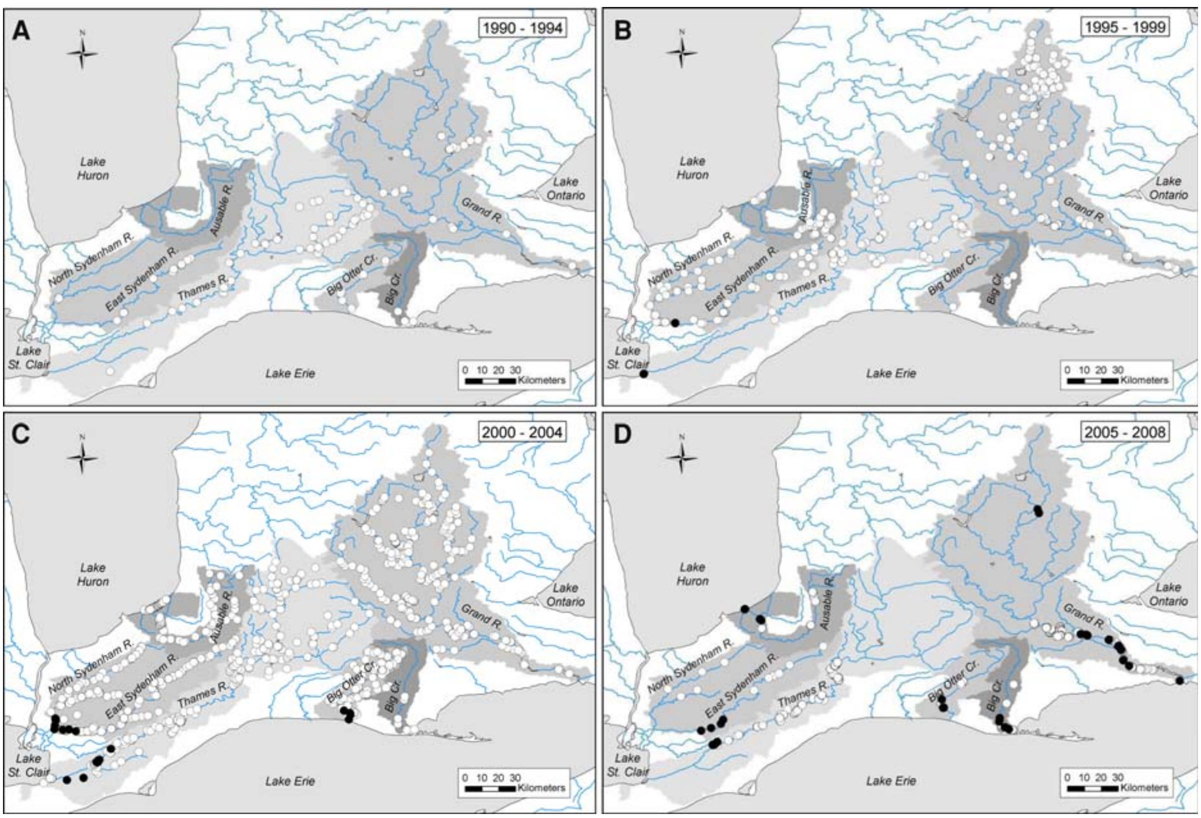

Fig. 2 Time series of sampling for round goby in tributaries of the lower Great Lakes, including: (A) Sampling 1990–1994, (B) 1995–2000 (C) 2000–2004, (D) 2005–2008. *Sources*: Mandrak et al. 2003, DePasquale (2006), Poos et al. (2007), Reid (2007), Poos et al. (2008); N.E. Mandrak (Fisheries and Oceans Canada; unpublished data); A. J. Dextrase (Ministry of Natural Resources; unpublished data); M. Veliz (Ausable Bayfield Conservation Authority), and J. Zoltak (Ontario Federation of Anglers and Hunters, unpublished data). 2005–2008: This study

(Fig. 2), using identical sampling gear (i.e. 9.2 m long, 3.2 mm bag seine) and methodology as in the Ausable, Grand Rivers and Thames Rivers.

We also conducted sampling in Big Creek and Big Otter Creek, which are not species at risk hotspots, but are also undergoing recent secondary invasion of the round goby. Fish sampling in Big Creek and Big Otter Creek were conducted in September 2004 ($n = 4$, $n = 4$ respectively) and July 2008 ($n = 12$, $n = 14$, respectively) using a 9.2 m long, 3.2 mm mesh bag seine at sites within randomly selected sample reaches. We include data from Big Creek and Big Otter Creek to provide context to compare the rate of spread in areas of lower diversity of benthic fish species and mussels (but with some species at risk).

Evaluating current vs. Historical sampling in tributaries of the lower Great Lakes

To evaluate the sampling effort in these watersheds since 1990 (i.e., when round goby was first detected in the Great Lakes basin), we used distribution data for fishes from an extensive national database containing data from more than 30 government agencies and museums from across North America (N.E. Mandrak, unpublished data). This database currently has 378,901 fully geo-referenced records for 229 freshwater fish species, including government agencies such as the Royal Ontario Museum, Ontario Ministry of Natural Resources, Fisheries and Oceans Canada, universities and previous published work (Holm 2001; Dextrase et al. 2003; Cudmore et al. 2004; Poos et al. 2008). Fish species inventories were sub-divided into four time periods; (A) sampling 1990–1995, (B) 1995–2000 (C) 2000–2004, (D) 2005–2008 and the occurrences of round goby were noted (Fig. 2). In addition, records of round goby sightings were obtained for the watersheds of interest from the Invading Species Program database maintained by the Ontario Federation of Anglers and Hunters (J. Zoltak, Ontario Federation of Anglers and Hunters, pers. comm., www.invadingspecies.com). This database consists of sightings reported to the program by researchers and members of the public. Only sightings that had a high confidence rating were included (e.g. voucher specimen preserved or photo taken).

Identifying impacts of round goby invasion to recipient communities

To determine potential impacts on mussel and fish species associated with the secondary invasion of Great Lakes tributaries, we conducted a literature review of impacts of the primary invasion of round goby to recipient communities. Fish species that may be impacted from the secondary invasion of round goby were selected from a recent database of fish distributions in the Great Lakes (Mandrak and Crossman 1992; Hubbs and Lagler 2004; Mandrak unpublished data) and updated using recent surveys conducted on these systems (Cudmore et al. 2004; Poos et al. 2007; Poos et al. 2008; A. J. Dextrase (Ontario Ministry of Natural Resources, unpublished data); N.E. Mandrak (Fisheries and Oceans Canada, unpublished data). Similarly, mussel species that may be potentially impacted by the secondary invasion of round goby were identified from distribution records of unionid mussels (Clarke 1981; Metcalfe-Smith et al. 2005) and further updated with recent inventories in these systems (Metcalfe-Smith et al. 1998; 2003; 2007; Mandrak et al. 2003; J.D. Ackerman (University of Guelph, unpublished data). Due to its relatively small body size (adult round goby total length 61–176 mm; Johnson et al. 2005; Walsh et al. 2007), we restricted our assessment of round goby impacts to syntopic benthic fishes of a similar size, given that these size classes are likely to be in direct competition with round goby (Charlebois et al. 1997; French and Jude 2001). We assessed the potential for impact of round goby based on three categories, impact known (i.e. impact directly observed and demonstrated in the literature for the same species), direct impact not known but suspected (i.e. impact not directly observed but impact was suspected from literature due to overlap in life history characteristics, e.g. body size, diet or habitat), and impact not known and not suspected (i.e. not shown in literature and not suspected given life history characteristics). We used at risk categories identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2007), i.e. endangered, threatened, candidate, not at risk and not assessed. Hereafter, we refer to species-at-risk following COSEWIC's (2007) definition of those species listed as either threatened or endangered (unless otherwise noted). Using these criteria we evaluated the potential impacts of round gobies on 19 benthic fishes that occur in the watersheds of interest, including: three *Percina* darters (logperch, blackside darter, and river darter); six *Etheostoma* darters (greenside darter, rainbow darter, Iowa darter, fantail darter, least darter, and johnny darter); eastern sand darter (*Ammocrypta pellucida*); four *Noturus* catfishes (stonecat, tadpole madtom, brindled madtom, and northern madtom); two sculpin species (mottled sculpin and slimy sculpin); two minnows (longnose dace and central stoneroller); and, trout-perch (*Percopsis omiscomaycus*; Appendix Table 3).

The potential impacts of round goby on 36 species of freshwater mussels (Unionidae) were also evaluated using the same criteria (Appendix Table 4).

We sub-divided the potential impacts that round goby may have on aquatic species according to three potential mechanisms: (1) competition; (2) predation; and, (3) indirect effects on mussels through impacts on fish hosts (Fig. 1). Competition was defined as a shift in the organization of a community or an organism's habitat created by the addition of round goby, but not due to predatory effects (Jackson et al. 2001). Thus, competition may take the form of partitioning resources, habitats, or both. We define predation as simply the consumption of a prey species. We define indirect impacts as those which impact other species through an intermediary, such as the reduction in or the availability of hosts for parasites (Elton 1958). As most unionid mussels require a host species for the development and dispersal of their larvae, declines and losses of benthic fishes (through competition or predation) may lead indirectly to declines in freshwater mussels (Fig. 1). To estimate the potential of indirect impacts on mussels from reductions in benthic fishes, we listed all known host fish species for each mussel species. For this component we undertook a literature review of known mussel-host relationships (e.g. shown in laboratory experiments; Clarke 1981; Woolnough 2006; University of Ohio State 2008). Host fish previously not noted in the literature for Ontario species and identified with infestation experiments in the laboratory were included in our analysis (K. A. McNichols and J. D. Ackerman (University of Guelph), pers. comm.).

Using the mussel-fish host data, we separated the same benthic fishes (e.g., those <176 mm adult body length) that were either known or suspected from the literature to be impacted by the round goby, and compared the indirect impacts of losing those species on mussel species. Mussel species were suspected to have indirect impacts if greater than 50% of their host species were also thought to be impacted by round goby. This threshold was chosen arbitrarily, but supported by empirical models of species' co-extinctions (Koh et al. 2004). Koh et al. (2004) studied 20 well known host-affiliate systems and found that once the proportion of host extinction exceeded 50%, the subsequent proportion of affiliate extinction was above 0.2. We note that Koh et al. (2004) show that the relationship between host-affiliate systems can depend on the level of host specificity, however many unionid species (especially those that are at risk) are host specialists using one or only a few main hosts (Kat 1984; Watters 1992; Woolnough 2006; McNichols 2007). For example, laboratory studies have shown that the endangered round hickorynut (*Obovaria subrotunda*) uses solely the benthic fish Iowa darter (*Etheostoma exile*), fantail darter (*Etheostoma flabellare*) and blackside darter (*Percina maculata*), as fish hosts, despite the availability of several more abundant congeners (e.g. logperch and Johnny darter *Etheostoma nigrum*; Morris 2006; McNichols 2007). As such, despite the fact that Koh et al. (2004) do not directly report the relationship between mussel and fish hosts, and the exact thresholds of the percentage of fish host declines needed for the subsequent declines in mussel species are not known, we use these values as they likely represent realistic indirect impacts for mussel species.

Results

Field surveys

Round goby were captured in the lower portions of the Ausable, Grand, Sydenham, and Thames Rivers, as well as, Big Creek and Big Otter Creek. In total, 147 round gobies were captured, 73 adult and 74 young-of-the-year (YOY), between 2003 and 2008 (Table 1). Across all sites, round gobies were captured at <25% of the randomly selected reaches sampled in each drainage (range 2–23%), suggesting that upstream invasion is in progress (Fig. 2). All these sites where round goby were captured were below the first impassable barrier in each watershed, with the exception of the Grand River were they were captured above the first two barriers to fish migration (dams at Dunnville and Caledonia, Ontario). Sites occupied by the round goby varied from sites dominated by fines (clays and silts) to sites dominated by coarse substrate (large gravel and cobble). Flow at 0.6 × depth ranged from 0–0.37 m/s (i.e. pools to riffles).

A review of sampling data in these watersheds associated with other sampling programs identified that round goby had been sighted in three watersheds prior to the dates that we first captured them in our field work. For example, there is a record of a round goby from the lower East Sydenham River from

Table 1 The number of round gobies sampled in the present study in Great Lakes tertiary watersheds known as species-at-risk hotspots and the potential impacts on fish and mussel species

	Ausable River	Lower Grand River	Upper Grand River	Sydenham River	Lower Thames River	Upper Thames River	Big Creek	Big Otter Creek
Year of first sighting[a]	2007	2005	N/A	1998	2003	N/A	2008	2002
Year of first capture in areas with species at risk[b]	2007	2007	N/A	2007	2006	N/A	2008	2004
Number of round goby adults captured[b]	1	9	0	9	1	0	37	16
Number of round goby YOY captured[b]	27	4	0	2	40	0	0	1
Number of potentially impacted benthic fishes[c]	15	15	14	18	20	10	14	14
Number of benthic fish species-at-risk[c,d]	1	2	0	2	2	0	1	0
Number of potentially impacted unionid mussels[e]	24	31	31	32	26	26	22	22
Number of unionid mussel species-at-risk[d,e]	6	7	7	11	12	6	5	5

N/A denotes areas where round goby were not seen or captured

[a] *Sources*: N.E. Mandrak (Fisheries and Oceans Canada, unpublished data), J. Zoltak (Ontario Federation of Anglers and Hunters, unpublished data), A.J. Dextrase (Ontario Ministry of Natural Resources, unpublished data), this study

[b] *Sources*: This study

[c] *Sources*: Mandrak and Crossman (1992), Cudmore et al. (2004), Hubbs and Lagler (2004), DePasquale (2006), Poos et al. (2007) Reid (2007), Poos et al. (2008) A. J. Dextrase (Ontario Ministry of Natural Resources, unpublished data), N. E. Mandrak (Fisheries and Oceans Canada, unpublished data)

[d] Species-at-risk are those considered threatened or endangered by COSEWIC (2007)

[e] *Sources*: Clarke (1981); Metcalfe-Smith et al. (1998, 2003, 2005, 2007); J. D. Ackerman (University of Guelph, unpublished data)

1998, from Big Otter Creek in 2002, and from the Grand River in 2005 (Fig. 2). Comparing the temporal variation of round goby captured (Fig. 2), it appears that secondary invasion of round goby may have occurred as early as 2000 (perhaps as early as 1998 for the Sydenham River), although these areas were all in close proximity to lake systems and may not represent permanent movement upstream. In addition, there doesn‘t appear to be a reduction in spread between high diversity systems (e.g. Sydenham and Thames) and low diversity systems, such as Big Creek and Big Otter Creek (Table 1). In fact, more young of the year (YOY) round goby were captured in high diversity systems than low diversity systems, where only one was caught.

Identifying impacts of round goby invasion to recipient communities

Our literature review revealed that impacts from the invasion of round goby into the Great Lakes have been documented for numerous small benthic fishes (Table 2). Eighty-nine percent (17/19) of the benthic fishes found in our study watersheds have been either previously shown to be affected by round goby or are suspected in the literature (Table 2; Fig. 3). For

Table 2 Literature review of impacts from the primary invasion of the round goby (*Neogobius melanostomus*) to recipient communities of small bodied benthic fish in the Laurentian Great Lakes and potential indirect impacts to freshwater mussels (Unionidae)

Impact	Recipient species	Evidence	Source/s
Competition	*C. bairdii*	Laboratory and diet studies; Declining populations	Chotkowski and Marsden (1999), Dubs and Corkum (1996), Ghedotti et al. (1995), Janssen and Jude (2001), Jude et al. (1995), Jude and Deboe (1996), and Lauer et al. (2004)
	C. cognatus	Suspected from habitat	Chotkowski and Marsden (1999), MacInnis and Corkum (2000)
	Etheostoma sp.	Suspected from diet and habitat	Barton et al. (2005), Carman et al. (2006), Dubs and Corkum (1996), Jude et al. (1995), and Thomas (1997)
	E. caeruleum	Direct observation	Diggins et al. (2002), French and Jude (2001), and Jude et al. (1992)
	E. nigrum	Overlap in habitat; Declining populations	Corkum et al. (1998), Lauer et al. (2004), and MacInnis and Corkum (2000)
	Noturus sp.	Suspected from habitat	MacInnis and Corkum (2000)
	N. miurus	Suspected from habitat	Corkum et al. (1998) and MacInnis and Corkum (2000)
	N. stigmosus	Direct observation	French and Jude (2001) and MacInnis and Corkum (2000)
	Percina sp.	Suspected from diet and habitat	Barton et al. (2005), Carman et al. (2006); Dubs and Corkum (1996), Jude et al. (1995), and Thomas (1997)
	P. caprodes	Laboratory studies; Declining populations	Balshine et al. (2005), French and Jude (2001), Jude et al. (1992), Jude et al. (1995), and Jude and Deboe (19960
Predation	*Cottus* sp. (YOY)	Suspected from size	Charlebois et al. (1997) and Jude et al. (1992)
	Etheostoma sp.	Suspected from size	Charlebois et al. (1997), French and Jude (2001), Jude et al. (1992), and Weimer and Sowinski (1999)
	E. blenniodes	Direct observation	Jude et al. (1995)
	E. caeruleum	Direct observation	Charlebois et al. (1997) and Jude et al. (1995)
	Noturus sp. (YOY)	Suspected from size	Charlebois et al. (1997)
	P. omiscomaycus	Direct observation	Charlebois et al. (1997) and French and Jude (2001)
Indirect	Unionidae	Suspected from loss/disruption of fish hosts (e.g. benthic fishes)	Berg et al. (2007), Box and Mossa (1999), DFO (2007), Dextrase et al. (2003), Kelner and Sietman (2000), McNichols (2007), Metcalfe-Smith et al. (2003), Morris (2006), and Woolnough (2006)

example, direct evidence of competition between benthic fishes and round gobies has been documented for five species that also occur in the tributaries of the lower Great Lakes. Previous studies on the impacts of round goby have noted that darters (e.g. *Etheostoma* and *Percina* sp.) were especially susceptible to competition from the round goby due to high overlap in diet, and habitats (Jude et al. 1995; Dubs and Corkum 1996; Thomas 1997; Barton et al. 2005; Carman et al. 2006). Studies have also documented the collapse of mottled sculpin populations due to the invasion of round goby (Ghedotti et al. 1995; Jude et al.1995; Dubs and Corkum 1996; Jude and Deboe 1996; Chotkowski and Marsden 1999; Janssen and Jude 2001; Lauer et al. 2004) and similar impacts are suspected for other sculpins like the slimy sculpin (*Cottus cognatus*; Chotkowski and Marsden 1999; MacInnis and Corkum 2000). In addition, round goby have been shown to impact small benthic madtoms, such as the brindled madtom (*Noturus miurus*) and northern madtom (*Noturus stigmosus*; Corkum et al. 1998; MacInnis and Corkum 2000; French and Jude 2001; Table 2). Predation by round goby was observed on numerous species, including the greenside darter (*Etheostoma blenniodes*), rainbow darter (*Etheostoma caeruleum*), and trout perch (*Percopsis omiscomaycus*; Jude et al. 1995; Charlebois et al. 1997; French and Jude 2001), and similar impacts are suspected for seven species with similar size classes (Table 2; Appendix Table 3).

Of the three mechanisms of potential round goby impact, it appears that competition between round goby and native benthic fishes may be the highest concern. Eighty-four percent (16/19) of fish species found in tributaries of the lower Laurentian Great Lakes were either shown or suspected to be impacted by the round goby versus fifty-three percent (10/19) of species which were identified in literature to be impacted by predation (Fig. 2; Appendix Table 3). For freshwater mussel species, we found no known evidence that round goby would prey upon unionid species. However we identified six species that may be indirectly impacted from the loss or disruption of their fish hosts (Fig. 3; Appendix Table 4).

The distribution of potential impacts of the secondary invasion of round goby into the lower Laurentian Great Lakes were largely associated with species with a conservation designation (Fig. 3). All fish species with a conservation designation were either shown or suspected to be impacted from the secondary invasion of round goby (Appendix Table 3). For example, previous studies have shown that round goby have the potential to compete with the endangered northern madtom (*Noturus stigmosus*; French and Jude 2001; MacInnis and Corkum 2000; Table 2; Appendix Table 3). Similarly, of the mussel species suspected to be impacted from the potential loss of their fish hosts, eighty-three percent (5/6) had a conservation designation (Fig. 3; Appendix Table 4). In addition, several species which are listed as Candidate species, due to recent declines (COSEWIC 2008), were also identified as potentially impacted by round goby (Fig. 4).

Discussion

We have documented the first evidence of the secondary invasion of round goby into tributaries of the lower Laurentian Great Lakes, that are species at risk hotspots (Staton and Mandrak 2006; Hutchings

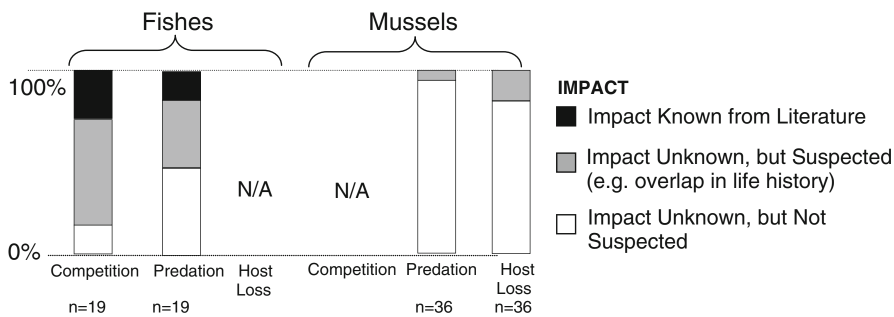

Fig. 3 The potential impact of the secondary invasion of round goby on small benthic fishes ($n = 20$) and mussels ($n = 36$) in the lower Great Lakes using three potential mechanisms of impact: competition (fish only), predation as identified in diet studies (Table 2), and loss of fish hosts (mussels only). Note: N/A–Not Applicable

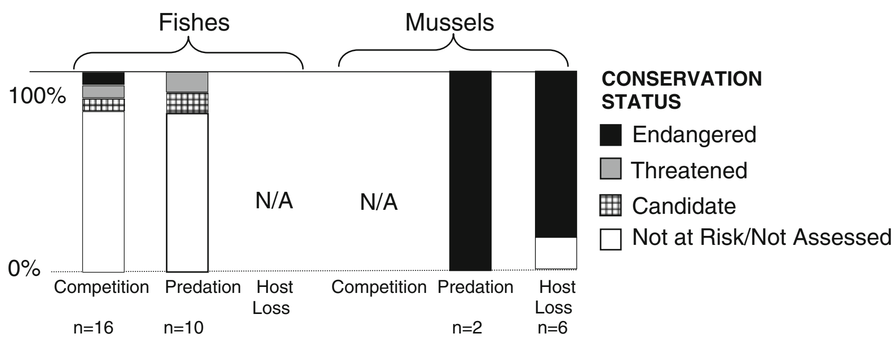

Fig. 4 The distribution of fish and mussel species with conservation designations, where the impact of secondary invasion of round goby is either known or suspected in the lower Laurentian Great Lakes. Species are shown using designations from the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2007, 2008). Note: Candidate species which are abundant in the Great Lakes are shown as not at risk (see Appendix Tables 3, 4). N/A–Not Applicable

and Festa-Bianchet 2009). This evidence is notable for several reasons. First it has been argued that a diverse native population can minimise or deter invasion of exotic species (Elton 1958; Ricciardi 2001). Previous studies which have documented secondary invasions of round goby have been restricted to areas with low species diversity (Phillips et al. 2003; Carman et al. 2006; Dunning et al. 2006; Irons et al. 2006) and it has been suggested that areas of high species diversity or complexity may be resistant to invasion (Lodge 1993; Bowers and de Szalay 2007; Carman et al. 2006; Cooper et al. 2007). When we compare the distribution of round goby in low diversity systems, like Big Creek and Big Otter Creek, with high diversity systems, it appears that this is not the case in the lower Laurentian Great Lakes. Second, previous studies have documented the lower Laurentian Great Lakes as areas with significant refuges of unionid mussels from the invasion of zebra mussels (Clarke 1992). As species invasion has been shown to facilitate interactions that may promote further invasions from other species (i.e. invasional meltdown, Ricciardi 2001), the secondary invasion of the round goby may provide an early exemplar of future Great Lakes invaders (Lodge 1993; Kolar and Lodge 2002). Finally, we demonstrate that the invasion of the round goby into species at risk hotspots creates new concerns for several species already undergoing declines due to other stresses and listed with a conservation designation (COSEWIC 2007, 2008). We provide novel insight into the potential new concerns for several of these endangered species (Appendix Tables 3, 4).

Documented impacts of invasion by round goby

The potential impact of round goby invasion into tributaries of the Laurentian Great Lakes and species at risk hotspots should raise considerable concern for endangered species. This region contains the greatest diversity of freshwater fishes and mussels, including those that are at risk, in all of Canada (Staton and Mandrak 2006). Specifically, we captured round gobies in the Thames and Sydenham Rivers, directly in sites with the highest diversity of threatened and endangered fish and mussel species in Canada (Metcalfe-Smith et al. 2003; Staton and Mandrak 2006; Poos et al. 2008). These sites are of particular importance ecologically, in that they contain 10 species-at-risk (six mussels and four fishes), six of which (five mussels, one fish) are endangered nationally (COSEWIC 2007) and two that are globally imperiled (Nature Serve 2008). Moreover, these sites also have the second highest total fish diversity and the highest mussel diversity in Canada (Metcalfe-Smith et al. 2003). Using a literature review of previously documented impacts, we evaluated the potential risk posed by the secondary invasion of round goby to the 19 benthic freshwater fishes and 36 freshwater mussels found in this area. We found that round gobies may not only negatively impact benthic fishes as previous shown (Table 2), but also indirectly impact the fish hosts necessary for mussel reproduction (Fig. 1). Our results suggest that, in particular, potential impacts of competition on native fishes and indirect loss of fish hosts for mussel species pose high levels of concern (Fig. 3).

Potential new concerns from the secondary invasion of round goby

The range extension of round goby into tributaries of the lower Laurentian Great Lakes represents a particular concern for a number of species that have not previously been assessed for their vulnerability to round goby. Therefore understanding potential new impacts to recipient communities remains an important task for mitigating and predicting future problems.

For fishes, a review of diet studies suggests that the majority of fish prey found in the diet of round gobies were less than 30 mm. For example, Weimer and Sowinski (1999) found fish of 17, 20, 21.5 and 25.1 mm total length in gobies of length 103, 113, 81, and 82 mm, respectively. These fish were all well within previously reported lengths of round goby in the Great Lakes, with total lengths of 61–152 mm (Walsh et al. 2007) and 60–176.6 mm (Johnson et al. 2005). As such, we suspect that the round goby may have the ability to prey upon species previously not considered in the literature, such as the least darter (*Etheostoma microperca*) with an average adult total length of 25 mm. Whereas piscivory impacts by round goby are generally low, these impacts may be large due to the exponential increase in abundance associated with initial establishment of invasive species in new habitats (Ricciardi 2001). In addition, as competition for food and habitat has contributed to the decimation of mottled sculpin and logperch populations in the nearby St. Clair River (Jude et al. 1995; Jude and DeBoe 1996), there remains considerable concern that competition may impact other native benthic darters. One species, which may be of particular concern, is the threatened eastern sand darter (*Ammocrypta pellucida*), which prefers well-oxygenated sand substrates (Holm and Mandrak 1996; Drake et al. 2008). Although previous studies have shown that round goby prefer cobble or gravel substrates, and not sand (Ray and Corkum 2001; Bauer et al. 2007), there is also evidence that large round gobies force juveniles from preferred rocky habitats into less desirable sandy habitats (Ray and Corkum 2001). This suggests that at high enough densities, there is potential for competition between round goby and eastern sand darter (Appendix Table 3). Round goby and eastern sand darter were captured at some of the same locations during our field surveys (Grand River, Sydenham River Thames River), and round goby was the most abundant species at 14 sites sampled in the lower end of Big Creek, a sand bed stream that is tributary to Lake Erie (A. Dextrase, unpublished data).

Previous studies of round goby diet have not overlapped with many of the Great Lakes populations of freshwater mussels species, as most of them were extirpated by the zebra mussel invasion. Gut content analyses of round gobies have shown that they prefer dreissenid mussels of smaller size, typically with size selection for 8–14 mm in shell length, with larger gobies eating larger mussels (Ghedotti et al. 1995; Ray and Corkum 1997). In addition Ray and Corkum (1997) suggest that round gobies can consume a maximum of 12.9 mm shell due to limitations in gape length. These data suggest that predation on native unionid mussels is unlikely, although several species, such as the rayed bean (*Villosa fabalis*) and mudpuppy mussel (*Simpsonaias ambigua*) have small adult length (20 and 25 mm, respectively; Metcalfe-Smith et al. 2005), which may provide alternative forage opportunities. Some studies have noted that round gobies in St. Clair River eat native mussels (*Pyganodon* spp.), fingernail clams (*Pisidium* spp.), and invasive dreissenid mussels (French and Jude 2001; Walsh et al. 2007). As only parts of the Thames River have been invaded by dreissenid mussels, (where they are present at low densities (A. Dextrase, unpublished data), and the remaining systems remain un-invaded, there may be a limited molluscan prey base available to round goby from the various species-at-risk hotspots. Accordingly, in the absence of dreissenid mussels, it is uncertain whether round goby will shift towards native unionid mussel species, which are readily available, but whose endobenthic burrowing behavior may allow them to escape predation (Bowers et al. 2005; Schwalb and Pusch 2007).

The potential indirect impact of the secondary invasion of round goby may be of particular concern as unionid mussels rely on specific host fish for the transformation of their larvae into juveniles (Kat 1984). Our evaluation identified six species, five with conservation designations, as potentially impacted from the loss, reduction, or disruption of their fish hosts (Figs. 2, 3). For example, globally imperilled species such as the northern riffleshell (*Epioblasma. torulosa rangiana*), snuffbox (*Epioblasma. triquetra*), and rayed bean, utilize fish hosts previously shown to be impacted by the round goby (e.g. logperch, Johnny darter, mottled sculpin; Chotkowski and Marsden 1999; French and Jude 2001; Nature Serve 2008). Other endangered species such as the round hickory nut or kidneyshell (*Ptychobranchus fasciolaris),* may also be of concern as they utilize species suspected to be impacted by the secondary invasion of round goby. If round goby impact benthic fishes, as previously shown (Table 2), considerable declines in these five endangered mussel species is likely to occur (Appendix Table 4). As there are few examples of indirect impacts of invasive species on native communities (Byers et al. 2002), understanding the relationship between mussel viability and the disruption or loss of their fish, will provide useful insights to ecosystem level affects of species invasion.

Uncertainty with evaluating round goby impacts

Whereas many invasive species have minimal detectable effects on ecosystems, others can cause considerable ecological damage (Byers et al. 2002). Such is the case for the round goby, which in 5 years expanded into all five Great Lakes and became established as a major component of fish assemblages throughout much of the region (Charlebois et al. 1997; Clapp et al. 2001; Corkum et al. 2004; Johnson et al. 2005). Furthermore, the round goby has been shown to have characteristics of a highly successful, highly damaging invasive species (Kolar and Lodge 2002). These characteristics include tolerance of a wide array of environmental conditions, broad diet, aggressive behavior, multiple within year spawning events and a relatively large body size and growth rate as compared to other small benthic fishes (Lodge 1993; Charlebois et al. 2001; Kolar and Lodge 2002; Corkum et al. 2004). In addition, the realized impacts of the round goby are equally disturbing. Round goby have been shown to have severely negative impacts on mottled sculpin and there is considerable concern that the same is likely true for other benthic fishes of similar size (Dubs and Corkum 1996; French and Jude 2001). At the same time, once invaders become established, eradication becomes unlikely and rapid response and impact assessments are needed to ensure impacts are minimized (Byers et al. 2002; Dextrase and Mandrak 2006).

The knowledge of impacts of the round goby are not well understood and difficult to predict (Charlebois et al. 2001; Jude 2001). Similar to most invasive species, data for rigorous analysis for round goby impacts simply does not exist (Lodge 1993). For example, from a literature review of known round goby impacts, studies which have directly observed or quantified impacts of round goby (e.g. through laboratory studies) are far fewer than those that develop suspected impacts based on extrapolations from similarities in life history characteristics (e.g. body size, diet, or habitat; Table 2). In addition, there are only few cases where round gobies have invaded riverine systems (Phillips et al. 2003; Carman et al. 2006; Dunning et al. 2006; Irons et al. 2006). Although it remains to be seen if round gobies will become hyper abundant in riverine species-at-risk hotspots as they have in lentic systems, previous findings of Jude et al. (1995) in Grand Calumet River suggests that round goby populations are almost as abundant in impacted lotic systems as they were in nearby Lake Michigan. Such data suggest that the impacts of round goby are likely to occur quickly and are likely to be substantial. There is also considerable uncertainty concerning the magnitude of impact that round gobies will have on the small aquatic species-at-risk studied here. Small aquatic species in general are often less studied than their more charismatic terrestrial counterparts or larger game species, where more economic and political attention is directed (Bruton 1995; Ricciardi and Rasmussen 1999). As specific experiments involving species at risk may be difficult due to the rare and endangered nature of those species, identifying potential risks from literature is fundamentally important step towards improving their recovery.

Despite these uncertainties, there are sufficient data to suggest swift management action is needed to prevent round goby impacts. Round gobies are known to be voracious predators, consuming all life stages of fish and mussels (Chotkowski and Marsden 1999; Weimer and Sowinski 1999; French and Jude 2001). In addition, the lack of invasion of dreissenid mussels into many of the tributaries of the lower Laurentian Great Lakes (and species at risk hotspots) may ironically accelerate the impacts of round goby invasion. Round goby possess molariform pharyngeal teeth (Ghedotti et al. 1995), which allow them to ontogenetically shift their diet to dreissenids (Jude et al. 1995; Ray and Corkum 1997; Djuricich and Janssen 2001; French and Jude 2001; Barton et al. 2005). The availability of dreissenid mussels may allow coexistence with native species due to resource partitioning (French and Jude 2001). Alternatively, as the diet overlap between smaller round goby and native benthic fishes is large; the lack in availability of dressineid mussels could lead to accelerated impacts (French and Jude 2001). Finally, the impacts shown in this study may be larger than we suggest. For example, indirect impacts of secondary invasion of the round goby may be larger than the loss of fish hosts and include impacts from loss of invertebrate prey, hybridization and disease (Corkum et al. 2004; Dextrase and Mandrak 2006; Walsh et al. 2007). Our analysis may also have been conservative as we did not consider the potential for competition and predation between round goby and the early life stages of larger fish species and freshwater mussels. Further, the majority of diet studies have reported results during day time feeding which may be reduced relative to night time (Johnson et al. 2008).

Ultimately, the impacts of the secondary invasion of round goby on susceptible species-at-risk will depend on continued upstream invasion of round goby and the densities of their populations. Although the relative abundances of round goby in drainages supporting large numbers of species-at-risk were relatively low, it appears that these areas are in the process of being colonized. The long distance dispersal (over 50 river km in some drainages) of round goby from founder populations in lakes Erie and St. Clair, suggests that dispersal and upstream colonization of species-at-risk hotspots and beyond is likely to continue. Human-mediated transport has likely assisted this colonization in the case of the Grand River. Negative interactions are likely to occur across entire watersheds as the round goby becomes established and expands its range. If our predictions of indirect impacts on endangered mussels are correct, then the round goby could negatively affect several endangered and threatened species (Fig. 3). Furthermore, as is often the case, the invasion of round goby may facilitate invasion from other species (e.g. zebra mussels), which to date have not entered many of these systems, but may no longer be limited (Ricciardi 2001). Further research and continual monitoring of the impact of round goby and species at risk is sorely needed. Assessments of potential impacts and their mechanisms, as shown here, provide valuable integration of field observations with basic ecological knowledge that can help facilitate necessary future research and support effective management action.

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Appendix

See Tables 3 and 4.

Table 3 List of small benthic fish species found in the lower Great Lakes and in species-at-risk hotspots and the predicted impacts from the secondary invasion from the round goby (*Neogobius melanostomus*)

Species	Status[a]	Potential impact from competition	Potential impact from predation	Mean size (mm)[b]
Eastern sand darter (*Ammocrypta pellucida*)*	Threatened	Suspected	Suspected[c]	64
Central stoneroller (*Campostoma anomalum*)	Not at risk	Not suspected	Not suspected	124
Mottled sculpin (*Cottus bairdii*)	(Candidate)	Known	Not suspected	76
Slimy sculpin (*Cottus cognatus*)	(Candidate)	Suspected	Not suspected	76
Greenside darter (*Etheostoma blennioides*)	Not at risk	Suspected	Known	76
Rainbow darter (*Etheostoma caeruleum*)	(Candidate)	Known	Known	50

Table 3 continued

Species	Status[a]	Potential impact from competition	Potential impact from predation	Mean size (mm)[b]
Iowa darter (*Etheostoma exile*)	Not assessed[d]	Suspected	Suspected	50
Fantail darter (*Etheostoma flabellare*)	Not assessed	Suspected	Suspected	50
Least darter (*Etheostoma microperca*)	Not at risk	Suspected[c]	Suspected	25
Johnny darter (*Etheostoma nigrum*)	Not assessed	Known	Suspected	58
Stonecat (*Noturus flavus*)	(Candidate)	Suspected	Not suspected	176
Tadpole madtom (*Noturus gyrinus*)	Not assessed	Suspected	Not Suspected	90
Brindled madtom (*Noturus miurus*)	Not at risk	Suspected	Not suspected	63.5
Northern madtom (*Noturus stigmosus*)*	Endangered	Known	Not suspected	76.5
Logperch (*Percina caprodes*)	Not assessed	Known	Not suspected	89
Blackside darter (*Percina maculata*)	Not at risk	Suspected	Suspected	58
River darter (*Percina shumardi*)	Candidate	Suspected	Suspected	58
Trout-perch (*Percopsis omiscomaycus*)	Not assessed	Not suspected	Known	89
Blacknose dace (*Rhinichthys cataractae*)	Not sssessed	Not suspected	Not suspected	76

Species whose status is shown in parentheses are Candidate species for assessment in Canada, but are secure in the Great Lakes basin. Species shown with *asterisk* on status are ranked as globally vulnerable (NatureServe 2008)

[a] *Sources*: COSEWIC (2007, 2008)

[b] *Source*: Hubbs and Lagler (2004)

[c] Species that have not been assessed by COSEWIC are generally secure in Canada

[d] Not previously identified in literature, but suspected (see "Discussion")

Table 4 List of mussel species found in the lower Great Lakes and in species-at-risk hotspots and the potential impacts from the secondary invasion of round goby

Species	Status[a]	Potential impact of predation	Mean size (mm)[b]	Percent of benthic fish hosts potentially impacted by round gobies (%)
Mucket (*Actinonaias ligamentina*)	Not assessed[c]	Not suspected	130	9
Elktoe (*Alasmidonta marginata*)	Not assessed	Not suspected	70	0
Slippershell (*Alasmidonta viridis*)	Not assessed	Not suspected	30	100[d]
Threeridge (*Amblema plicata*)	Not assessed	Not suspected	115	0
Cylindrical papershell (*Anodontoides ferussacianus*)	Not assessed	Not suspected	55	18
Purple wartyback (*Cyclonaias tuberculata*)	Not assessed	Not suspected	85	0
Spike (*Elliptio dilatata*)	Not assessed	Not suspected	95	20
Northen riffleshell (*Epioblasma t. rangiana*)	Endangered**	Not suspected	50	80[d]
Snuffbox (*Epioblasma triquetra*)	Endangered*	Not suspected	50	100[d]
Wabash pigtoe (*Fusconaia flava*)	Not Assessed	Not suspected	60	0
Plain pocketbook (*Lampsilis cardium*)	Not assessed	Not suspected	95	0
Wavy-rayed lampmussel (*Lampsilis fasciola*)	Endangered	Not suspected	60	33
Fatmucket (*Lampsilis siliquoidea*)	Not assessed	Not suspected	70	7
White heelsplitter (*Lasmigona complanata*)	Not assessed	Not suspected	140	0
Creek heelsplitter (*Lasmigona compressa*)	Not assessed	Not suspected	80	12
Flutedshell (*Lasmigona costata*)	Candidate	Not suspected	105	14
Fragile papershell (*Leptodea fragilis*)	Not assessed	Not suspected	100	0
Eastern Pondmussel (*Ligumia nasuta*)	Endangered	Not suspected	90	0

Table 4 continued

Species	Status[a]	Potential impact of predation	Mean size (mm)[b]	Percent of benthic fish hosts potentially impacted by round gobies (%)
Black sandshell (*Ligumia recta*)	Not assessed	Not suspected	150	0
Threehorn wartyback (*Obliquaria reflexa*)	Candidate	Not suspected	40	33
Hickorynut (*Obovaria olivaria*)	Candidate	Not suspected	30	0
Round hickorynut (*Obovaria subrotunda*)	Endangered	Not suspected	30	100[d]
Round pigtoe (*Pleurobema sintoxia*)	Endangered	Not suspected	70	0
Pink heelsplitter (*Potamilus alatus*)	Not assessed	Not suspected	110	0
Kidneyshell (*Ptychobranchus fasciolaris*)	Endangered	Not suspected	95	75[d]
Giant floater (*Pyganodon grandis*)	Not assessed	Not suspected	95	12
Pimpleback (*Quadrula pustulosa*)	Candidate	Not suspected	70	0
Mapleleaf (*Quadrula quadrula*)	Threatened	Not suspected	90	0
Mudpuppy mussel (*Simpsonaias ambigua*)	Endangered**	Suspected[d]	25	0
Creeper (*Strophitus undulatus*)	Not assessed	Not suspected	70	26
Lilliput (*Toxoplasma parvus*)	Candidate	Not suspected	25	25
Fawnsfoot (*Truncilla donaciformis*)	Endangered	Not suspected	35	0
Deertoe (*Truncilla truncata*)	Candidate	Not suspected	60	0
Paper pondshell (*Utterbackia imbecillis*)	Not assessed	Not suspected	70	0
Rayed bean (*Villosa fabalis*)	Endangered*	Suspected[d]	20	60[d]
Rainbow (*Villosa iris*)	Endangered	Not suspected	50	33

Species shown with * on status are ranked as globally vulnerable, whereas species shown with ** are ranked as globally imperilled (Nature Serve 2008)

[a] *Sources*: COSEWIC (2007, 2008) and Nature serve 2008

[b] *Source*: Metcalfe-Smith et al. (2007)

[c] Species that have not been assessed by COSEWIC are generally secure in Canada

[d] Not previously identified in literature, but suspected (see "Discussion")

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