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COVER: Wingless Mountain Grasshopper (*Booneacris glacialis*) near Amherst, Nova Scotia. See the article in this issue by John Klymko *et al.*, pages 319–329. Records from 1967 and 2016 confirm the presence of this native species in the province. Photo: John Klymko, 13 September 2016.

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Orthoptera and allies in the Maritime provinces, Canada: new records and updated provincial checklists

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Abstract

We provide an updated checklist of Orthoptera and their allies for each Maritime province of Canada with details for 21 new species records. Drumming Katydid (*Meconema thalassinum*), recorded from Nova Scotia (NS) and Prince Edward Island (PEI), and Sprinkled Grasshopper (*Chloealtis conspersa*), recorded from New Brunswick (NB) are reported for the first time from the Maritimes as a whole. We report range extensions in the Maritime region for Australian Cockroach (*Periplaneta australasiae*; NB), Treetop Bush Katydid (*Scudderia fasciata*; NS), Short-legged Camel Cricket (*Ceuthophilus brevipes*; PEI), Spotted Camel Cricket (*Ceuthophilus maculatus*; PEI), Roesel's Shield-backed Katydid (*Roeseliana roesellii*; NS), and Black-horned Tree Cricket (*Oecanthus nigricornis*; PEI). Short-winged Mole Cricket (*Neoscapteriscus abbreviatus*; NB) and European Mole Cricket (*Gryllotalpa gryllotalpa*; NS) are reported as adventives (non-native species that are believed to be not yet established), new to Canada from the Maritimes. Other new records for species not known to be established are Lined Earwig (*Doru taeniatum*; NS), Australian Cockroach (*Periplaneta australasiae*; PEI), American Cockroach (*Periplaneta americana*; NB), Brown Cockroach (*Periplaneta brunnea*; PEI), Smooth Cockroach (*Nyctibora laevigata*; NB), West Indian Leaf Cockroach (*Blaberus discoidalis*; NB), an unidentified *Parcoblatta* species (NB), Brown-banded Cockroach (*Supella longipalpa*; PEI), Praying Mantis (*Mantis religiosa*; NB), and American Bird Grasshopper (*Schistocerca americana*; NS).

Key words: Orthopteroid; Orthoptera; Dermaptera; Blattodea; Mantodea; Maritime provinces; new species; range extensions

Introduction

A comprehensive treatment of Canada's Orthoptera and allies (orthopteroids), including Canadian range maps for all reported species, was published in 1985 (Vickery and Kevan 1985). This was quickly followed by an update of the Canadian fauna with provincial-level checklists (Vickery and Scudder 1987). Since then, reports of new orthopteroid records for the Maritime provinces have appeared in several publications, most notably Catling *et al*. (2013) with ten new provincial records. Other recent reports include Chandler (1992), Catling *et al*. (2009), McAlpine (2009), Scudder and Vickery (2010), McAlpine and Ogden (2012), Clements *et al*. (2013), and McAlpine *et al*. (2015).

In this paper, we add to this growing body of work with 21 new provincial records and provide updated provincial checklists to reflect the additions since 1987. Although only species with an extant or previously established population should be considered part of the region's fauna, we follow Vickery and Scudder (1987) and report non-native species that have been collected in a jurisdiction but are not believed to be established there. These are adventive species and include intercepts taken from shipped goods and vehicles.

Vouchers reported here have been deposited in the New Brunswick Museum (NBM, with accession number indicated), the Atlantic Forestry Centre (AFC), the Université de Moncton (UDM), the Nova Scotia Museum (NSM), the Nova Scotia Department of Natural Resources collection at Shubenacadie (NSNR), the private collection of J.B.O. (JBO), and Agriculture and Agri-food Canada, Charlottetown (AACC). Common names are from CESCC (2016), except where mentioned in Table 1.

A contribution towards the cost of this publication has been provided by the Thomas Manning Memorial Fund of the Ottawa Field-Naturalists' Club.

TABLE 1. Orthoptera and allies (Orthopteroids) in the Maritime provinces of Canada: New Brunswick (NB), Prince Edward Island (PEI), and Nova Scotia (NS).

Order	Family	Subfamily	Species*	Common name†	Occurrence‡ NB	PEI	NS
Dermaptera	Spongiphoridae	Labiinae	*Labia minor* (L. 1758)	Lesser Earwig	N		N
	Forficulidae	Forficulinae	*Forficula auricularia* L. 1758	European Earwig	N-9	N-6	N
			Doru taeniatum (Dohrn 1862)	Lined Earwig	A-6		A-11
Mantodea	Mantidae	Mantinae	*Mantis religiosa* (L. 1758)	Praying Mantis	A/N-11		A/N-4
Blattodea	Blattidae	Blattinae	*Blatta orientalis* L. 1758	Oriental Cockroach			N
			Periplaneta americana (L. 1758)	American Cockroach	A/N-11		N
			Periplaneta australasiae (Fabricius 1775)	Australian Cockroach	N-11	A/N-11	N
			Periplaneta brunnea Burmeister 1838	Brown Cockroach		A/N-11	N-4
		Nyctoborinae	*Nyctibora laevigata* (Beauvois 1805)	Smooth Cockroach[a]	A-11		
		Polyzosteriinae	*Eurycotis floridana* (Walker 1868)	Skunk Cockroach[a]			A
	Blaberidae	Blaberinae	*Blaberus discoidalis* Serville 1839	West Indian Leaf Cockroach[a]	A-11		
		Panchlorinae	*Panchlora nivea* (L. 1758)	Green Banana Cockroach[a]	A		A
		Oxyhaloinae	*Rhyparobia maderae* (Fabricius 1781)	Madeira Cockroach[a]	A		
	Epilampridae	Epilamprinae	*Colapteroblatta nigra* (Brunner von Wattenwyl 1892)	Round-backed Cockroach[a]			A
	Ectobiidae	Pseudophyllodromiinae	*Supella longipalpa* (Fabricius 1798)	Brown-banded Cockroach		A/N-11	N-4
		Blattellinae	*Blattella germanica* (L. 1767)	German Cockroach	N	N	N
		Ectobiinae	*Ectobius lapponicus* (L. 1758)	Dusky Cockroach	N-7	N-1	N-7
Orthoptera	Rhaphidophoridae	Ceuthophilinae	*Ceuthophilus brevipes* Scudder 1862	Short-legged Camel Cricket	X	X-11	X
			Ceuthophilus guttulosus Walker 1869	Speckled Camel Cricket			X
			Ceuthophilus maculatus (Harris 1841)	Spotted Camel Cricket	X	X-11	X
	Tettigoniidae	Phaneropterinae	*Scudderia curvicauda* (De Geer 1773)	Curve-tailed Bush Katydid	X	X	X
			Scudderia fasciata (Beutenmüller 1894)	Treetop Bush Katydid	X-10		X-11
			Scudderia furcata Brunner von Wattenwyl 1878	Fork-tailed Bush Katydid	X-8	X-6	X
			Scudderia pistillata Brunner von Wattenwyl 1878	Broad-winged Bush Katydid	X	X-6	X
			Scudderia septentrionalis (Serville 1839)	Northern Bush Katydid	X-10		
		Tettigoniinae	*Roeseliana roeselii* (Hagenbach 1822)	Roesel's Shield-backed Katydid	N-3		N-11
		Conocephalinae	*Conocephalus brevipennis* (Scudder 1862)	Short-winged Meadow Katydid	X-5		
			Conocephalus fasciatus (De Geer 1773)	Slender Meadow Katydid	X	X	X
			Neoconocephalus ensiger (Harris 1841)	Sword-bearing Conehead Katydid	X		N
			Neoconocephalus retusus (Scudder 1878)	Round-tipped Conehead Katydid			V-2
			Orchelimum gladiator Bruner 1891	Gladiator Meadow Katydid	X-6	X-5	
		Meconematinae	*Meconema thalassinum* (De Geer 1773)	Drumming Katydid		N-11	N-11
	Gryllotalpidae	Gryllotalpinae	*Gryllotalpa gryllotalpa* (L. 1758)	European Mole Cricket[b]			A-11
		Scapteriscinae	*Neoscapteriscus abbreviatus* (Scudder 1869)	Short-winged Mole Cricket[b]	A-11		
	Gryllidae	Gryllinae	*Acheta domesticus* (L. 1758)	House Cricket		N	N
			Gryllus pennsylvanicus Burmeister 1838	Fall Field Cricket	X	X	X
		Nemobiinae	*Allonemobius allardi* (Alexander and Thomas 1959)	Allard's Ground Cricket	X		X

TABLE 1. *(continued)*

Order	Family	Subfamily	Species*	Common name†	Occurrence‡ NB	PEI	NS
			Allonemobius fasciatus (De Geer 1773)	Striped Ground Cricket	X	X	X
			Eunemobius carolinus (Scudder 1877)	Carolina Ground Cricket	X	X	X
			Neonemobius palustris (Blatchley 1900)	Sphagnum Ground Cricket	X-5		X
		Oecanthinae	*Oecanthus nigricornis* Walker 1869	Black-horned Tree Cricket	X-4	X-11	X-5
	Acrididae	Cyrtacanthacridinae	*Schistocerca nitens* (Thunberg 1815)	Gray Bird Grasshopper[b]			A
			Schistocerca americana (Drury 1773)	American Bird Grasshopper			A-11
		Melanoplinae	*Booneacris glacialis* (Scudder 1863)	Wingless Mountain Grasshopper	X	X	X
			Melanoplus bivittatus (Say 1825)	Two-striped Grasshopper	X	X	X
			Melanoplus borealis (Fieber 1853)	Northern Grasshopper	X	X	X
			Melanoplus fasciatus (Walker 1870)	Huckleberry Grasshopper	X	X	X
			Melanoplus femurrubrum (De Geer 1773)	Red-legged Grasshopper	X	X	X
			Melanoplus keeleri Thomas 1874	Keeler's Grasshopper	X		X
			Melanoplus punctulatus (Scudder 1862)	Grizzly Grasshopper	X-6		
			Melanoplus sanguinipes (Fabricius 1798)	Migratory Grasshopper	X	X	X
			Melanoplus stonei Rehn 1904	Stone's Grasshopper	X	X-6	
		Oedipodinae	*Camnula pellucida* (Scudder 1862)	Clear-winged Grasshopper	X	X	X
			Chortophaga viridifasciata (De Geer 1773)	Green-striped Grasshopper	X	X-6	X
			Dissosteira carolina (L. 1758)	Carolina Grasshopper	X	X	X
			Pardalophora apiculata (Harris 1835)	Coral-winged Grasshopper	X		
			Spharagemon bolli Scudder 1875	Boll's Grasshopper	X-6		
			Trimerotropis verruculata (Kirby 1837)	Crackling Grasshopper	X	X	X
			Stethophyma gracile (Scudder 1862)	Graceful Sedge Grasshopper	X	X	X
			Stethophyma lineatum (Scudder 1862)	Striped Sedge Grasshopper	X	X	X
		Gomphocerinae	*Chloealtis conspersa* (Harris 1841)	Sprinkled Grasshopper	X-11		
			Pseudochorthippus curtipennis (Harris 1835)	Marsh Meadow Grasshopper	X	X	X
			Orphulella speciosa (Scudder 1862)	Pasture Slant-faced Grasshopper	X		
	Tetrigidae	Tetriginae	*Nomotettix cristatus* (Scudder 1862)	Crested Pygmy Grasshopper	X	X	X
			Tetrix arenosa Burmeister 1838	Obscure Pygmy Grasshopper	X		X
			Tetrix brunneri (Bolivar 1877)	Brunner's Pygmy Grasshopper	X		X
			Tetrix ornata (Say 1824)	Ornated Pygmy Grasshopper	X	X	X
			Tetrix subulata (L. 1761)	Granulated Pygmy Grasshopper	X	X	X
		Batrachideinae	*Tettigidea lateralis* (Say 1824)	Black-sided Pygmy Grasshopper	X		X

*Dermaptera, Mantodea, Blattodea, and Orthoptera names follow Hopkins *et al.* (2017), Otte *et al.* (2017), Beccaloni (2014), and Cigliano *et al.* (n.d.), respectively.
†Common names are from CESCC (2016), except where indicated with superscripts: a. Beccaloni (2014), b. Cigliano *et al.* (n.d.).
‡A = adventive, a non-native species that has been reported from, but not become established in a region; A/N = questionable adventive, used for non-native species when it is not clear whether it has become established; N = non-native, established; V = vagrant, present only as transients away from the species' normal range; X = native. The justification for the occurrences can be found in Vickery and Kevan (1985) and Vickery and Scudder (1987), and in the following citations, noted after the type of occurrence: 1. Chandler (1992); 2. Catling *et al.* (2009); 3. McAlpine (2009); 4. Scudder and Vickery (2010); 5. McAlpine and Ogden (2012); 6. Catling *et al.* (2013); 7. Clements *et al.* (2013); 8. McAlpine *et al.* (2015); 9. Tourneur (2017); 10. Lewis and McAlpine (2018); 11. Klymko *et al.* (current article).

New Provincial Records

DERMAPTERA

Forficulidae

Forficulinae

Doru taeniatum (Dohrn 1862), Lined Earwig — **Nova Scotia**: Colchester County: Truro, 4 September 1991, T.D. Smith (NSNR).

Presumably this is an adventive occurrence. This earwig is considered adventive in New Brunswick (NB) and Ontario (ON), the only other provinces where this species has been reported (Vickery and Scudder 1987; Catling *et al*. 2013).

MANTODEA

Mantidae

Mantinae

Mantis religiosa (L. 1758), Praying Mantis — **New Brunswick**: Saint John County: Saint John, August 1979 (NBM-44584); Westmorland County: Moncton, 2 September 1994, "Terry M." (UDM).

It is unclear if *M. religiosa* is established anywhere in the Maritimes, despite attempts made to introduce the species in Atlantic Canada (Vickery and Kevan 1985). The species has been taken recently in the Annapolis Valley, Nova Scotia (NS), but it is unclear if a sustaining population exists there (Scudder and Vickery 2010). The NB specimens are likely from releases and not established populations.

BLATTODEA

Blattidae

Blattinae

Periplaneta americana (L. 1758), American Cockroach — **New Brunswick:** Saint John County: Saint John, 10 June 1902, W. McIntosh (NBM-30126), 29 August 1980, in shipment (NBM-31836); York County: Fredericton, [no date], C.C. Smith (AFC); Nashwaaksis IGA, "Bananas imported", 21 March 1967 (AFC); Restigouche County: Dalhousie, "ex. auto from Cuba", 8 August 1966 (AFC).

This cosmopolitan species has been found in buildings across Canada, but there are no previous records for NB (Vickery and Kevan 1985; Vickery and Scudder 1987). It is not known if the 1902 Saint John record and undated Fredericton record represent adventive occurrences or established populations.

Periplaneta brunnea Burmeister, 1838, Brown Cockroach — **Prince Edward Island**: Prince County: O'Leary, "Packed in with Bananas", 1992, J.G. Stewart (AACC); Queens County: Charlottetown, "Found in apt.", 15 April 1991, J.G. Stewart (AACC); Kings County: Souris, December 1985, L.S. Thompson (AACC).

In Canada, *P. brunnea* is often considered an adventive species (Vickery and Scudder 1987), although Scudder and Vickery (2010) report that it has become established, at least temporarily, in NS. In Prince Edward Island (PEI), the O'Leary record appears to have been an interception of insects on imported goods; it is not known if established colonies existed at Charlottetown or Souris.

Periplaneta australasiae (Fabricius 1775), Australian Cockroach — **Prince Edward Island**: Queens County: Charlottetown, January 1986, L.S. Thompson (AACC); 1988, F. Legault (AACC). **New Brunswick:** Westmorland County: Sackville, Mount Allison Campus, Flemington Building, 45.9001°N, 64.3726°W, 9 March 2017, found dead, N.A. Donaher, J. Klymko (NBM-53103), 17 May 2017, found alive, P.J. Cormier, J. Klymko (NBM-53104).

This exotic species is established at Mount Allison University in Sackville, NB, and has been since at least 2006 when J.K. saw a live individual. It is not known if this species is established in PEI. It has been considered established elsewhere in Canada, including NS (Vickery and Kevan 1985; Vickery and Scudder 1987).

Blaberidae

Blaberinae

Blaberus discoidalis Serville 1839, West Indian Leaf Cockroach — **New Brunswick**: Saint John County: Saint John, 28 April 1981, found in fruit shipment in grocery store, C. Bree (NBM-30033; Figure 1).

In Canada, this species occurs in greenhouses and has been used in laboratory study (Vickery and Kevan

FIGURE 1. West Indian Leaf Cockroach (*Blaberus discoidalis*). Specimen in New Brunswick Museum. Collected in Saint John, New Brunswick, in late April 1981 by C. Bree. Photo: P.M. Catling in 2011.

1985). The only previous occurrence in Canada was in Quebec (QC) where it was reared in laboratories (Vickery and Scudder 1987). The Saint John specimen is presumably an intercept. The species is widespread in the Greater Antilles and northern South America (Rehn and Hebard 1927), where many Canadian fruit imports originate.

ECTOBIIDAE

Blattellinae

Parcoblatta sp. — **New Brunswick**; Kings County; Clifton Royal, October 1992, R. Perry, abundant in trailer from southeastern USA (NBM-52790).

The only specimen available is a female, which is morphologically unidentifiable to the species level. We attempted species-level identification with DNA barcoding; however, several attempts at polymerase chain reaction amplification were unsuccessful. The specimen presumably originated in the southeastern United States of America (USA), where eight *Parcoblatta* species occur (Beccaloni 2014). No *Parcoblatta* species have been reported from the Maritimes, although *P. pennsylvanica*, *P. virginica*, *P. uhleriana*, and *P. caudelli* have been reported elsewhere in Canada (Vickery and Scudder 1987).

Nyctiborinae

Nyctibora laevigata (Beauvois 1805), Smooth Cockroach — **New Brunswick**: Saint John County: Saint John, 30 June 1900, P.R. McIntosh (NBM-31837; Figure 2).

This species is native to the Caribbean and perhaps Panama, and it has been reported as an adventive in the USA, Canada, and Europe (Gutiérrez and Pérez-Gelabert 2000). In Canada, it has been recorded in ON and QC (Vickery and Scudder 1987). We assume that the Saint John specimen was intercepted.

Pseudophyllodromiinae

Supella longipalpa (Fabricius 1798), Brown-banded Cockroach — **Prince Edward Island**: Queens County: Charlottetown, "Found in home, family from Ontario", March 1986, L.S. Thompson (AACC).

It can be inferred from the label that the Charlottetown specimen was part of an adventive population. In Newfoundland and Labrador it is considered adventive (Vickery and Scudder 1987) whereas in NS and several more western provinces it is considered established (Scudder and Vickery 2010). Where it occurs in Canada, it is domiciliary (Vickery and Kevan 1985).

ORTHOPTERA

RHAPHIDOPHORIDAE

Ceuthophilinae

Ceuthophilus brevipes (Scudder 1862), Short-legged Camel Cricket — **Prince Edward Island**: Queens County: Uigg, MacPhail Woods Ecological Project, pit-

FIGURE 2. Smooth Cockroach (*Nyctibora laevigata*). Specimen in New Brunswick Museum. Collected in Saint John, New Brunswick, on 30 June 1900 by P.R. McIntosh. Photo: D.F. McAlpine in 2018.

fall trap, 46.1594°N, 62.8213°W, 24 August, 2 September 2015, N.D. Brown (NBM-53087, 53088).

This northeastern flightless species was expected on PEI; it is also known from other islands including Newfoundland, Anticosti Island, and Cape Breton (Vickery and Kevan 1985).

Ceuthophilus maculatus (Harris 1841), Spotted Camel Cricket — **Prince Edward Island**: Queens County: Rice Point, December 1982, "found in Fulton's basement", L.S. Thompson (AACC); Donagh, 46.26029°N, 62.97452°W, July 2016, J.D. McAskill (NBM-53089).

Vickery and Kevan (1985) note that the species is sometimes found in cellars, as is the case for the earliest PEI record. The record from Donagh is from a natural forest habitat. Unlike *C. brevipes*, *C. maculatus* is not known from other major Canadian islands, such as Newfoundland, Anticosti Island, and Cape Breton (Vickery and Kevan 1985).

Tettigoniidae

Phaneropterinae

Scudderia fasciata (Beutenmüller 1894), Treetop Bush Katydid — **Nova Scotia**: Cumberland County: 1.1 km southwest of Mosleys Pond, open spruce (*Picea* spp.) forest with Eastern White Pine (*Pinus strobus* L.), swept from heather (Ericaceae) understorey, 45.9135°N, 64.0984°W, 13 September 2016, J.K. (NBM-53094).

Scudderia fasciata was first reported from the Maritimes based on NB records by Lewis and McAlpine (2018). Our NS record, and additional NB records reported below under Other Notable Records, demonstrate how widespread the species is. *Scudderia fasciata* is associated with treetops, especially those of conifers (Himmelman 2009), where it would be out of sight of collectors. Perhaps that is the reason that this large species eluded detection in the Maritimes in the past.

Tettigoniinae

Roeseliana roeselii (Hagenbach 1822), Roesel's Shield-backed Katydid — **Nova Scotia**: Colchester County: Five Islands Provincial Park, swept from small wet meadow, 45.4058°N, 64.0221°W, 13 August 2016, J.B.O. (JBO; Figure 3).

This exotic species was first documented in North America at Montréal, QC, in 1952 (Urquhart and Beaudry 1953). Since that time, it has become established through much of the northeast, including NB (McAlpine 2009; Catling *et al*. 2013), and its spread into other Maritime provinces was anticipated (McAlpine and Ogden 2012).

Meconematinae

Meconema thalassinum (De Geer 1773), Drumming Katydid — **Prince Edward Island**: Prince County: Borden-Carleton, flower garden, 46.2548°N, 63.6954°W, 18 September 2013, J.K. and S.L.R. (NBM-46201); Queens County: Brackley Beach, PEI National Park,

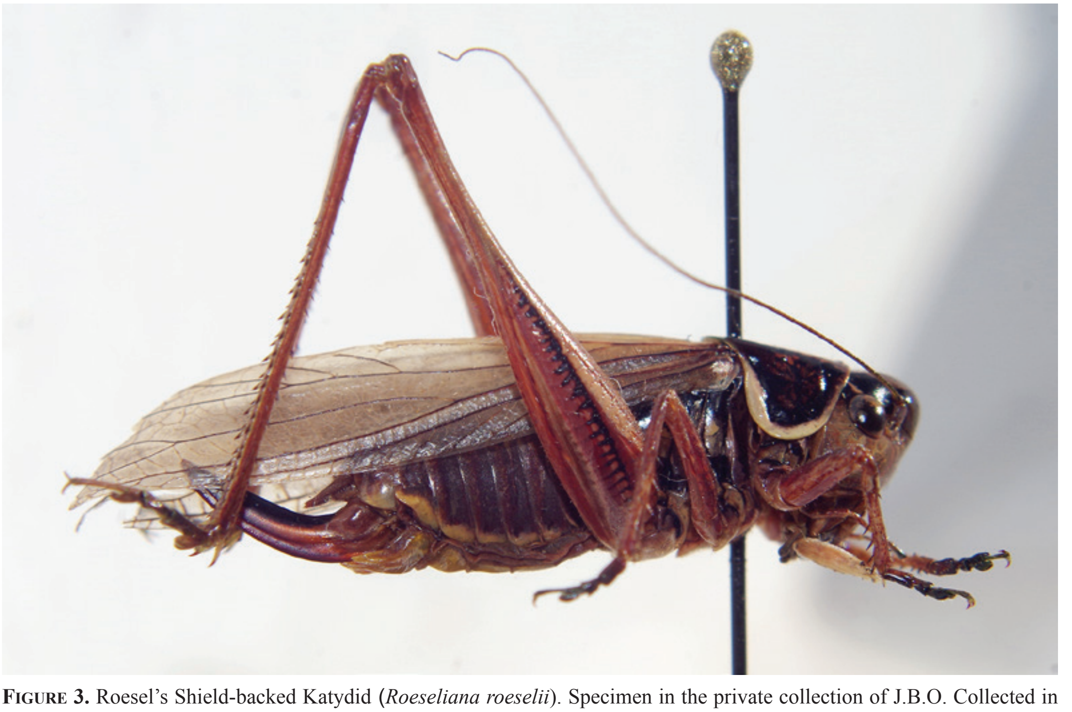

FIGURE 3. Roesel's Shield-backed Katydid (*Roeseliana roeselii*). Specimen in the private collection of J.B.O. Collected in Five Islands Provincial Park, Nova Scotia, on 13 August 2016 by J.B. Ogden. Photo: J.B. Ogden in 2018.

inside park entrance kiosk, 46.4277°N, 63.1997°W, 16 August 2016, D.J. Terstege (photo record, see www.inaturalist.org/observations/3901605); Tea Hill, on window screens at house, 46.2033°N, 63.0571°W, 18 August 2016, 19 August 2016, A.Y. Laurin (photo records, see www.inaturalist.org/observations/5419927, www.inaturalist.org/observations/5419996); Mount Stewart, Allisary Creek, 46.3703°N, 62.8494°W, 20 August 2016, R.W.H. (NBM-53090); Stanhope, PEI National Park, attracted to light at campground, 46.4217°N, 63.1106°W, 27 August 2016, R.W.H. (photo record, see https://www.inaturalist.org/observations/4000961); Mount Stewart, under canopy at gas station, 46.3672°N, 62.8751°W, 19 September 2016, R.W.H. (NBM-53091); Cavendish, attracted to lights at campground, 46.4841°N, 63.3653°W, 28 July 2017, J.B.O. and N. Ogden (NSNR); Kings County: Summerville, attracted to light, 46.2110°N, 62.7301°W, 30 August 2015, 2 September 2015, R.W.H. (Figure 4); **Nova Scotia**: Halifax County: Halifax, Victoria Park, 44.6410°N, 63.5796°W, 29 August 2016, S.L.R. (NBM-53092); Dartmouth, Elliot Street, 44.6707°N, 63.5602°W, 2 September 2016, S.L.R. (NBM-53093).

Meconema thalassinum, which is native to Europe, was first reported in North America in 1960 from Long Island, New York, where it had been established since at least 1957 (Gurney 1960a,b). Since then, records have been published for New York State (Sismondo 1978;

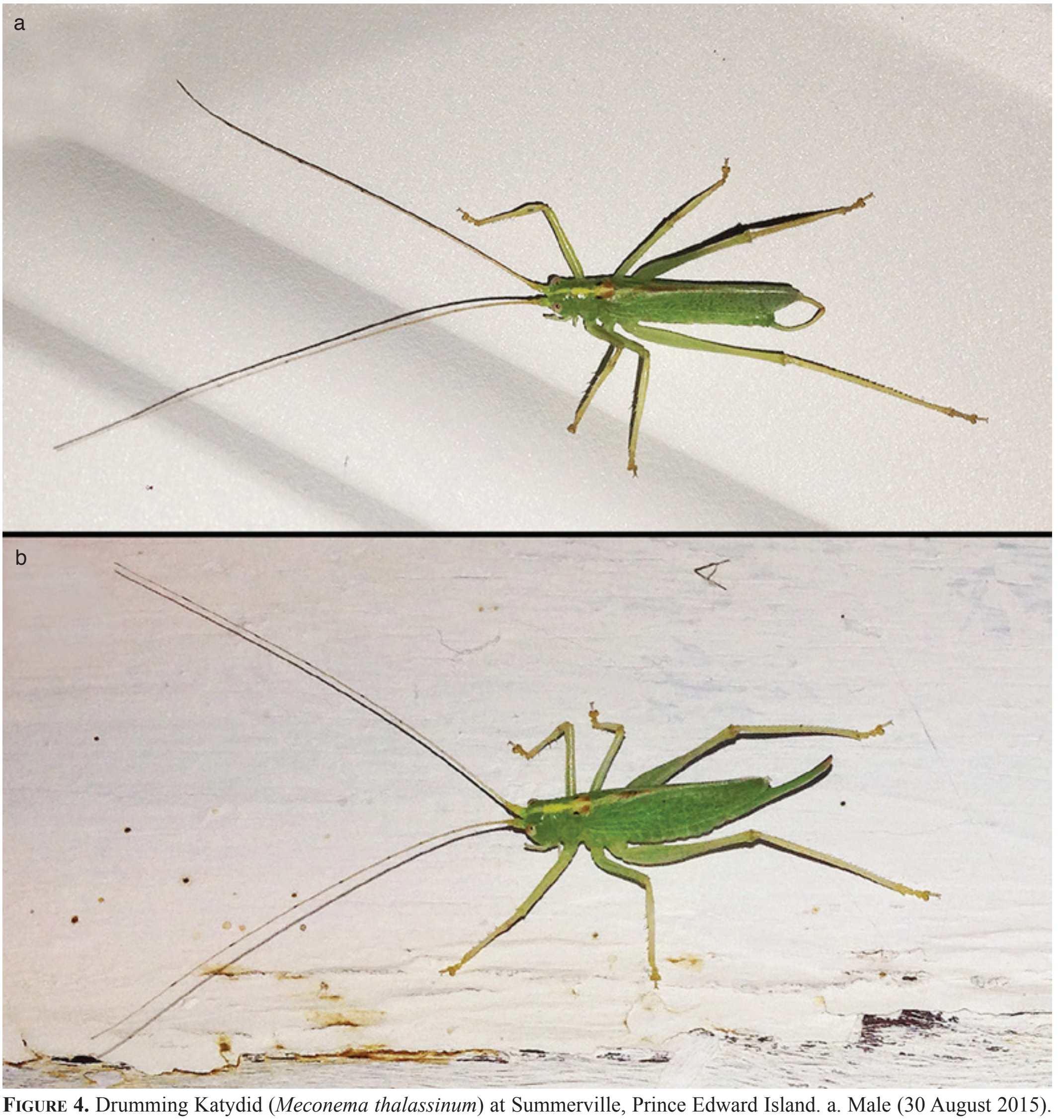

FIGURE 4. Drumming Katydid (*Meconema thalassinum*) at Summerville, Prince Edward Island. a. Male (30 August 2015). b. Female (2 September 2015). Photos: R.W. Harding.

Hoebeke 1981), Rhode Island (Hoebeke 1981), Michigan (Bland 2003), ON (Marshall *et al*. 2004), Connecticut (Maier 2005), British Columbia and Washington (Cannings *et al*. 2007), and Massachusetts (Himmelman 2009). Although it has not been reported for PEI in the primary literature, records were documented in Nature PEI's newsletter (Harding 2017). The closest known record to the Maritimes is at Mount Desert Island, Maine (2012 photo record by B. Woo, see bugguide.net/node/view/681733). The number of locations known for this species in PEI suggests that it has been established there for some time.

Gryllotalpidae
Gryllotalpinae

Neoscapteriscus abbreviatus Scudder 1869, Short-winged Mole Cricket — **New Brunswick**: Kings County: Grand Bay-Westfield, 45.3171°N, 66.2018°W, 25 October 1991, in home, family recently moved from Oakville, Ontario, D.F.M. (NBM-52789).

This South American native has been established in Florida since 1899 (Walker and Nickle 1981). The NB specimen was likely transported north in horticultural material, either to ON then NB, as the label suggests is possible, or directly to NB. The species has not previously been reported from Canada.

Gryllotalpa gryllotalpa (L. 1758), European Mole Cricket — **Nova Scotia:** Halifax County: Sackville, in delicatessen, 17 October 1988, G. MacLellan (NSM).

This Palaearctic species is established in New Jersey, New York, Massachusetts, and possibly Florida, and it has been recorded as an intercept in Pennsylvania (Nickle and Castner 1984). Why the NS specimen was found in such an odd circumstance is unclear, but, like *Neoscapteriscu abbreviatus*, it may have been brought into the Maritimes in horticultural material. It has not previously been reported from Canada.

Gryllidae
Oecanthinae

Oecanthus nigricornis Walker 1869, Black-horned Tree Cricket — **Prince Edward Island**: Kings County: Murray Harbour, Thomas Island, 46.0275°N, 62.5069°W, 1 September 2015, M.A. Arsenault (NBM-53096); Summerville, attracted to light, 46.2110°N, 62.7301°W, 19 September 2015, 20 September 2015, R.W.H. (photo records, see Harding 2016); Queens County: Mount Stewart, Allisary Creek, 46.3703°N, 62.8494°W, 27 August 2016, R.W.H. (NBM-53097).

Although it has not been reported in the primary literature, a PEI record was documented in Nature PEI's newsletter (Harding 2016). This Nearctic species, known from southern ON, southern QC, and much of the eastern USA (Capinera *et al.* 2004), was noticed in NB by naturalists in about 1990 or earlier, and, by the early 2000s, it was known to be widespread across southern NB (McAlpine and Ogden 2012). That this species, now common in the Maritimes, was not reported in historical works (e.g., Vickery *et al.* 1974; Vickery and Kevan 1985) suggests that it may have colonized the area recently.

Acrididae
Cyrtacanthacridinae

Schistocerca americana (Drury 1770), American Bird Grasshopper — **Nova Scotia**: Halifax County: intercepted in vegetables originally from USA, 17 July 1983 (NSM); Lake Echo, flew in window, April 2008, L. MacDonald (NSM).

This species has a core range in the southeastern USA and much of Latin America. It is known to be a long-distance migrant, with presumed migrants reaching southern ON and Massachusetts (Vickery and Kevan 1985). It has also been recorded from numerous locations as an intercept, and it is assumed that the Lake Echo record was inadvertently carried in from elsewhere, given how early in the season it was recorded.

Gomphocerinae

Chloealtis conspersa (Harris 1841), Sprinkled Grasshopper — **New Brunswick**: Northumberland County: Portage Island. 47.1566°N, 65.03745°W, 6 August 2015, J.K. (NBM-53099); Charlotte County: Mill Cove Creek, Campobello Island, salt marsh, net sweeping, 44.9274°N, 66.9108°W, 26 September 2016, D.F.M. (NBM-52791).

This species was expected in NB and the Maritimes. Vickery and Kevan (1985) map a record from the area of Calais, Maine, which is adjacent to the NB border and close to the Charlotte County, NB, record.

Other Notable Records

ORTHOPTERA

Tettigoniidae

Phaneropterinae

Scudderia fasciata (Beutenmüller 1894), Treetop Bush Katydid — **New Brunswick**: York County: Fredericton, 26 September 2008, C.I.G.A. (photo record, see bugguide.net/node/view/228908); Kent County: Kouchibouguac National Park, 14 September 2012, D.A.D. (Figure 5).

Lewis and McAlpine (2018) reported the first Maritimes records of *S. fasciata* based on specimens collected in NB in 2013 and 2017. The photographic records reported here represent earlier NB records.

Acrididae
Melanoplinae

Booneacris glacialis (Scudder 1863), Wingless Mountain Grasshopper — **Nova Scotia**: Halifax County: Caribou Bog, NE of Dartmouth, 1967, P. Ward (NSM); Cumberland County: Amherst, 900 m south of Mosleys Pond, treed bog, 45.9126°N, 64.0924°W, 13 September 2016, J.K. (NBM-53101; Figure 6).

FIGURE 5. Treetop Bush Katydid (*Scudderia fasciata*), in Kouchibouguac National Park, New Brunswick, 14 September 2012. Photo: D.A. Doucet.

FIGURE 6. Wingless Mountain Grasshopper (*Booneacris glacialis*), near Amherst, Nova Scotia, 13 September 2016. Photo: J. Klymko.

Vickery (1961) reports that specimens taken in Shelburne County, NS, by C.E. Atwood had been misplaced at the Royal Ontario Museum. The species is listed as "X?" for NS in Vickery and Scudder's (1987) Canadian checklist. The X is notation given to native species, and the question mark either means they doubted the veracity of the record, or they doubt the species persists in the province. No other specimens had been found in NS despite many attempts to recapture the species, as reported by Vickery *et al*. (1974). The 1967 and 2016 records confirm the species' presence in NS. *Booneacris glacialis* was also listed as "X?" for PEI in Vickery and Scudder's (1987) Canadian checklist, presumably because surveys to relocate the only known colony, one reported by Walker (1915) from Dundee, have proven unsuccessful (see Vickery *et al*. 1974).

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The spiders of Prince Edward Island: experts and citizen scientists collaborate for faunistics

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Abstract

Although lists of spider species have been compiled for all of Canada's provinces and territories, the spider fauna of Prince Edward Island (PEI) is poorly known. Based on the efforts of citizen scientists, naturalists, and scientists on PEI and researchers at the Centre for Biodiversity Genomics, we present the first comprehensive list of spider species on the island, increasing the known number from 44 to 198. The Centre for Biodiversity Genomics conducted intensive collection in Prince Edward Island National Park; Nature PEI citizen scientists and naturalists contributed specimens from across the island from several different habitats. This provincial list is dominated by the araneoid families, Linyphiidae, Theridiidae, and Araneidae, with 55, 27, and 22 species, respectively. Several non-native species, such as the theridiid Eurasian False Black Widow Spider (*Steatoda bipunctata* (L.)) and the araneid Red-sided Sector Spider (*Zygiella atrica* (C.L. Koch)), have been collected in several locations on the island, suggesting that they are well established. This work highlights the effectiveness of collaboration among citizen scientists, naturalists, and professional researchers to further our knowledge of species diversity and distributions.

Key words: Maritime provinces; Araneae; Prince Edward Island; PEI; faunistics; citizen science; Arachnida

Introduction

Faunistic studies provide crucial biodiversity information and help accumulate the species distribution, habitat use, and relative abundance data necessary for conservation. Furthermore, faunistic studies record introduced species and their potential establishment as well as the movement of native species into new habitats or geographic areas over time. In several areas of the world, including Canada, the distribution of some species groups is poorly known. Obtaining a faunal baseline for a region is important because it allows tracking of future changes in species composition. Such temporal data are valuable in determining changes in, and relative abundances of, local species assemblages including decline or even extirpations of native species caused by, for example, climate change, the introduction and establishment of non-native species, or direct human alteration of landscapes and habitat (Shochat *et al.* 2004).

Spiders are a ubiquitous, diverse group, with about 47 000 species described worldwide (World Spider Catalog 2018). Spider species lists and preliminary conservation status assessments have recently been compiled for all Canadian provinces and territories (CESCC 2016). Some provinces and one territory—British Columbia (Bennett *et al.* 2017), Yukon (Dondale *et al.* 1997), Manitoba (Aitchison-Benell and Dondale 1990), Quebec (Paquin and Dupérré 2003), and Newfoundland and Labrador (Pickavance and Dondale 2005; Perry *et al.* 2014)—have produced peer-reviewed or otherwise expert-created lists (e.g., online resources). Less comprehensive (but still useful) lists, resulting from habitat or area-specific ecological or faunistic studies, are available for Nova Scotia (Dondale 1956), Alberta (Buddle 2001; Holmberg and Buckle 2002), Ontario (Dondale 1971; Dondale and Redner 1994), Saskatchewan (Doane and Dondale 1979), New Brunswick (Boiteau 1983), Nunavut (Leech 1966; Pickavance 2006), and Northwest Territories (Working Group on General Status of NWT Species 2016).

Before the work reported here, no dedicated spider faunistics or ecological studies had occurred on Prince

Edward Island (PEI), and the spiders of the island appeared to be the most poorly known of the Canadian provinces and territories. To our knowledge, most of the 44 recorded species for PEI (Paquin *et al.* 2010; CESCC 2016) are a result of casual collecting by visiting entomologists/arachnologists or dedicated surveys focussed on documenting the distribution of a particular species (e.g., Knysh and Giberson 2012). In comparison, despite Nunavut's remoteness and small human population, it has at least 96 species of spiders (Pickavance 2006; CESCC 2016), and Nova Scotia and New Brunswick, the provinces bordering PEI, have 446 and 390 known species, respectively (Paquin *et al.* 2010; CESCC 2016).

Citizen science, the engagement of citizens to aid in the collection and/or processing of scientific data (Silvertown 2009), allows scientists to leverage the data acquisition power of the public (e.g., Prudic *et al.* 2017). This is particularly relevant in the context of faunistics because obtaining sufficient specimens to provide good coverage for a particular province (or over other broad spatial scales) could be a daunting task without the help of numerous volunteers (Acorn 2017).

PEI, which is approximately 5660 km^2 in area and lies on the east coast of Canada in the Gulf of St. Lawrence, is the smallest and most densely populated province (Statistics Canada 2016). Approximately 14 km of water separates PEI from the mainland (New Brunswick and Nova Scotia), and the adjacent ocean heavily influences the temperate climate. PEI generally has warmer winters and cooler summers than the nearby mainland, with average annual temperatures for January and July (1981–2010) of -7 ± 2.3°C (mean ± SD) and 19 ± 1.2°C, respectively (ECCC 2017). In winter, PEI is surrounded by sea-ice that contributes to long, cool springs, while warming of the shallow Gulf of St. Lawrence in summer results in lengthy, mild autumns.

About 75% of the land is under 45 m elevation (Loo and Ives 2003). The province is over 90% privately owned (Statistics Canada 2016) and has a long history of land alteration and disturbance (Loo and Ives 2003; Sobey and Glen 2004). Most of the original Acadian Forest was cleared for agriculture by European settlers beginning in 1723, and, by 1900, an estimated 70% of the island was cleared (Loo and Ives 2003). Regenerated forest on former agricultural land and remaining fragments of original forest show a high degree of disturbance (Loo and Ives 2003; Sobey and Glen 2004). Forests currently make up 44% of the total area, active agriculture 38%, abandoned farmland 4%, while wetlands (6%) and coastal sand dunes (1%) are relatively rare habitats (Statistics Canada 2016).

Recently, a DNA barcoding project conducted by the Centre for Biodiversity Genomics (CBG) increased the number of spider species known from PEI to 82 (Blagoev *et al.* 2016). Most of the new records were produced after the data compilation that resulted in the most recent wild species report from the Canadian Endangered Species Conservation Council (CESCC 2016). Building on that momentum, a project organized by Nature PEI involving numerous citizen scientists, in combination with experts, confirmed the presence of many of the previously documented species and further increased the list of spider species. Here we present the most comprehensive list of the 198 species now known to constitute the spider fauna of PEI.

Methods

Specimen collection and curation

In 2015, Nature PEI naturalists recruited volunteer citizen scientists to collect spiders from across PEI (Figure 1). Participants were given specific instructions via a training workshop and a field manual composed of a variety of papers and online resources (e.g., Martin 1977). The workshop described techniques for the selection of survey areas, collection and preservation of specimens, and recording and submission of field data on data cards. Specimen collection techniques consisted of pitfall trapping, sweep netting, foliage beating, aspiration, Berlese funnel extraction, and hand collecting. In total, 29 collectors (20 of whom were previously associated with Nature PEI) from across PEI contributed specimens.

Adult spiders were identified to species level by J.J.B., data-labelled, and stored in 80% ethanol in screw-cap vials with polyseal caps. A database of all specimens examined was created using Excel (Microsoft, Corp., Redmond, Washington, USA) and maintained by Nature PEI. Additional older specimens (<50) were supplied by the University of Prince Edward Island (UPEI) from beach collections and some sampling of other habitats, and are included in the Nature PEI survey. Specimens, excluding the UPEI beach specimens, have been deposited in the New Brunswick Museum in Saint John, New Brunswick (accession numbers: NBM-010790 to NBM-011349).

We compiled the list of species documented previously (i.e., Dondale and Redner 1978, 1982, 1990; Platnick and Dondale 1992; Dondale *et al.* 2003; Paquin *et al.* 2010) and, more recently by the CBG's DNA barcoding initiative (Blagoev *et al.* 2016) and CESCC (2016). We also searched (directly or via personal communication) the Canadian National Collection of Insects, Arachnids and Nematodes, New Brunswick Museum, Nova Scotia Museum of Natural History, UPEI, and Agriculture Canada collections in Charlottetown, but these yielded no additional records.

The CBG project used hand collecting, sieving, sweep netting, and trapping (Malaise, pan, pitfall, sticky) techniques at various sites along the trails of Prince Edward Island National Park, and one specimen was collected in Miscouche (Figure 1).

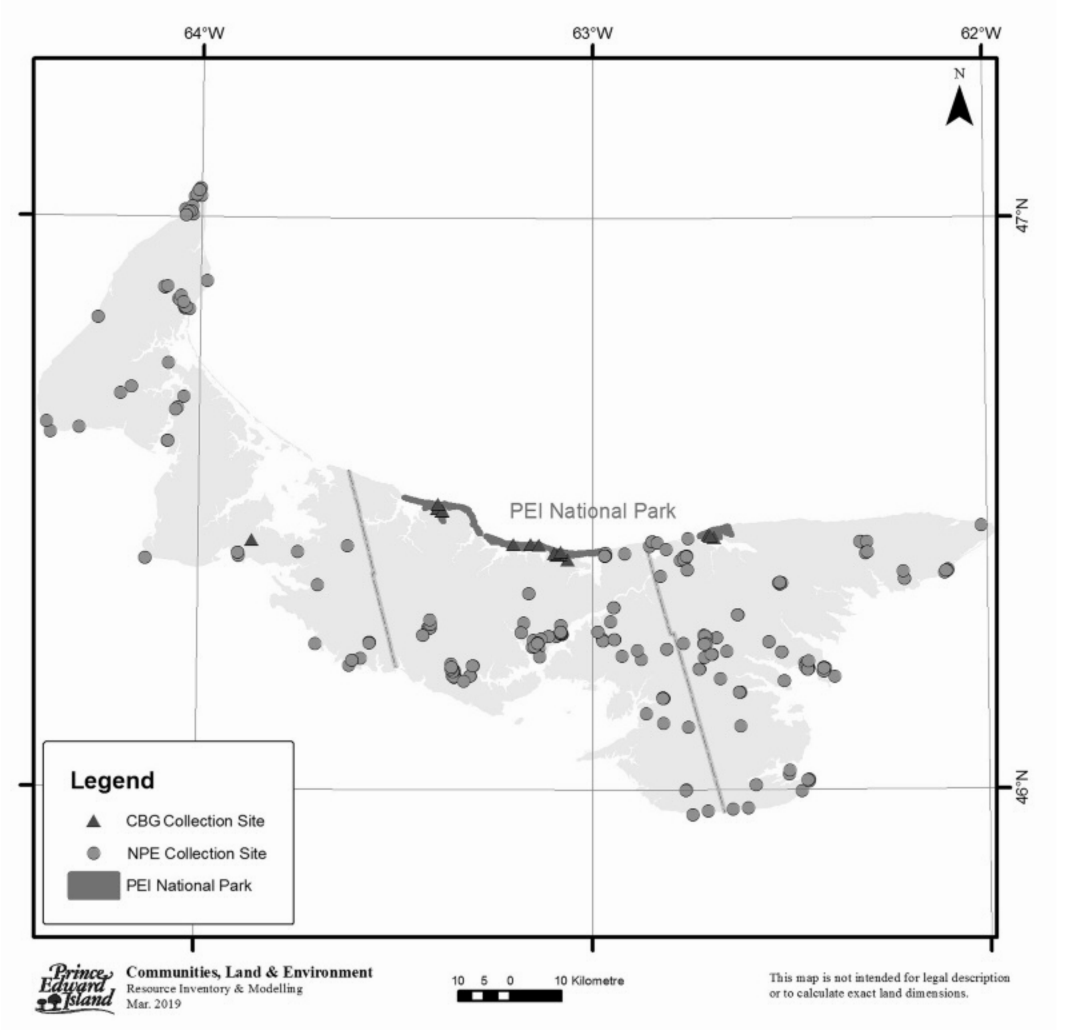

FIGURE 1. Spider collection sites on Prince Edward Island, Canada, in association with the efforts by the Centre for Biodiversity Genomics (CBG) and Nature PEI's citizen scientist campaign (NPE).

Nomenclature, specimen identification, habitat and locality data

Nomenclature follows the World Spider Catalog (2017); species are listed by family in alphabetical order. J.J.B. used various identification guides (e.g., Dondale and Redner 1978, 1990; Platnick and Dondale 1992; Dondale *et al*. 2003; Paquin and Dupérré 2003) and primary literature (e.g., Millidge 1983) to identify species and their preferred habitats. Specimens collected by the CBG were identified by G.A.B. using DNA barcoding and comparative morphology. Specimen data and photographs of barcoded specimens are available at the Barcode of Life Data System website (www.boldsystems.org; Ratnasingham and Hebert 2007).

Results

Before the CBG and Nature PEI activities, our literature, online, and museum searches yielded six other species records bringing the total to 44 species (Blagoev *et al.* 2016). More recent efforts by the CBG (G.A.B. unpubl. data) have added a further 69 new species many of which overlapped with the citizen science initiative reported here. The Nature PEI effort yielded 130 species from 737 adult specimens (over 4300 specimens collected in total). Barcode data recovered 82 species from Prince Edward Island National Park, of which 46 were new records for PEI. The complete list of spiders known to occur in PEI now comprises 198 species representing 20 families.

Some records, especially among the 44 known before Blagoev *et al.* (2016), have not been confirmed through barcoding or Nature PEI's initiative. These include Starbellied Orbweaver (*Acanthepeira stellata* (Walckenaer)), Sickle Big-headed Money Spider (*Baryphyma trifrons* (O. Pickard-Cambridge)), Autumn Money Spider (*Erigone autumnalis* Emerton), Maritime Patterned Money Spider (*Grammonota maritima* Emerton), Saxatile Thin-Legged Wolf Spider (*Pardosa saxatilis* (Hentz)), Common Pirate Wolf Spider (*Pirata piraticus* (Clerck)), and Punctate False Black Widow Spider (*Steatoda albomaculata* (De Geer)).

Nearly 10% (19 species) of the new records are non-native species. In comparison, only about 5% of all spider species recorded in Canada are introduced (Paquin *et al*. 2010; R.B. unpubl. data). Some of PEI's introduced species—e.g., Cross Orbweaver (*Araneus diadematus* Clerck), Zebra Jumping Spider (*Salticus scenicus* (Clerck)), Long-bodied Cellar Spider (*Pholcus phalangioides* (Fuesslin)), and Barn Funnelweaver (*Tegenaria domestica* (Clerck))—are cosmopolitan and synanthropic. None of the species recorded in this checklist is endemic to PEI.

Annotated list of species

Species are organized alphabetically by family, genera, and species. Data sources for physical specimens are indicated by NPE (Nature PEI), CBG (Centre for Biodviersity Genomics), or CNC (Canadian National Collection of Insects, Arachnids and Nematodes), with the NPE records solely due to NPE citizen scientist effort; otherwise literature records are indicated by reference (e.g., Dondale *et al.* 2003). Counties are indicated in bold followed by specific collection localities. Original 44 species (before NPE or CBG, i.e., 2015) are indicated as *. Probable records (R.B. pers. obs., cannot locate record) are indicated as † but not included in totals. Common names are from CESCC (2016). If the species is introduced, the origin is indicated; if native, the global range is stated (World Spider Catelog 2018).

AGELENIDAE (4 species)

Agelenopsis potteri (Blackwall, 1846) Nearctic
Common Grass Funnelweaver

Prince: Augustine Cove, Central Kildare, St. Nicholas, Norway; **Queens:** Bonshaw, Cavendish; Charlottetown, Dalvay, Marshfield St. Catherines, Orwell Cove; **Kings:** Abney, Brudenell, Cherry Island; Savage Harbour, Summerville
Habitat: Gardens, fields, and open forest, common around human dwellings
Data source: CBG, NPE

Agelenopsis utahana (Chamberlin & Ivie, 1933)
Northern Grass Funnelweaver Nearctic

Prince: Central Kildare; **Queens:** Brookvale, Charlottetown, Dalvay, Donagh, Wood Islands; **Kings:** Brudenell, Forest Hill, Launching
Habitat: Gardens, fields, and open forest, common around human dwellings
Data source: CBG, NPE

Coras montanus (Emerton, 1890) Nearctic
Northern Spurred Woodland Spider

Prince: Augustine Cove
Habitat: Litter of mixed coniferous forest; under bark; in crevices between rocks
Data source: NPE

Tegenaria domestica (Clerck, 1758) Palearctic
Barn Funnelweaver (introduced)

Prince: North Tryon; **Queens:** Charlottetown, St. Catherines; **Kings:** Summerville
Habitat: Cool, dark, humid areas such as basements and sheds
Data source: NPE

AMAUROBIIDAE (2 species)

Callobius bennetti (Blackwall, 1846) Nearctic
Eastern Laceweaver

Kings: Greenwich
Habitat: Litter of mixed coniferous forest; under (shoreside) stones
Data source: CBG

Cybaeopsis euopla (Bishop & Crosby, 1935) Nearctic
Common Spined Laceweaver

Queens: Dalvay; **Kings:** Launching
Habitat: Litter of mixed coniferous forest
Data source: CBG, NPE

ARANEIDAE (22 species)

**Acanthepeira stellata* (Walckenaer, 1805)
Starbellied Orbweaver Nearctic

Unknown collection locality
Habitat: Deciduous trees and shrubs, in forage crops, and in tall grass and weeds
Data source: Dondale *et al.* 2003

Araneus corticarius (Emerton, 1884) Nearctic
Humped Bog Orbweaver

Prince: Portage; **Queens:** Marshfield; **Kings:** Launching
Habitat: Bogs and swamps
Data source: NPE

Araneus diadematus Clerck, 1757 Palearctic
Cross Orbweaver (introduced)

Prince: North Tryon; **Queens:** Bonshaw, Cavendish, Charlottetown, St. Catherines, Donagh; **Kings:** Georgetown Royalty, Summerville, Launching, High Bank, Thomas Island, West St. Peters
Habitat: Widespread, particularly common around human-made structures and gardens
Data source: CBG, NPE

Araneus groenlandicola (Strand, 1906) Nearctic
Northern Bog Orbweaver

Queens: Blooming Point
Habitat: Bogs, low shrubs, stunted trees
Data source: NPE

**Araneus marmoreus* Clerck, 1758 Holarctic
Marbled Orbweaver

Prince: Central Kildare, Freeland, North Tryon; **Queens:** Donagh, Glenfinnan, Marshfield; **Kings:** Launching
Habitat: Tall grasses/shrubs in marshes, sometimes moist open forest areas
Data source: Dondale *et al*. 2003, NPE

Araneus nordmanni (Thorell, 1870) Holarctic
Normann's Orbweaver

Queens: Bonshaw, Cavendish, Dalvay; **Kings:** Brudenell, Summerville
Habitat: Mixed coniferous forest; trees and tall shrubs near forest
Data source: CBG, NPE

**Araneus saevus* (L. Koch, 1872) Holarctic
Common Orbweaver

Queens: Bonshaw
Habitat: Trunks and lower branches of trees, mixed coniferous forest
Data source: Dondale *et al*. 2003, NPE

Araneus trifolium (Hentz, 1847) Nearctic
Shamrock Orbweaver

Queens: Blooming Point, Dalvay, Donagh; **Kings:** Greenwich, High Bank, Launching, Summerville, West St. Peters
Habitat: Tall shrubs and herbs
Data source: CBG, NPE

**Araniella displicata* (Hentz, 1847) Holarctic
Six-spotted Yellow Orbweaver

Queens: Cavendish, Dalvay; **Kings:** Greenwich, New Perth, Summerville
Habitat: Shrubs and herbs, deciduous trees, sometimes in conifers
Data source: Dondale *et al*. 2003, CBG, NPE

**Argiope aurantia* Lucas, 1833 Nearctic
Yellow Garden Orbweaver
Queens: Cavendish, Charlottetown, Donagh, Orwell Cove; **Kings:** St. Catherines, Summerville
Habitat: Open areas e.g., gardens, meadows, old fields, shrubs, tall grasses
Data source: CBG, NPE

**Argiope trifasciata* (Forsskål, 1775) Nearctic
Banded Garden Orbweaver

Prince: Central Kildare, North Cape, Norway, St. Nicholas; **Queens:** Blooming Point, Cavendish, Charlottetown, Donagh, Grandview; **Kings:** Summerville, West St. Peters
Habitat: Open areas e.g., gardens, meadows, old fields, shrubs, tall grasses
Data source: CBG, NPE

Cyclosa conica (Pallas, 1772) Holarctic
Common Trashline Orbweaver

Prince: Augustine Cove; **Queens:** Cavendish, Dalvay
Habitat: Shrubs and trees, mixed coniferous forest
Data source: CBG, NPE

Eustala cepina (Walckenaer, 1841) Nearctic
Riparian Duncecap Orbweaver

Kings: Greenwich
Habitat: Grassland, marshes, dune plants, roadside weeds, and garden crops
Data source: CBG

Eustala emertoni (Banks, 1904) Nearctic
no common name

Queens: Dalvay
Habitat: Fields, open forests, and marshes
Data source: CBG

Eustala rosae Chamberlin & Ivie, 1935 Nearctic
no common name

Queens: Dalvay
Habitat: Fields, open forests, and marshes
Data source: CBG

**Hypsosinga pygmaea* (Sundevall, 1831) Holarctic
Common Dark-eyed Orbweaver

Queens: Blooming Point, Covehead; **Kings:** Greenwich
Habitat: Wet meadows, shrubs and herbs of forest edges and roadsides
Data source: Dondale *et al.* 2003, CBG, NPE

Hypsosinga rubens (Hentz, 1847) Nearctic
Forest Dark-eyed Orbweaver

Kings: Head of Cardigan
Habitat: Shrubs and herbs in forests, leaf litter and loose bark
Data source: NPE

**Larinioides cornutus* (Clerck, 1758) Holarctic
Furrow Orbweaver

Prince: North Tryon, Coleman, Norway; **Queens:** Bonshaw, Brookvale, Cavendish, Covehead, Dalvay, Donagh, Kellys Cross; **Kings:** Forest Hill, Head of Cardigan, Milltown Cross, Savage Harbour, Summerville

Habitat: Common on human-made structures (e.g., fences, buildings), hedges, and shrubs
Data source: CBG, NPE

Larinioides patagiatus (Clerck, 1758) Holarctic
Ornamental Orbweaver

Queens: Dalvay
Habitat: Common on human-made structures (e.g., fences, buildings), hedges, and shrubs, particularly near coniferous forest
Data source: CBG

Mangora placida (Hentz, 1847) Nearctic
Tuft-legged Orbweaver

Queens: Brackley Beach, Cavendish, **Kings:** Head of Cardigan
Habitat: Undergrowth of deciduous forests, but may also be found in tall grass
Data source: CBG, NPE

**Neoscona arabesca* (Walckenaer, 1841) Nearctic
Arabesque Orbweaver

Prince: Augustine Cove, Central Kildare; **Queens:** Blooming Point, Bonshaw, Covehead, Dalvay, Glenfinnan, Lake Verde, Marshfield, Mount Albion, South Melville, Wood Islands; **Kings:** Abney, Corraville, Forest Hill, Greenwich, High Bank, Launching, Little Sands, New Perth, Savage Harbour, St. Peters Harbour, Summerville
Habitat: Tall weeds and grasses
Data source: Dondale *et al.* 2003, CBG, NPE

**Zygiella atrica* (C.L. Koch, 1845) Palearctic
Red-sided Sector Spider (introduced)

Prince: Norway, North Tryon; **Queens:** Cavendish, Charlottetown, Covehead, Bonshaw, Donagh; **Kings:** Brudenell, Greenwich, Head of Cardigan, Launching, Savage Harbour, St. Catherines, Summerville
Habitat: Heath plants and boulders along coastlines, also on human-made structures (e.g., fences, barns, windows)
Data source: Dondale *et al.* 2003, CBG, NPE

CLUBIONIDAE (13 species)
Clubiona abboti Koch, 1866 Nearctic
Abbot's Sac Spider

Queens: Brackley Beach, Covehead, Dalvay; **Kings:** Summerville
Habitat: Litter of forests and meadows, under stones, in bogs/wetlands
Data source: CBG, NPE

Clubiona bryantae Gertsch, 1941 Nearctic
Bryant's Sac Spider

Queens: Covehead; **Kings:** Corraville
Habitat: Litter from meadows, forest edges, litter from spruce-fir forests, herbaceous vegetation in bogs/swamps
Data source: CBG, NPE

**Clubiona canadensis* Emerton, 1890 Nearctic
Canada Harpoon Sac Spider

Prince: Norway; **Queens:** Bonshaw, Brackley Beach, Cavendish, Dalvay; **Kings:** Greenwich, Savage Harbour, Woodville Mills
Habitat: Trees and shrubs, under loose bark, under stones, in leaf litter and moss
Data source: Dondale and Redner 1982, CBG, NPE

Clubiona johnsoni Gertsch, 1941 Nearctic
Johnson's Sac Spider

Queens: Brackley Beach, Covehead
Habitat: On the ground of meadows, bogs, and forests, and from shrubs and beach litter
Data source: CBG

Clubiona kastoni Gertsch, 1941 Nearctic
Kaston's Sac Spider

Queens: Covehead
Habitat: Forest litter, on beaches and sand dunes, or on bogs
Data source: CBG

Clubiona kiowa Gertsch, 1941 Nearctic
Kiowa Sac Spider

Queens: Covehead
Habitat: Plant litter in marshes
Data source: CBG

Clubiona moesta Banks, 1896 Holarctic
Mournful Sac Spider

Queens: Dalvay
Habitat: Branches of trees, under loose bark, in hayfields
Data source: CBG

Clubiona norvegica Strand, 1900 Holarctic
Norway Harpoon Sac Spider

Prince: Norway; **Queens:** Covehead
Habitat: In sphagnum bogs, beach grasses, and salt marshes, on buildings, rocky lake shores, at the margins of prairie sloughs, occasionally in foliage
Data source: CBG, NPE

Clubiona obesa Hentz, 1847 Nearctic
Trilobed Sac Spider

Queens: Cavendish
Habitat: Low-growing shrubs in deciduous forests, on trunks, and in tall grasses
Data source: CBG

Clubiona pallidula (Clerck, 1757) Palearctic (introduced)
European Sac Spider

Queens: Cavendish
Habitat: On shrubs, herbs, under bark
Data source: CBG

Clubiona quebecana Dondale & Redner, 1976
Quebec Sac Spider Nearctic

Queens: Dalvay
Habitat: Trunks and larger branches of deciduous trees such as oaks
Data source: CBG

**Clubiona riparia* L. Koch, 1866 Holarctic
Riparian Sac Spider

Prince: Coleman; **Queens:** Blooming Point, Charlottetown; **Kings:** St. Catherines, Summerville
Habitat: In tall grass in marshes and near sloughs and lakes, mixed forest on the ground
Data source: Dondale and Redner 1982, NPE

Clubiona trivialis C.L. Koch, 1843 Holarctic
Conifer Sac Spider

Queens: Marshfield; **Kings:** Launching, Savage Harbour, St. Catherines, Thomas Island
Habitat: Spruce, fir, and pine foliage, sphagnum bogs, low deciduous shrubs, and loose bark, stones, and leaf litter in mixed forests
Data source: NPE

DICTYNIDAE (9 species)
**Argenna obesa* Emerton, 1911 Nearctic
Short-eared Meshweaver

Queens: Covehead, Cavendish
Habitat: Wetland, river banks, moist forest clearings
Data source: CBG

Cicurina brevis (Emerton, 1890) Nearctic
Small-eared Meshweaver

Queens: Brackley Beach; **Kings:** Launching, Greenwich
Habitat: Mostly in forest, but also fields under rocks and in rotten logs, in litter
Data source: CBG, NPE

Dictyna bostoniensis Emerton, 1888 Nearctic
Boston Thread Meshweaver

Queens: Covehead
Habitat: Mixed forest; shrubs and herbs
Data source: CBG

Dictyna brevitarsa Emerton, 1915 Nearctic
Short-heeled Thread Meshweaver

Queens: Dalvay; **Kings:** Greenwich
Habitat: Mixed coniferous forest; shrubs and herbs
Data source: CBG

Dictyna volucripes Keyserling, 1881 Nearctic
Truncated Thread Meshweaver

Prince: North Cape, Norway; **Queens:** Brackley Beach
Habitat: Shrubs and vegetation in open fields, potentially forest clearings
Data source: CBG, NPE

Emblyna annulipes (Blackwall, 1846) Holarctic
Common Ribbon Meshweaver

Prince: West Point; **Queens:** Dalvay
Habitat: Mixed forest litter, on low vegetation and trees
Data source: CBG, NPE

Emblyna manitoba (Ivie, 1947) Nearctic
Manitoba Ribbon Meshweaver

Queens: Covehead
Habitat: Mixed forest, low vegetation
Data source: CBG

Emblyna phylax (Gertsch & Ivie, 1936) Nearctic
Grooved Ribbon Meshweaver

Queens: Bonshaw; **Kings:** Greenwich
Habitat: Mixed forest, litter, and low vegetation
Data source: CBG, NPE

Emblyna sublata (Hentz, 1850) Nearctic
Wide Ribbon Meshweaver

Kings: Summerville, Head of Cardigan
Habitat: Vegetation in fields, shrubs, apple orchards on trees
Data source: NPE

GNAPHOSIDAE (4 species)
**Gnaphosa parvula* Banks, 1896 Nearctic
Slender Ground Spider

Kings: Corraville
Habitat: Under stones, boards, and beach debris, in meadows and bogs
Data source: Platnick and Dondale 1992, NPE

**Herpyllus ecclesiasticus* Hentz, 1832 Nearctic
Parson Ground Spider

Queens: Dalvay; **Kings:** Summerville
Habitat: In buildings and under logs and stones, but also associated with deciduous trees, pine, and pitcher plants
Data source: CBG, NPE

Micaria pulicaria (Sundevall, 1831) Holarctic
Iridescent Antmimic Ground Spider

Queens: Donagh
Habitat: Fields, meadows, deciduous and mixed forests, bogs, and fens; on beaches and salt marshes; and in buildings
Data source: NPE

**Zelotes fratris* Chamberlin, 1920 Holarctic
Common Preening Ground Spider

Queens: Covehead, Dalvay, Marshfield, Savage Harbour
Habitat: In litter of deciduous and coniferous forest, orchards, meadows, and in salt- and freshwater marshes
Data source: Platnick and Dondale 1992, CBG, NPE

HAHNIIDAE (4 species)
Antistea brunnea (Emerton, 1909) Nearctic
Brown Comb-tailed Spider

Kings: Launching, New Zealand
Habitat: Wet areas in mixed forest
Data source: NPE

Cryphoeca montana Emerton, 1909 Nearctic
Mountain Comb-tailed Spider

Queens: Dalvay
Habitat: Mixed coniferous forest; under bark; shrubs
Data source: CBG

Neoantistea gosiuta Gertsch, 1934 Nearctic
Goshute Comb-tailed Spider

Queens: Dalvay
Habitat: Mixed coniferous forest
Data source: CBG

Neoantistea magna (Keyserling, 1887) Nearctic
Thick-hooked Comb-tailed Spider

Queens: Bonshaw, Dalvay; **Kings:** New Zealand
Habitat: Mixed coniferous woods; back of beaches; bogs.
Data source: CBG, NPE

LINYPHIIDAE (55 species)
Agyneta fabra (Keyserling, 1886) Nearctic
Double-knobbed Short-legged Sheetweaver

Queens: Cavendish, Dalvay
Habitat: Mixed forest litter
Data source: CBG

Agyneta unimaculata (Banks, 1892) Nearctic
One-spotted Short-legged Sheetweaver

Queens: Brackley Beach
Habitat: Mixed forest litter
Data source: CBG

Allomengea dentisetis (Grube, 1861) Holarctic
Toothed Tuft-horned Sheetweaver

Prince/Queens: Malpeque Bay
Habitat: Coastal barrens and near ponds on ground/low vegetation
Data source: CNC

**Baryphyma trifrons* (O. Pickard-Cambridge, 1863)
Sickle Big-headed Money Spider Holarctic

Locality unavailable
Habitat: Low shrubs and litter, damp habitats
Data source: Unavailable

Bathyphantes canadensis (Emerton, 1882)
Canada Shield Sheetweaver Holarctic

Prince: Central Kildare
Habitat: Mixed forest litter
Data source: NPE

Centromerus denticulatus (Emerton, 1909) Nearctic
Toothy Spurred Sheetweaver

Queens: Dalvay
Habitat: Mixed forest litter
Data source: CBG

Centromerus persolutus (O. Pickard-Cambridge, 1875)
Thin-faced Spurred Sheetweaver Nearctic

Queens: Dalvay
Habitat: Mixed forest litter
Data source: CBG

Centromerus sylvaticus (Blackwall, 1841) Holarctic
Common Spurred Sheetweaver

Kings: Greenwich
Habitat: Mixed forest litter
Data source: CBG

Ceraticelus bulbosus (Emerton, 1882) Holarctic
Hump-eyed Armoured Money Spider

Queens: Bonshaw
Habitat: Mixed forest, grass, and litter
Data source: NPE

Ceraticelus emertoni (O. Pickard-Cambridge, 1874)
Emerton's Armoured Money Spider Nearctic

Kings: St. Catherines
Habitat: Crop fields, coastal grasslands
Data source: NPE

Ceraticelus fissiceps (O. Pickard-Cambridge, 1874)
Bicolored Armoured Money Spider Nearctic

Prince: Augustine Cove, Central Kildare; **Queens:** Bonshaw, Charlottetown; **Kings:** Forest Hill, Kingsboro, Launching, Lorne Valley
Habitat: Mixed forest litter and low shrubs
Data source: NPE

Ceraticelus similis (Banks, 1892) Nearctic
Broad Armoured Money Spider

Queens: Cavendish, Dalvay
Habitat: Mixed forest litter and low shrubs
Data source: CBG

Ceratinella brunnea Emerton, 1882 Nearctic
Brown Waxed Money Spider

Queens: Bonshaw, Cavendish, Dalvay, Kellys Cross; **Kings:** Greenwich, New Zealand
Habitat: Mixed forest and adjacent grasslands, low shrubs
Data source: CBG, NPE

Ceratinopsis nigriceps Emerton, 1882 Nearctic
Stump-armed Arboreal Money Spider

Queens: Kellys Cross; **Kings:** Cardigan, Kingsboro, Launching, Summerville
Habitat: Mixed forest
Data source: NPE

Collinsia plumosa (Emerton, 1882) Nearctic
Feathered Money Spider

Queens: Dalvay; **Kings:** East Lake, Greenwich
Habitat: Mixed forest, low bushes and ground
Data source: CBG, NPE

Diplocephalus subrostratus (O. Pickard-Cambridge, 1873)
Common Muppet Money Spider Holarctic

Queens: Brackley Beach, Cavendish
Habitat: Mixed forest, meadows
Data source: CBG

**Diplostyla concolor* (Wider, 1834) Holarctic
Long-spined Sheetweaver

Queens: Brackley Beach, Cavendish, Orwell; **Kings:** Greenwich, Launching, Savage Harbour
Habitat: Mixed forest, low shrubs and bushes, beaches, gardens, cultivated lands
Data source: CBG, NPE

Drapetisca alteranda Chamberlin, 1909 Nearctic
Northern Long-toothed Sheetweaver

Queens: Bonshaw, Dalvay
Habitat: Mixed forest
Data source: CBG, NPE

Erigone aletris Crosby & Bishop, 1928 Holarctic
Common Money Spider

Prince: North Tryon; **Queens:** Cavendish, Charlottetown; **Kings:** Greenwich, Kingsboro
Habitat: Mixed forest, bogs, litter, stones and low herbs near beaches
Data source: CBG, NPE

Erigone arctica (White, 1852) Holarctic
Circumpolar Money Spider

Prince: Miscouche
Habitat: Moist open habitats e.g., heathlands
Data source: CBG

**Erigone autumnalis* Emerton, 1882 Holarctic
Autumn Money Spider
Locality unavailable
Habitat: Fields
Data source: Unavailable

Erigone blaesa Crosby & Bishop, 1928 Nearctic
Faltering Money Spider

Queens: Cavendish; **Kings:** Cherry Island
Habitat: Litter near fresh and saltwater beaches/shores, sand dunes
Data source: NPE

**Erigone dentipalpis* (Wider, 1834) Palearctic
Toothed-palped Money Spider (introduced)

Kings: Head of Cardigan, Summerville
Habitat: Coastal barrens, mixed forest, gardens
Data source: NPE

**Grammonota angusta* Dondale, 1959 Nearctic
Slender Patterned Money Spider

Prince: Augustine Cove, Miscouche, Norway; **Queens:** Bonshaw, Cavendish, Charlottetown, Dalvay, Kellys Cross; **Kings:** Kingsboro, Launching, New Perth, Summerville, Thomas Island
Habitat: Mixed forest, low vegetation, gardens
Data source: CBG, NPE

Grammonota gentilis Banks, 1898 Nearctic
Kinsman Patterned Money Spider

Prince: Miscouche; **Queens:** Cavendish, Dalvay; **Kings:** Summerville
Habitat: Mixed forest
Data source: CBG, NPE

**Grammonota maritima* Emerton, 1925 Nearctic
Maritime Patterned Money Spider
Locality unavailable
Habitat: Coastal barrens
Data source: Unavailable/specimen record unverifiable

Grammonota pictilis (O. Pickard-Cambridge, 1875)
Painted Patterned Money Spider Nearctic

Queens: Brackley Beach, Cavendish, Dalvay
Habitat: Coniferous foliage
Data source: CBG

Grammonota vittata Barrows, 1919 Nearctic
Banded Patterned Money Spider

Queens: Glenfinnan
Habitat: Low vegetation, especially near bogs
Data source: NPE

Hypomma marxi (Keyserling, 1886) Nearctic
Marx's Under-eyed Money Spider

Kings: Lorne Valley
Habitat: Bogs/marshes
Data source: NPE

Hypselistes florens (O. Pickard-Cambridge, 1875)
Splendid Money Spider Nearctic

Prince: Portage; **Queens:** Covehead, Dalvay, Marshfield, Mount Albion; **Kings:** Greenwich, Head of Cardigan, Launching, New Perth
Habitat: Mixed coniferous forest
Data source: CBG, NPE

†*Improphantes complicatus* (Emerton, 1882) Holarctic
Folded Sheetweaver

Common in surrounding provinces
Habitat: Mixed coniferous forest, coastal barrens
Data source: Unavailable

Kaestneria pullata (O. Pickard-Cambridge, 1863)
Dark Sheetweaver Holarctic

Prince: Portage; **Queens:** Dalvay
Habitat: Shrubs and herbs in and near mixed forest
Data source: CBG, NPE

Lepthyphantes alpinus (Emerton, 1882) Holarctic
Alpine Fine Sheetweaver

Queens: Dalvay
Habitat: Mixed coniferous forest
Data source: CBG

Lepthyphantes leprosus (Ohlert, 1865) Palearctic
Household Fine Sheetweaver (introduced)

Queens: St. Catherines
Habitat: Mixed coniferous forest, buildings
Data source: NPE

Lepthyphantes turbatrix (O. Pickard-Cambridge, 1877)
Disruptive Fine Sheetweaver Nearctic

Queens: Dalvay; **Kings:** Greenwich
Habitat: Mixed forest, stones near beaches
Data source: CBG

Mermessus trilobatus (Emerton, 1882) Holarctic
Common Harvester Money Spider

Queens: Covehead, Donagh
Habitat: Mixed forest, coastal barrens
Data source: CBG, NPE

Mermessus undulatus (Emerton, 1914) Nearctic
Undulating Harvester Money Spider

Queens: Dalvay; **Kings:** Corraville
Habitat: Mixed forest, coastal barrens
Data source: CBG, NPE

Microlinyphia pusilla (Sundevall, 1830) Holarctic
Lesser Platform Sheetweaver

Queens: Donagh; **Kings:** Savage Harbour, Summerville
Habitat: Low vegetation in heathlands, dunes, saltmarshes
Data source: NPE

Microneta viaria (Blackwall, 1841) Holarctic
Roadside Sheetweaver

Queens: Dalvay
Habitat: Mixed forest
Data source: CBG

Neriene clathrata (Sundevall, 1830) Holarctic
Latticed Dome Sheetweaver

Queens: Brackley Beach; **Kings:** Summerville
Habitat: Mixed forest, meadows, shrubs
Data source: CBG, NPE

Neriene montana (Clerck, 1757) Palearctic
Old World Dome Sheetweaver (introduced)

Queens: Cavendish
Habitat: Low vegetation and shrubs in mixed forest
Data source: CBG

Neriene radiata (Walckenaer, 1841) Holarctic
Filmy Dome Sheetweaver

Queens: Dalvay; **Kings:** Forest Hill
Habitat: Shrubs and tree foliage in mixed forest
Data source: CBG, NPE

Oreonetides rotundus (Emerton, 1913) Nearctic
Rounded Sheetweaver

Queens: Kellys Cross
Habitat: Bogs and similar moist habitats
Data source: NPE

Phlattothrata flagellata (Emerton, 1911) Nearctic
Whipped Blahblah Money Spider

Queens: Cavendish, Dalvay, Kellys Cross
Habitat: Low foliage and litter of mixed forest
Data source: CBG, NPE

Pityohyphantes costatus (Hentz, 1850) Nearctic
Common Hammock Sheetweaver

Kings: Launching
Habitat: Mixed coniferous forest
Data source: NPE

Pocadicnemis americana Millidge, 1976 Nearctic
American Hairy-legged Money Spider

Queens: Dalvay; **Kings:** Greenwich
Habitat: Mixed coniferous forest litter
Data source: CBG

Poeciloneta calcaratus (Emerton, 1909) Nearctic
Spurred Variegated Sheetweaver

Prince: Augustine Cove; **Queens:** Bonshaw, Dalvay; **Kings:** Launching
Habitat: Mixed coniferous forest litter, beach and shrub litter
Data source: CBG, NPE

Porrhomma terrestre (Emerton, 1882) Nearctic
Terrestrial Wide-eyed Sheetweaver

Queens: Covehead
Habitat: Mixed coniferous forest
Data source: CBG

Sciastes truncatus (Emerton, 1882) Nearctic
Short-armed Money Spider

Queens: Dalvay
Habitat: Mixed coniferous forest, understorey, and litter
Data source: CBG

Scylaceus pallidus (Emerton, 1882) Nearctic
Blemish Money Spider

Queens: Dalvay
Habitat: Mixed coniferous forest, especially on ground in mosses
Data source: CBG

Soulgas corticarius (Emerton, 1909) Nearctic
Coathook Money Spider

Prince: Central Kildare; **Queens:** Covehead, Dalvay
Habitat: Mixed coniferous forest litter and coastal areas
Data source: CBG, NPE

Wabasso quaestio (Chamberlin, 1949) Nearctic
Short-tongued Money Spider

Kings: Kingsboro
Habitat: Mixed coniferous forest, moist open areas, coastal barrens
Data source: NPE

Walckenaeria communis (Emerton, 1882) Nearctic
Common Erudite Money Spider

Queens: Dalvay; **Kings:** Corraville, Launching
Habitat: In moss and moist litter in mixed coniferous forest, bogs, pond and lake shores
Data source: CBG, NPE

Walckenaeria exigua Millidge, 1983 Nearctic
Small Horned Erudite Money Spider

Queens: Dalvay
Habitat: In moss and moist litter in mixed coniferous forest, bogs, shrub areas
Data source: CBG

Walckenaeria lepida (Kulczyński, 1885) Holarctic
Pleasant Erudite Money Spider

Queens: Charlottetown, Dalvay, Kellys Cross; **Kings:** Launching
Habitat: Mixed forest or shrub litter
Data source: CBG, NPE

Walckenaeria pinocchio (Kaston, 1945) Nearctic
Pinocchio Erudite Money Spider

Queens: Dalvay
Habitat: Mixed coniferous forest
Data source: CBG

LIOCRANIDAE (1 species)
Agroeca ornata Banks, 1892 Nearctic
Ornated Spiny-legged Spider

Prince: Central Kildare; **Queens:** Dalvay; **Kings:** Greenwich, Launching
Habitat: Ground litter or decaying logs in mixed forests, and on the ground in pastures, meadows, marshes, sphagnum bogs, mosses, and lichens
Data source: CBG, NPE

LYCOSIDAE (12 species)
Alopecosa aculeata Charitonov 1931 Holarctic
Pointed Wolf Spider

Prince: North Tryon; **Queens:** Marshfield
Habitat: Sunlit forest glades and shrubby meadows
Data source: NPE

**Arctosa littoralis* (Hentz, 1844) Nearctic
Shoreline Wolf Spider

Kings: Greenwich, Launching
Habitat: Sandy beaches of both fresh- and salt-water
Data source: Dondale and Redner 1990, NPE

Gladicosa gulosa (Walckenaer, 1837) Nearctic
Drumming Sword Wolf Spider

Kings: Summerville
Habitat: Open deciduous forest
Data source: NPE

Pardosa fuscula (Thorell, 1875) Nearctic
Brown Thin-legged Wolf Spider

Kings: Abney, Corraville
Habitat: Moist habitats, mainly fresh and salt marshes, bogs, and meadows, occasionally coniferous forest
Data source: NPE

**Pardosa moesta* Banks, 1892 Nearctic
Shiny Thin-legged Wolf Spider

Queens: Covehead, Brackley Beach; **Kings:** Abney, Corraville, Launching, Greenwich
Habitat: Meadows, hayfields, marshes, bogs, open forest, and urban lawns
Data source: Dondale and Redner 1990, CBG, NPE

**Pardosa saxatilis* (Hentz, 1844) Nearctic
Saxatile Thin-legged Wolf Spider

Collection locality not listed in source
Habitat: Grassy fields and meadows, but also found in marshes, bogs, deciduous woods, and sandy beaches
Data source: Dondale and Redner 1990

Pardosa xerampelina (Keyserling, 1877) Nearctic
Ubiquitous Thin-legged Wolf Spider

Prince: Central Kildare
Habitat: Short grass, among herbs along streams, in dry stony river beds and lakeshores, in cultivated fields, along roadsides, in open forests
Data source: NPE

**Pirata piraticus* (Clerck, 1757) Holarctic
Common Pirate Wolf Spider

Collection locality not listed in source
Habitat: Marshes (fresh and salt), swamps, bogs, and shores of lakes and streams
Data source: Dondale and Redner 1990

Piratula cantralli (Wallace & Exline, 1978) Nearctic
Cantrall's Pirate Wolf Spider

Queens: Glenfinnan, Dalvay; **Kings:** Corraville
Habitat: Marshes
Data source: CBG, NPE

Piratula minuta (Emerton, 1885) Nearctic
Small Pirate Wolf Spider

Queens: Dalvay
Habitat: Meadows, hayfields, marshes, swamps, and bogs
Data source: CBG

Trochosa ruricola (De Geer, 1778) Holarctic
Eurasian Litter Wolf Spider (introduced)

Queens: Cavendish, Covehead, Dalvay, Harrington; **Kings:** Savage Harbour, Summerville
Habitat: Forest, scrub, grasslands, lawns
Data source: CBG, NPE

**Trochosa terricola* Thorell, 1856 Holarctic
Common Litter Wolf Spider

Prince: Cap Egmont; **Queens:** Harrington, Dalvay, Charlottetown
Habitat: Forest, grasslands, heathlands, under stones and logs
Data source: Dondale and Redner 1990, CBG, NPE

PHILODROMIDAE (11 species)
**Philodromus cespitum* (Walckenaer, 1802)
Common Running Crab Spider Holarctic

Queens: Covehead, Dalvay, Donagh
Habitat: On grasses, shrubs, and trees
Data source: Dondale and Redner 1978, CBG, NPE

Philodromus histrio (Latreille, 1819) Holarctic
Attractive Running Crab Spider

Kings: Greenwich
Habitat: On sagebrush in the west and on heath plants, weeds, and tall grasses
Data source: CBG

Philodromus oneida Levi, 1951 Nearctic
Oneida Running Crab Spider

Queens: Dalvay
Habitat: Foliage of various trees
Data source: CBG

Philodromus peninsulanus Gertsch, 1934 Nearctic
Peninsular Running Crab Spider

Queens: Dalvay
Habitat: Openings in mixed coniferous forest
Data source: CBG

**Philodromus placidus* Banks, 1892 Nearctic
Conifer Running Crab Spider

Kings: Launching
Habitat: Foliage of conifers
Data source: Dondale and Redner 1978, NPE

Philodromus praelustris Keyserling, 1880 Nearctic
Resplendant Running Crab Spider

Queens: Brackley Beach, Dalvay; **Kings:** Head of Cardigan
Habitat: Tree trunks and branches, and on wooden fences and buildings
Data source: CBG, NPE

Philodromus rufus Dondale, 1964 Nearctic
White-striped Running Crab Spider

Prince: Augustine Cove, Central Kildare, Norway; **Queens:** Brackley Beach, Cavendish, Covehead, Dalvay, Marshfield; **Kings:** Cardigan, Launching, New Perth, Summerville
Habitat: Foliage of coniferous and deciduous trees and shrubs
Data source: CBG, NPE

Thanatus formicinus (Clerck, 1757) Holarctic
Ant Running Crab Spider

Kings: West St. Peters
Habitat: Mixed coniferous forest, under stones, and in grasses and low shrubs in meadows or orchards
Data source: NPE

Thanatus striatus C.L. Koch, 1845 Holarctic
Hairy Running Crab Spider

Queens: Brackley Beach
Habitat: Grassland litter and low vegetation
Data source: CBG

Tibellus maritimus (Menge, 1875) Holarctic
Grooved Running Crab Spider

Queens: Brackley Point; **Kings:** Greenwich
Habitat: Tall grass
Data source: CBG

Tibellus oblongus (Walckenaer, 1802) Holarctic
Slender Running Crab Spider

Prince: North Cape; **Queens:** Blooming Point, Grandview, South Melville; **Kings:** Head of Cardigan, Summerville
Habitat: Tall grass
Data source: NPE

PHOLCIDAE (1 species)
Pholcus phalangioides (Fuesslin, 1775) Palearctic
Long-bodied Cellar Spider (introduced)

Prince: North Tryon; **Queens:** Donagh; **Kings:** Brudenell, Head of Cardigan, Summerville
Habitat: In houses and other buildings
Data source: NPE

PHRUROLITHIDAE (2 species)
Phrurotimpus borealis (Emerton, 1911) Nearctic
Greater Antmimic Corinne Spider

Queens: Brackley Beach, Cavendish; **Kings:** Greenwich
Habitat: Leaf litter of coniferous or deciduous forest, prairies, bogs, swamps, and meadows, on rocky hillsides, and under stones and beach debris
Data source: CBG

Scotinella minnetonka (Chamberlin & Gertsch, 1930)
Midwestern Antmimic Corinne Spider Nearctic

Kings: Greenwich
Habitat: On ground in pastures, meadows, swamps, deciduous forests, under stones
Data source: CBG

PISAURIDAE (1 species)
**Dolomedes triton* (Walckenaer, 1837) Nearctic
Six-spotted Fishing Spider

Queens: Dalvay; **Prince:** Huntley, Gordon's Pond, MacNeill's Mills; **Queens:** Brackley Beach, Cavendish; **Kings:** Head of Cardigan, Forest Hill
Habitat: At the margins of ponds, lakes, and the quiet parts of rivers and streams
Data source: Knysh and Giberson 2012, CBG, NPE

SALTICIDAE (10 species)
Eris militaris (Hentz, 1845) Nearctic
Bronze Jumping Spider

Prince: Central Kildare, Portage, St. Nicholas, Norway, Coleman; **Queens:** Avondale, Cavendish, Bonshaw, Blooming Point, Dalvay, Charlottetown, Covehead, Marshfield; **Kings:** Abney, Brudenell, Greenwich, Head of Cardigan, Forest Hill, Launching, Milltown Cross, Savage Harbour, Summerville, West St. Peters
Habitat: On foliage of grasses, herbs, orchards, deciduous trees, shrubs
Data source: CBG, NPE

Evarcha hoyi (Peckham & Peckham, 1883) Nearctic
Hoy's Knobbed Jumping Spider

Kings: Launching, Forest Hill
Habitat: Shrubs, herbs, grasses, and other low vegetation
Data source: NPE

Neon nelli Peckham & Peckham, 1888 Nearctic
Nell's Tiny Jumping Spider

Queens: Cavendish, Brackley Beach, Dalvay
Habitat: Mixed hardwood leaf litter
Data source: CBG

**Pelegrina flavipes* (Peckham & Peckham, 1888)
Big-headed White-cheeked Jumping Spider Nearctic

Prince: Norway; **Queens:** Bonshaw, Charlottetown, Donagh; **Kings:** Forest Hill, Kingsboro, Launching, Savage Harbour, Summerville, Thomas Island, Woodville Mills
Habitat: Mixed coniferous foliage and bark, tall grasses in marshlands and fields
Data source: NPE

Pelegrina proterva (Walckenaer, 1837) Nearctic
Common White-cheeked Jumping Spider

Prince: Central Kildare, Norway; **Queens:** Cavendish, Bonshaw, Brackley Beach, Dalvay, Donagh, Kelly's Cross, Marshfield; **Kings:** Cape Bear, Forest Hill, Lorne Valley, Launching, Savage Harbour, Summerville
Habitat: Woodland understorey
Data source: CBG, NPE

Phidippus princeps (Peckham & Peckham, 1883)
Sinuous Tufted Jumping Spider Nearctic

Kings: Summerville
Habitat: Old fields, goldenrod
Data source: NPE, previous record unverifiable (immature *Phidippus* specimen)

Salticus scenicus (Clerck, 1757) Palearctic
Zebra Jumping Spider (introduced)

Prince: North Tryon; **Queens:** Brackley Beach, Donagh, Winsloe; **Kings:** Summerville
Habitat: On and in houses and other buildings, on fences, meadows, and fields
Data source: CBG, NPE

**Sittiflor floricola palustris* (Peckham & Peckham, 1883)
Flower Patterned Jumping Spider Nearctic

Prince: West Point, Central Kildare; **Queens:** Covehead, Mount Albion, Wheatley River
Habitat: Bogs, marshes, fens, and meadows
Data source: CBG, NPE

Synageles venator (Lucas, 1836) Palaearctic
Palaearctic Antmimic Jumping Spider (introduced)

Queens: Charlottetown
Habitat: Sand dunes on the coast, tussocky or scrub vegetation close to wet areas
Data source: NPE

**Tutelina similis* (Banks, 1895) Nearctic
Thick-spined Jumping Spider

Kings: Launching
Habitat: Grasslands, meadows, and other areas of low vegetation
Data source: NPE

TETRAGNATHIDAE (10 species)

**Pachygnatha brevis* Keyserling, 1884 Nearctic
Northeastern Thick Long-jawed Spider

Queens: Bonshaw, Marshfield; **Kings:** Forest Hill, Lorne Valley
Habitat: Swamps and salt marshes or plant debris near water
Data source: Dondale *et al.* 2003, NPE

**Tetragnatha caudata* Emerton, 1884 Nearctic
Tailed Long-jawed Spider

Prince: Portage
Habitat: Bogs, marshes, and swamps among reeds and tall grasses
Data source: Dondale *et al.* 2003, NPE

**Tetragnatha dearmata* Thorell, 1873 Holarctic
Uncommon Long-jawed Spider

Queens: Dalvay
Habitat: On trees and understorey shrubs in mixed coniferous forests, and swamp grasses
Data source: Dondale *et al.* 2003, CBG

Tetragnatha elongata Walckenaer, 1841 Nearctic
Elongated Long-jawed Spider

Queens: Blooming Point**,** Culloden, Dalvay, Glenfinnan Avondale, South Melville; **Kings:** Launching
Habitat: On branches that overhang streams, especially near forest
Data source: CBG, NPE

**Tetragnatha extensa* (L., 1758) Holarctic
Northern Long-jawed Spider

Queens: Covehead; **Kings:** Head of Cardigan, Milltown Cross, St. Peters Harbour, Summerville
Habitat: Widespread on shrubs and trees in meadows
Data source: Dondale *et al.* 2003, CBG, NPE

Tetragnatha guatemalensis O. Pickard-Cambridge, 1889
Guatemala Long-jawed Spider Nearctic

Queens: Covehead, Dalvay
Habitat: Streamside or lakeside shrubs and tall herbs
Data source: CBG

**Tetragnatha laboriosa* Hentz, 1850 Nearctic
Silver Long-jawed Spider

Prince: Kelvin, Miscouche, North Tryon; **Queens:** Blooming Point, Cavendish, Covehead, Glenfinnan; **Kings:** Corraville, Greenwich, St. Peters Harbour, Summerville
Habitat: Fields, roadsides, and crops, near or away from water, but also bogs, meadows, and marshes
Data source: Dondale *et al.* 2003, CBG, NPE

Tetragnatha shoshone Levi, 1981 Holarctic
Shoshone Long-jawed Spider

Queens: Cavendish, Dalvay; **Kings:** Greenwich
Habitat: Tall plants near lakes
Data source: CBG

Tetragnatha versicolor Walckenaer, 1841 Nearctic
Common Long-jawed Spider

Queens: Cavendish, Dalvay
Habitat: Trees and shrubs near water, but also mixed conifer forest
Data source: CBG

Tetragnatha viridis Walckenaer, 1841 Nearctic
Green Long-jawed Spider

Queens: Dalvay; **Kings:** Greenwich, St. Peters Harbour
Habitat: On coniferous trees, namely pine and balsam fir
Data source: CBG, NPE

THERIDIIDAE (27 species)

**Canalidion montanum* (Emerton, 1882) Holarctic
Montane Cobweaver

Queens: Dalvay
Habitat: Shrubs and trees in mixed coniferous forest
Data source: CBG

Crustulina sticta (O. Pickard-Cambridge, 1861)
Common Dimpled Widow Spider Holarctic

Queens: Covehead
Habitat: Among stones and among herbs and litter near beaches
Data source: CBG

Dipoena nigra (Emerton, 1882) Nearctic
Common Highbrowed Cobweaver

Kings: Corraville
Habitat: Mixed forest and shrubs
Data source: NPE

Enoplognatha latimana Hippa & Oksala, 1982
Cavernous Long-jawed Cobweaver Palearctic (introduced)

Prince: West Point; **Queens:** Donagh, Grandview; **Kings:** St. Peters Harbour, Summerville
Habitat: Fields and field margins; open, dry habitats, low vegetation, and shrubs
Data source: NPE

**Enoplognatha ovata* (Clerck, 1757) Palearctic
Polymorphic Long-jawed Cobweaver (introduced)

Prince: Central Kildare; **Queens:** Blooming Point, Cavendish, Charlottetown, Dalvay, Donagh, South Melville; **Kings:** Little Sands, Summerville
Habitat: Fields and field margins, open habitats, low vegetation and shrubs, gardens
Data source: CBG, NPE

Euryopis argentea Emerton, 1882 Holarctic
Black-headed Triangular Cobweaver

Queens: Covehead
Habitat: Mixed forest litter
Data source: CBG

Euryopis funebris (Hentz, 1850) Nearctic
Eastern Triangular Cobweaver

Queens: Covehead
Habitat: Mixed forest litter
Data source: CBG

Neospintharus trigonum (Hentz, 1850) Nearctic
Horned Parasitic Cobweaver

Queens: Cavendish, Dalvay
Habitat: Mixed forest
Data source: CBG

Neottiura bimaculata (L., 1767) Palearctic
Bimaculated Cobweaver (introduced)

Queens: Covehead; **Kings:** Greenwich
Habitat: Low vegetation and bushes, sometimes low branches of trees, broad habitats
Data source: CBG

Parasteatoda tabulata (Levi, 1980) Palearctic
Wandering House Cobweaver (introduced)

Prince: Central Kildare, North Tryon; **Queens:** Charlottetown, Donagh; **Kings:** Brudenell, Elliotvale, Savage Harbour, Summerville, West St. Peters
Habitat: In houses, sheds, other buildings, sometimes gardens
Data source: NPE

Parasteatoda tepidariorum (C. L. Koch, 1841)
Common House Cobweaver South America (introduced)

Queens: Charlottetown
Habitat: In houses, sheds, other buildings, sometimes gardens
Data source: NPE

Phoroncidia americana (Emerton, 1882) Nearctic
Hump-backed Cobweaver

Kings: Launching
Habitat: Coniferous tree foliage (e.g., cedar, pine) near farms and adjacent fields, sometimes litter
Data source: NPE

Platnickina tincta (Walckenaer, 1802) Palearctic
Conifer Cobweaver (introduced)

Queens: Cavendish, Marshfield; **Kings:** Savage Harbour
Habitat: Shrubs and tree foliage, gardens, parks, roadsides
Data source: CBG, NPE

Robertus riparius (Keyserling, 1886) Nearctic
Bent Immaculate Cobweaver

Kings: Launching, New Zealand
Habitat: Mixed coniferous forest litter
Data source: NPE

Rugathodes sexpunctatus (Emerton, 1882) Holarctic
Six-spotted Cobweaver

Queens: Cavendish
Habitat: Mixed coniferous forest, shrubs, gardens, parks
Data source: CBG

**Steatoda albomaculata* (De Geer, 1778) Holarctic
Punctate False Black Widow Spider

Locality unavailable
Habitat: Sandy areas, sparsely vegetated areas, rocky ground
Data source: Unavailable/specimen record unverifiable

Steatoda bipunctata (L., 1758) Palearctic
Eurasian False Black Widow Spider (introduced)

Prince: Traveller's Rest, North Tryon, Central Kildare; **Queens:** Charlottetown, Marshfield; **Kings:** Head of Cardigan, Summerville
Habitat: Near human-made structures, e.g., fences, buildings, houses, sheds
Data source: NPE

Theridion differens Emerton, 1882 Nearctic
Common Long-legged Cobweaver

Prince: Central Kildare; **Queens:** Brackley Beach, Covehead, Marshfield
Habitat: Low vegetation in mixed coniferous forest, wetland areas
Data source: CBG, NPE

Theridion frondeum Hentz, 1850 Nearctic
Eastern Long-legged Cobweaver

Prince: Portage; **Queens:** Blooming Point, Dalvay, South Melville, Wood Islands; **Kings:** Summerville
Habitat: Deciduous forest, shrubs and herbs
Data source: CBG, NPE

**Theridion glaucescens* Becker, 1879 Nearctic
Large-spined Long-legged Cobweaver

Queens: Dalvay
Habitat: Mixed coniferous forest, low foliage
Data source: CBG

Theridion murarium Emerton, 1882 Nearctic
Fence Long-legged Cobweaver

Prince: Central Kildare; **Queens:** Dalvay; **Kings:** New Perth
Habitat: Mixed coniferous forest
Data source: CBG, NPE

Theridion pictum (Walckenaer, 1802) Holarctic
Wetland Long-legged Cobweaver

Queens: Charlottetown, Dalvay
Habitat: Mixed coniferous forest
Data source: CBG, NPE

Theridion varians Hahn, 1833 Palearctic
Eurasian Long-legged Cobweaver (introduced)

Prince: North Tryon; **Queens:** Cavendish; **Kings:** Summerville
Habitat: Tree and shrub foliage, fences, grasslands
Data source: CBG, NPE

Theridula emertoni Levi, 1954 Nearctic
Emerton's Bitubercled Cobweaver

Queens: Blooming Point
Habitat: Mixed coniferous forest
Data source: NPE

Thymoites unimaculatus (Emerton, 1882) Nearctic
Spotted Cobweaver

Queens: Covehead; **Kings:** Canavoy
Habitat: Fields, mixed coniferous forest, marshes
Data source: CBG, NPE

Wamba crispulus (Simon, 1895) Nearctic
Bayonet Cobweaver

Prince: Central Kildare; **Queens:** Dalvay
Habitat: Mixed coniferous forest, grasslands
Data source: CBG, NPE

Yunohamella lyrica (Walckenaer, 1841) Holarctic
Lyric Cobweaver

Queens: Dalvay; **Kings:** Launching
Habitat: Most common in dry, pine-dominated areas, but also in other coniferous trees and grasslands
Data source: CBG, NPE

THERIDIOSOMATIDAE (1 species)
Theridiosoma gemmosum (L. Koch, 1877) Holarctic
Common Eastern Ray Spider

Queens: Dalvay; **Kings:** Greenwich
Habitat: Damp areas (e.g., swamps), or wet cliff faces and overhanging stream banks, grassy fields with rose bushes, mossy ground in white spruce stand
Data source: CBG

THOMISIDAE (8 species)
Bassaniana utahensis (Gertsch, 1932) Nearctic
Utah Bark Crab Spider

Prince: Central Kildare; **Queens:** Brackley Beach
Habitat: Under tree bark and in litter of mixed forest
Data source: CBG, NPE

**Misumena vatia* (Clerck, 1757) Holarctic
Goldenrod Crab Spider

Prince: North Cape, St. Nicholas; **Queens:** Cavendish, Covehead, Dalvay, Donagh; **Kings:** Greenwich, Head of Cardigan, Launching, Summerville, West St. Peters
Habitat: On flowers and foliage of many herbs, shrubs, and deciduous trees in pastures, meadows, and orchards
Data source: CBG, NPE

**Ozyptila distans* Dondale & Redner, 1975 Nearctic
Distant Leaflitter Crab Spider

Queens: Brackley Beach, Dalvay, Kellys Cross; **Kings:** Greenwich, Head of Cardigan
Habitat: Swamps, sphagnum bogs, abandoned fields, and pine litter
Data source: Dondale and Redner 1978, CBG, NPE

Tmarus angulatus (Walckenaer, 1837) Nearctic
Tuberculated Crab Spider

Kings: Head of Cardigan, Summerville
Habitat: Mixed forest and nearby grasslands and shrub vegetation
Data source: NPE

Xysticus canadensis Gertsch, 1934 Holarctic
Boreal Ground Crab Spider

Queens: Dalvay
Habitat: Mixed coniferous forest
Data source: CBG

Xysticus emertoni Keyserling, 1880 Holarctic
Emerton's Ground Crab Spider

Kings: Corraville, Summerville
Habitat: Fields, meadows, bogs, and herbaceous vegetation
Data source: NPE

Xysticus punctatus Keyserling, 1880 Nearctic
Punctated Ground Crab Spider

Queens: Dalvay; **Kings:** Savage Harbour
Habitat: On trees and litter of mixed coniferous forest
Data source: CBG, NPE

Xysticus triguttatus Keyserling, 1880 Nearctic
Three-banded Ground Crab Spider

Prince: Central Kildare
Habitat: On ground in grasslands, on shrubs and herbs
Data source: NPE

ULOBORIDAE (1 species)
Hyptiotes gertschi Chamberlin & Ivie, 1935 Nearctic
Gertsch's Triangle Weaver

Kings: Launching
Habitat: Mixed coniferous forest, pine stands on trees
Data source: NPE

Discussion

We have shown that collaboration among experts and volunteer citizen scientists can contribute effectively to our understanding of the diversity and distribution of species. Broad-scale contributions from the public overcame the logistic difficulties associated with collecting specimens from a diverse range of habitats and geographic locations across PEI. The naturalists engaged, organized, and trained citizens in collection and preservation techniques and the experts identified, recorded, and prepared voucher specimens. This approach is particularly important in efforts to document the current state of biodiversity, including the conservation status of species across the globe.

We have increased the number of spider species known to occur on PEI to 198 through the combined efforts of professional researchers using DNA barcoding technology and comparative morphology and through the help of citizen scientists using traditional collecting and identification methods. Concerted volunteer effort in combination with novel technology, such as DNA barcoding, have produced a baseline record of spider diversity for the province.

The CBG and Nature PEI studies complemented each other in unforeseen ways. Although the CBG surveyed one protected area intensively, citizen scientists surveyed a range of habitat types over a wide geographic area, demonstrating that many of the species collected within the 27-km^2 national park are distributed across the entire province. The increased number of specimens collected via a citizen science approach can result in an increased opportunity for studies of species occurrence, relative abundance, and relationships (Acorn 2017). In addition, an especially noteworthy positive outcome is that more active community engagement in conservation was encouraged and the project was widely reported through various media (e.g., CBC News 2016), providing positive feedback for involvement in community collection efforts.

Collaboration among experts and citizen scientists in this time of rapid species loss is imperative to help document the diversity and distribution of species on earth (Ceballos *et al.* 2015). It does take effort by professionals and naturalists to engage and train the public in such ventures, but fortunately, there are ever-growing opportunities for academics and governmental and non-governmental agencies to engage the public and inform them about how they can contribute to these efforts (Bonney *et al.* 2009, 2014; Prudic *et al.* 2017).

The citizen science approach also presents some challenges; for example, participants tend to sample sites familiar to them and the quality of specimens and associated data submitted can be highly variable. Thus, less than 20% of the over 4300 specimens collected by the Nature PEI citizen scientists were adults that could be positively identified by morphological characteristics. Nonetheless, their efforts yielded about a quarter of the total number of species, with many others overlapping the parallel DNA barcoding. Efforts to conduct faunistic surveys such as these even in a province of this size would be more challenging without contributions from the public.

PEI lies in the Gulf of Saint Lawrence with New Brunswick to its west and south, and Nova Scotia to its east and south. Thus, unsurprisingly and similar to other species groups, the PEI spider fauna largely represents a subset of species found in those adjacent provinces (e.g., Adler *et al.* 2005; Majka *et al.* 2008). Many were likely able to colonize PEI when it was connected to the mainland some 10 000 years ago (Shaw *et al.* 2002). However, the proximity of the adjacent mainland means that many spider species are capable of colonizing the island via aerial ballooning (Greenstone 1990) or even via natural rafts, such as floating algae (Coffin *et al.* 2017). Humans have likely introduced others accidentally. Despite PEI's relatively small human population, it is densely populated and is a popular tourist destination during summer months.

Some species previously reported from PEI were not collected during the Nature PEI or CBG studies. This absence could indicate that these species are rare on PEI, are present in habitats that were not well surveyed in the two studies (e.g., *Pirata piraticus* in wetlands), were originally misidentified, or simply no longer exist on the island. Although PEI is the smallest province in Canada, it possesses a diversity of habitat types. As with other animal groups, some spider species are habitat generalists, while others are specialists depending on their physiological requirements. In some cases, narrow physiological requirements dictate that species distributions may change dramatically across very small spatial scales (e.g., microhabitats; DeVito *et al.* 2004). For example, DeVito *et al.* (2004) found that three species of wolf spider distributed themselves in proximity to a river corresponding to their desiccation thresholds. A high turnover in species across the landscape may mean that some are missed in faunistic studies. Despite intensive sampling by the CBG, it was spatially restricted and focussed on the national park, whereas the efforts by Nature PEI were broad in geographic scope, but much less intensive and often consisted of a single collection at a given site.

As is typical for many groups in eastern North America, several introduced species are now well established on PEI. The degree to which introduced species may affect native species is not well known, but some evidence supports the idea that such introductions could lead to competitive exclusion (Houser *et al.* 2014).

Some species collected in this project (e.g., *Gladicosa gulosa*) are otherwise known only from more southern localities (e.g., southern Nova Scotia, Quebec, or Ontario) in Canada or in the continental United States (Dondale and Redner 1990). PEI lies near the boreal-temperate transition zone and the discovery of such species could indicate a northward shift in their range. Because we do not have reliable information about the past presence of species on the island, it is impossible to know for certain how long this species or others have existed there. This is in contrast to species such as *Misumena vatia* or *Pardosa xerampelina*, which have been collected in all other provinces in Canada and some territories, as well as the Magdalen Islands, in the case of the latter, but never before documented from PEI (Dondale and Redner 1978, 1990).

The finding that the Linyphiidae was the most speciose group in this collection is typical of other spider lists in Canada (e.g., Dondale *et al.* 1997; Pickavance and Dondale 2005), including those from community ecology studies (e.g., Buddle 2001). Indeed, the Linyphiidae is the second most speciose family globally (second to the Salticidae), boasting over 4500 species (World Spider Catalog 2017), but their diversity is especially high in northern environments (e.g., Bowden and Buddle 2010).

Although we have made substantial progress in documenting the spiders of PEI, we expect that many additions remain to be made. Moreover, additional species could be found through further collection in areas that were not well sampled during this effort, such as sand dunes, hardwood stands, and various agricultural fields, marshes, and upper tree canopies, which could yield some unique species (Larrivée and Buddle 2009). Collection in these areas could also benefit from more intensive pitfall trapping.

We achieved strategic collaboration among professional, naturalists, and citizen scientists, and emphasize that these relationships are mutually beneficial where professionals are aided by the collection of data and citizens can learn more about local species and their natural history. We hope that our efforts inspire others to participate in such collaborative projects and to continue to contribute to social networks and online depositories dedicated to documenting species (e.g., iNaturalist). Still, professionally led research projects on biodiversity in PEI would likely yield further records and provide a better portrait of species community structure.

Author Contributions

R.C. indicated the need for a study and initiated discussion. J.J.B., K.M.K., G.A.B., R.B., and R.C. conceptualized the study and methods, J.J.B., G.A.B., and R.B. produced or compiled data. R.C. procured funding for the NPE portion of the project. K.M.K., R.C., C.F.H., and R.W.H. contributed to project administration by supervising and leading the NPE citizen science specimen collection initiative. M.A.A. created the map figure. J.J.B. and R.B. wrote the original draft of the article and undertook revisions. All authors contributed to revisions and approved the final manuscript.

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New records for Eastern Mosquito Fern (*Azolla cristata*, Salviniaceae) in Canada

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Abstract
We report a cluster of Eastern Mosquito Fern (*Azolla cristata,* Salviniaceae) populations in five watersheds within a 56-km^2 area of Leeds and Grenville County, Ontario. Some of the recently discovered populations were immense, one containing over two million individuals in 2016. These eastern Ontario populations are persistent, having been observed *in situ* continuously for four years. One population was confirmed after an apparent absence of at least 30 years and another was reported as present (or at least recurring) for approximately 50 years. We observed that Canadian *A. cristata* is capable, at least experimentally, of overwinter dormancy and subsequent renewal. *Azolla cristata* in eastern Ontario and western Quebec appears to represent naturally (if sporadically) occurring populations, likely transported from adjacent northern New York populations by migratory waterfowl. These natural occurrences are expected to be more frequent as climate change continues to reduce environmental barriers to the northward establishment of this and other southern taxa.

Key words: *Azolla cristata*; Eastern Mosquito Fern; climate change; native biodiversity; pteridophyte; Frontenac Axis; Ontario; Quebec

Introduction
The Salviniaceae is a small, cosmopolitan, mainly tropical family of aquatic, heterosporous, free-floating ferns (Svenson 1944; Lumpkin 1993). *Azolla*, the larger of the two genera in the family (traditionally seen as the distinct family, Azollaceae), is characterized by small, dichotomously branching, free-floating plants with lobed fronds (Figure 1) and short thread-like roots extending into the water (Cody and Britton 1989). *Azolla* is ephemeral (Evrard and Van Hove 2004), with populations experiencing brief periods of explosive growth followed by long periods of apparent absence or obscurity that can last for years, as found in this study. Populations frequently form mats several hectares in size that can extend more or less continuously for kilometres (Figure 2; Darbyshire 2002; Darbyshire and Thomson 2004).

All three species of *Azolla* occurring in Canada (Macoun 1890; Brunton 1986; Cody and Britton 1989) are rare here, and many populations have been considered to be non-native. The cosmopolitan Large Mosquito Fern (*Azolla filiculoides* J.-B. Lamark) is native in parts of western North America and is probably introduced in southern British Columbia (BC; Douglas *et al.* 2000; F. Lomer pers. comm. 4 December 2017). A sterile *Azolla* specimen from Brantford, Ontario (ON; *C. J. Rothfels and S. R. Spisani 795*, 24 September 2003, HAM, D.F.B. personal herbarium) is believed to be *A. filiculoides* (based on the morphological distinctions described in Methods). It is reported elsewhere in the Great Lakes Region from the Niagara Frontier area of western New York (NY; Eckel 2005, although not repeated in Weldy *et al.* 2018).

Occurrences of Mexican Mosquito Fern (*Azolla mexicana* Schlechtendal & Chamisso ex C. Presl), a widespread native species in western North America (Lumpkin 1993), are scattered through interior southern BC (Brunton 1986; Goward 1994). It is of conservation concern and assessed (COSEWIC 2008) and listed as threatened in Canada (SARA 2019). *Azolla mexicana* has also been discovered recently in coastal BC as an adventive beyond its natural range (Klinkenberg 2017).

Eastern Mosquito Fern (*Azolla cristata* G.-F. Kaulfuss (*A. caroliniana* auct., non C.L. Willdenow)); is found irregularly across much of the eastern United States and southward into South America (Svenson 1944; Wherry 1961; Lumpkin 1993; Crow and Hellquist 2000; Pereira *et al.* 2011). It is considered a secure species on a global scale (G5) but uncommon to rare in some northern portions of its North American range and critically imperilled (S1S2) in Canada in ON and BC (NatureServe 2019). The Canadian status of *A. cristata,* however, is ambiguous and it has not been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Possible native populations have been reported in the western Lake Ontario area (both historical and contemporary at Hamilton and the Niagara Peninsula), near Ivy Lea (Leeds and Grenville County, hereafter, L & G County), and from York County (Pryer 1987; Eckel 2005; Oldham and Brinker 2009). Populations found along the Rideau and Ottawa Rivers in ON and Quebec (QU) were reported to represent non-native introductions (Darbyshire 2002; Darbyshire and Thom-

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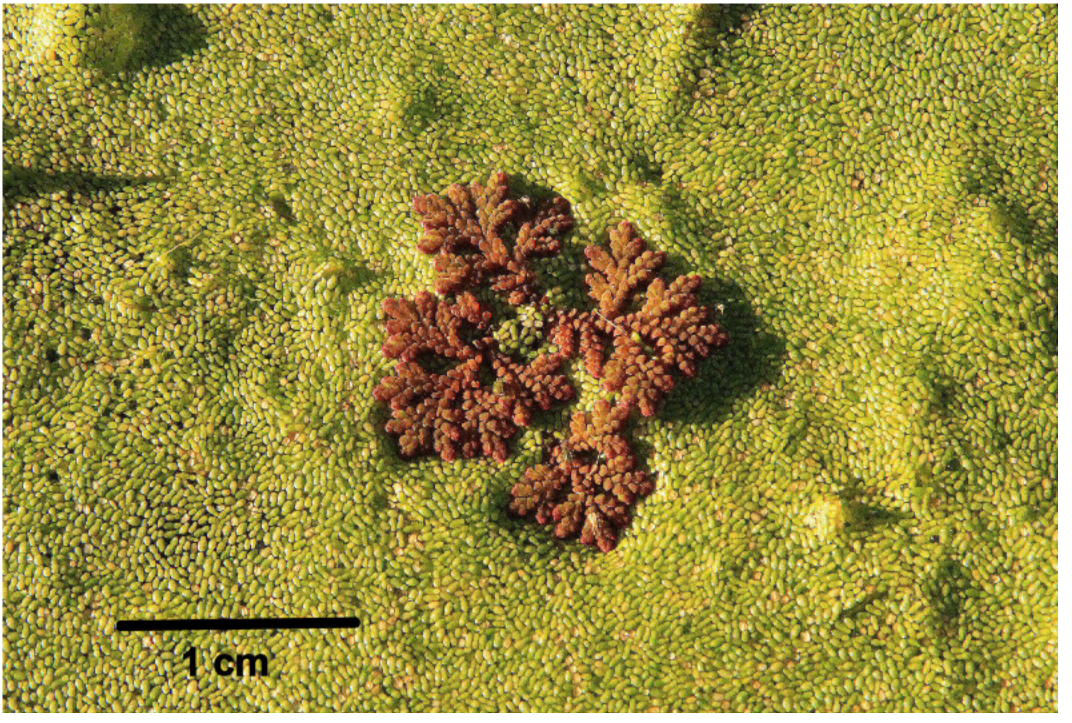

FIGURE 1. Single Eastern Mosquito Fern (*Azolla cristata*) plant in a watermeal (*Wolffia* spp.) mat at Maple Grove, Gananoque River, Leeds and Grenville County, Ontario. Photo: D.F. Brunton, 21 September 2016.

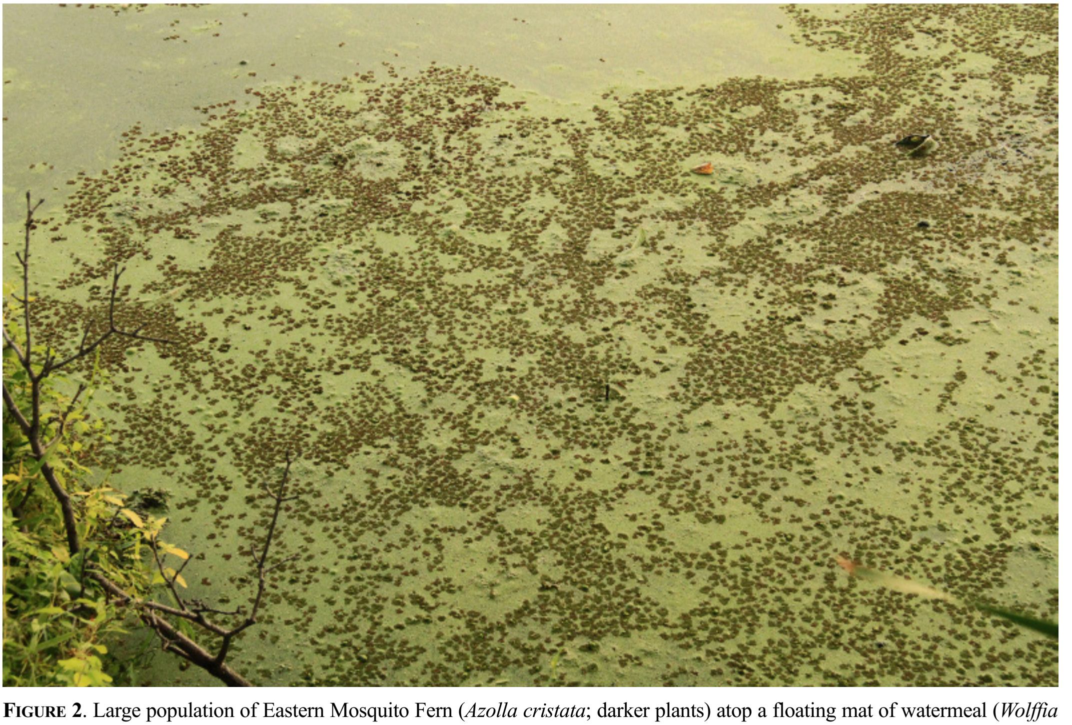

FIGURE 2. Large population of Eastern Mosquito Fern (*Azolla cristata*; darker plants) atop a floating mat of watermeal (*Wolffia* spp.), Star Duckweed (*Lemna trisulca*), and Great Duckweed (*Spirodella polyrhiza*) at Kinsman Park, Gananoque, Leeds and Grenville County, Ontario. Photo: D.F. Brunton, 27 September 2016.

son 2004). Recent occurrences in urban areas in southern BC are reported as being introduced (Douglas *et al.* 2000; Klinkenberg 2017). Eastern Canadian *A. cristata* populations have been considered incapable of persisting in the wild for more than one or two seasons (Darbyshire 2002), presumably constrained by Canadian winter conditions. It has been suggested that introduced Canadian populations likely resulted from the dumping of the contents of home aquaria into local waterways (Darbyshire 2002; Darbyshire and Thomson 2004; Klinkenberg 2017).

The discovery and rediscovery of vast and long-persisting populations of *A. cristata* in eastern ON are reported here and the implications of those discoveries are reviewed.

Methods

Following the September 2014 opportunistic discovery of *A. cristata* near Gananoque (L & G County, ON), ground- and water-based field surveys were undertaken from September through November 2014–2017 in the southern Frontenac Axis area. We investigated potentially suitable still, protected, open water sites in an approximately 1500-km² area within 25 km of the north shore of the St. Lawrence River between Kingston and Brockville. Several L & G County site visits were also conducted in July and early August 2015. These were unsuccessful, although *Azolla* plants were detected at those sites later in the autumn of both 2014 and 2015 (Figures 1, 2, and 3; Table 1). Accordingly, mid-summer searches were not undertaken thereafter.

At each location, we conducted binocular-assisted visual surveys of creek and pond surfaces within 50–300 m of public roadways. Boat surveys also were conducted in September 2014 and 2016 along lower portions of the Gananoque River between Gananoque Lake and its outlet into the St. Lawrence River. Based on the strong association of *Azolla* populations with large mats of the aquatic Columbia Watermeal (*Wolffia columbiana* H. Karsten) and Northern Watermeal (*Wolffia borealis* (Engelmann) Landolt & Wildi ex Gandhi, Wiersema & Brouillet), we searched 15 large *Wolffia* mats evident from satellite imagery (GoogleEarth) on 8 November 2016 (Figure 4).

We collected voucher specimens for all distinct *A. cristata* populations discovered. These are deposited in herbariums at Agriculture and Agri-Food Canada (DAO), the Canadian Museum of Nature (CAN), the University of Guelph (OAC), the University of Manitoba (WIN), and/or D.F.B.'s personal herbarium (DFB). We reviewed the *Azolla* populations annually to determine their persistence. We also reviewed earlier herbarium voucher specimens in DAO, CAN, and the Royal Botanical Gardens (HAM) for additional records. In 2015 and 2016, we conducted informal interviews on

FIGURE 3. Dense, free-floating mat of brick-red Eastern Mosquito Fern (*Azolla cristata*) plants at Maple Grove, Gananoque River, Leeds and Grenville County, Ontario. Photo: D.F. Brunton, 5 October 2014.

Table 1. Summary of observations of Eastern Mosquito Fern (*Azolla cristata*) in Leeds and Grenville County, Ontario, Canada.

Year	Gananoque River (St. Lawrence River through Maple Grove to Marble Rock)		Sucker Brook, Maple Grove	Landon's Bay, St. Lawrence River	Knight's Creek, Ivy Lea	Gray's Creek, Front of Leeds and Gananoque Township
	Lower 10.8 km	Marble Rock				
2014	Abundant (deep drifts of plants at river mouth)	Abundant	—*	—	—	—
2015	None	Rare	—	—	—	—
2016	Abundant (no drifts)	Common	Common	Common	Abundant (forming drifts)	Rare
2017	Abundant (no drifts)	Common	None	—	Abundant	None

Note: Abundant = continuous mat; Common = scattered patches 0.5–2 m across; Rare = individual plants or small patches <30 cm wide.
*Not searched.

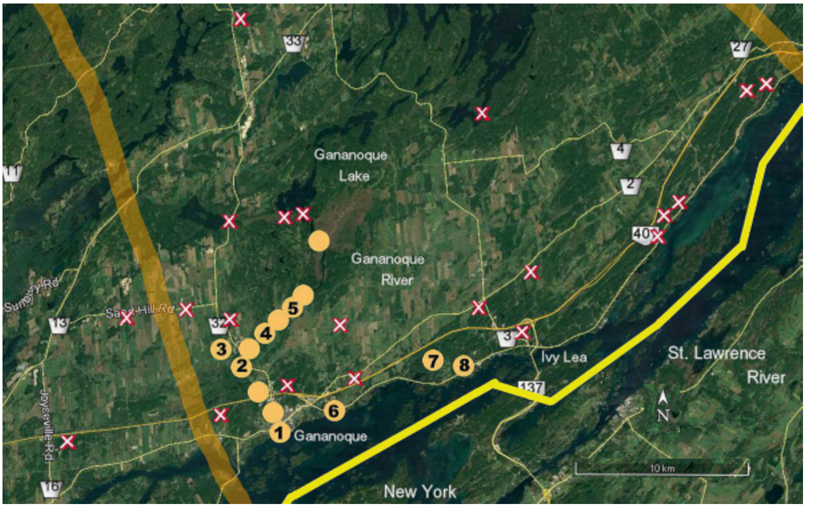

FIGURE 4. Locations of Eastern Mosquito Fern (*Azolla cristata*) in Leeds and Grenville County, Ontario. Circles = *Azolla* population (2014–2017); X = site where *A. cristata* was searched for but not found in suitable *Wolffia–Lemna* vegetation (2014–2017); broad vertical lines = approximate limit of Frontenac Axis; broad yellow [light] line indicates Canada–United States border. Numbers identify populations referred to in the text: 1, Gananoque; 2, Maple Grove; 3, Sucker Brook; 4, Gananoque River main channel; 5, Marble Rock; 6, Gray's Creek; 7, Landon Bay; 8, Knight's Creek. Base image: Gananoque, 44.406450°N, 76.091095°W, Google Earth Pro 7.3.1.4507. Imagery date: 3 July 2018. Accessed: 14 March 2019.

site with long-time residents to obtain historical information on particular sites and populations.

Azolla taxonomy and identification is complex, and that of *A. cristata* is particularly challenging, largely because of the rarity of sporocarp and megaspore production (Svenson 1944; Lumpkin 1993). All known *Azolla* specimens from eastern Canada are sterile. Their identification relies on subtle microscopic characters, such as leaf trichome shape. Trichomes of the typically smaller-leaved *A. cristata* are bi- to tri-cellular compared with unicellular trichomes in *A. filiculoides* (Evrard and Van Hove 2004). The latter species (and *A. mexicana*) also frequently produce sporocarps (Svenson 1944; Lumpkin 1993). The specimens in question were examined in either a fresh or rehydrated condition through a light dissecting microscope (Wild M3B; Leica Microsystems, Wetzlar, Germany) at 40× magnification, with measurements made with the aid of an in-mount graticule (ocular micrometer).

Azolla cristata nomenclatural remains unsettled because of problems in interpretation of type specimens. Recent reviews of that problem conclude that *A. cristata* is the older, most appropriate name for this species (Evrard and Van Hove 2004; Pereira *et al.* 2011) and we follow that interpretation.

To assess the cold tolerance of *A. cristata*, plants from the Knight's Creek, L & G County population were collected in November 2016 and maintained in cultivation over winter. One sample of approximately 20 floating fronds was kept in a container of creek water in a refrigerator at 4°C, and later became frozen in ice for approximately two weeks. A second, similar sample was maintained at approximately 17°C in the low natural light of a windowsill. Both were periodically examined through the winter season and into spring, with changes in size and appearance documented photographically.

Results

New eastern Ontario discoveries of Azolla cristata

In September 2014, *A. cristata* was discovered along the Gananoque River in L & G County in patches that were almost continuous for 10.8 km upstream from the St. Lawrence River (Figures 1, 2, and 3). Subsequently, persistent populations of *A. cristata* have been found along tributaries of the St. Lawrence River in five separate watersheds within an area of approximately 56 km^2 in southern L & G County (Figure 4). Locations include the main course of the Gananoque River and its tributary Sucker Brook. The other subwatersheds encompass Gray's Creek, Knight's Creek (Figure 5), and Landon's Bay, all of which empty directly into the St. Lawrence River.

New records of *A. cristata* found from 2014 to 2017 were all within the Frontenac Axis (Table 1; Figure 4), a rugged upland landscape of erosion-resistant Precambrian bedrock characterized by an abundance of water bodies (Keddy 1995). In September 2014, we discovered large populations of *A. cristata* along the Gananoque River in patches extending from its confluence with the St. Lawrence River upstream for 10.8 km. The plants were conspicuous, forming large, dense, free-floating mats (Figure 3) suspended within a 5–10 mm thick growth of watermeal (*W. borealis* and *W. columbiana*), Small Duckweed (*Lemna minor* L.), Star Duckweed (*Lemna trisulca* L.), and Great Duckweed (*Spirodela polyrhiza* (L.) Schleiden). The brick-red colour of the *Azolla* patches was so conspicuous that the species was first noted from a vehicle moving at freeway speed on the Highway 401 bridge over the Gananoque River. In the Gananoque area, we observed the strong affinity of *Azolla* plants for *Wolffia* mats. Although some of the *Wolffia* mats examined did not support *Azolla*, all L & G County *A. cristata* populations were found amongst *Wolffia*.

In years of high abundance, *Azolla* was observed to grow in continuous expanses and was found in all the *Wolffia–Lemna* mats occupying side bays and shallow, quiet shore areas with reduced current along the lower Gananoque River. The *Wolffia–Lemna* mats remained continuously dense from the St. Lawrence River at Gananoque upstream for 10.8 km to Marble Rock. In some years, *A. cristata* plants and mat fragments piled up with millions of *Wolffia* plants into 10+ cm deep "drifts" on river obstructions and along the last several hundred metres of the Gananoque River shore in the

FIGURE 5. Portion of Knight's Creek Eastern Mosquito Fern (*Azolla cristata*) population (dark mat) in dense watermeal (*Wolffia* spp.) growth, Ivy Lea, Leeds and Grenville County, Ontario. Photo: D.F. Brunton, 10 November 2016.

town of Gananoque. The adjacent river shore at each site was distinguished by the great abundance of Tuckahoe (*Peltandra virginica* (L.) Schott & Endlicher), an otherwise provincially rare species (Oldham and Brinker 2009) with southern affinities (Toner *et al.* 1995).

Between September and November 2016, we also conducted searches for *Azolla* at 15 possible sites in southern L & G County where particularly large *Wolffia* mats were evident on GoogleEarth satellite imagery (Figure 4). Although these *Wolffia* mats appeared to be virtually identical in form, situation, and floristic association to the Gananoque River populations, we did not find any *Azolla* at these locations.

Overwintering of Azolla cristata

In our winter dormancy experimentation, refrigerated material from Knight's Creek failed to produce any new growth by late March (following a two-week freezing period). However, virtually all fronds from the second (room temperature) sample showed abundant new growth at the tips (Figure 6). Although the central axis of most of these plants was decaying, many bud tips were producing new growth, including several fragments that had already separated from the parent plant. The growth on most fronds, including fragments, continued vigorously into mid-April, at which time over half of most fronds constituted fresh green growth. It appears that *A. cristata* fronds, at least at room temperature, are capable of perennating from bud tips when those fronds persist in a dormant state throughout the winter months.

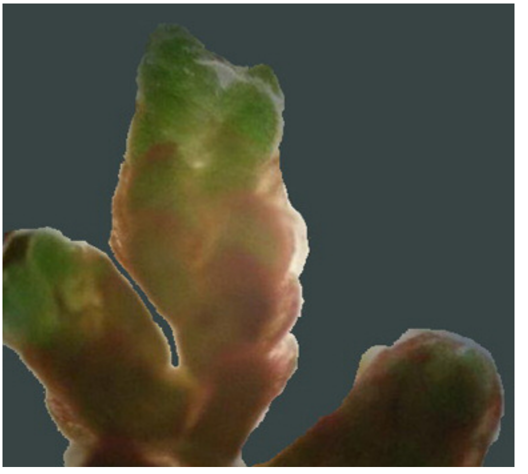

FIGURE 6. Pale-green-coloured, compressed, turion-like leaf-bundles (possibly winter buds) at tips of decaying Eastern Mosquito Fern (*Azolla cristata*) branches. Cultivated plants collected from Knight's Creek, Ivy Lea, Leeds and Grenville County, Ontario. Photo: H. Bickerton, 30 March 2017.

Discussion

Historical status of Azolla cristata in Canada

Azolla cristata has been recorded growing outside cultivation in Canada in BC, southern ON, and southern QC. The BC records are all recent discoveries in artificial and/or recently disturbed wetland habitats in the urbanized southwestern part of the province (lower mainland and adjacent Vancouver Island). With no previous history of occurrence in western North America (Lumpkin 1993), and its occurrence only in disturbed sites heavily used by humans, the BC populations are reasonably considered to represent anthropogenic occurrences (Klinkenberg 2017). At least some historical southern ON records, however, were considered likely to represent natural range expansions (Macoun 1890; Cody and Schueler 1988).

Azolla cristata was first collected in Canada at Burlington Beach (western Lake Ontario), ON in 1862 (Macoun 1890; Cody and Britton 1989). It was not reported again in Canada until 1981 when a large population was found at the mouth of Knight's Creek in L & G County near Gananoque. Robert Griffin (pers. comm. 27 September 2016) reported observations of large *A. cristata* populations along the Gananoque River between Gananoque Lake and Marble Rock settlement "every few years" since the late 1960s. Griffin independently identified the species at that location years previously but was unaware of its significance until advised during the present study. Although abundant in 1981 (Cody and Schueler 1988), and despite periodic site inspections through 2000 (D.F.B. pers. obs.), *A. cristata* was not observed again at Knight's Creek until 2016 (H.J.B. pers. obs.).

Darbyshire (2002) discovered *A. cristata* at several locations in Ottawa, ON, and Gatineau, QC, in both the Rideau Canal and Rideau River in both 1997 and 1998. In 1998, *A. cristata* was observed only along the Ottawa River. This occurrence extended semi-continuously for ~10 km of the Rideau River in ON and 5 km of the Ottawa River in ON and QC. It could not be found in follow-up site visits in 1999 but was reported again from that area in 2003 when a large population was found in a different area of the Rideau River (Darbyshire and Thomson 2004). Although waterfowl dispersal was regarded as a possible vector, the urban location of these occurrences suggested to those investigators that the 2003 occurrence most likely resulted from the dumping of home aquaria (Darbyshire and Thomson 2004).

Discoveries of short-lived *Azolla* occurrences (believed to be *A. cristata*) were made elsewhere in southern ON after 2000. These were found either in artificial or disturbed wetlands and/or following wetland vegetation planting of nursery stock plants, e.g., in the Royal Botanic Garden, Hamilton (C. Rothfels pers. comm. 17 March 2004), Oshawa Second Marsh, Durham Regional Municipality (D. Leadbeater and J. Kamstra pers. comm. September 2017), and Niagara Regional Municipality (A. Garofalo pers. comm. November 2016). Most represented small populations but some (e.g., Oshawa

Second Marsh) involved thousands of plants covering several hectares. None of these populations are believed to have persisted more than two years.

Origins and dispersal

Azolla cristata is abundant and perhaps increasing in abundance in wetlands in the Oswego, NY area, ~100 km directly south of the L & G County sites (A. Nelson pers. comm. 23 December 2014; E. Hellquist pers. comm. 1 May 2018). Indeed, it was known to be common, even abundant, in eastern Lake Ontario shore marshes as long ago as the mid-19th century (Paine 1865). *Azolla* is known from wetlands frequented by migratory waterfowl along the NY shore of the Great Lakes from St. Lawrence County (Eldblom and Johnson 2010) to the Niagara Frontier region (Soper 1949; Eckel 2005; Weldy *et al.* 2018).

Waterfowl are widely identified as the probable vector for both short and long distance movements of many aquatic plant species (Garcia-Alverez *et al.* 2015; Coughlan *et al.* 2017). We frequently observed waterfowl, including Wood Ducks (*Aix sponsa*) and Canada Geese (*Branta canadensis*), loafing or preening in *A. cristata* patches along the Gananoque River, the former also apparently feeding among beds of *Azolla* and *Wolffia*. In October 2016, we observed plants adhering to the breast feathers of free-ranging Mute Swans (*Cygnus olor*) that were swimming through dense *Azolla* at the mouth of the Gananoque River. *Lemna* spp., a major constituent of the *Wolffia–Lemna* mats favoured by *A. cristata*, are known as a preferential, high-nutrient food source for waterfowl in general and swans in particular (Lumsden *et al*. 2017).

Costea *et al.* (2016) suggest that transport of plant propagules by waterfowl (internally) represents an underappreciated long-distance movement mechanism for various species in North America and indeed, Lovas-Kiss *et al.* (2018) document the long-distance transport of viable *Azolla* relative Floating Fern (*Salvinia natans* (L.) C. Allioni) macrospores in Europe. Similarly, Cranfill (1980) suggested that *A. cristata* populations in Kentucky may result from repeated introductions by migrating waterfowl. The suggestion by Cody and Schueler (1998) that such a process could explain the long periods of time between *Azolla* observation at Knight's Creek, L & G County, is supported by the distribution and habitat patterns noted here for both *Azolla* and waterfowl. Accordingly, dispersal by waterfowl from adjacent northern NY also seems the most plausible explanation for the comparable mass occurrences of *A. cristata* in L & G County and elsewhere in eastern ON and western QC.

The local distribution of *A. cristata* within individual waterways may also benefit from the physical transport of propagules by external agents. A large (0.6-ha) floating section of marsh turf consisting of Cattail (*Typha latifolia* L.) lifted off from the adjacent Wiltse Creek marsh in 1981 and blocked the section of the Gananoque River where *A. cristata* mats has been periodically observed since the 1960s. Smaller examples of such sediment-gouging marsh vegetation "rafts" occur sparingly but regularly along the river (R. Griffin pers. comm. 27 September 2016). Although no *Azolla* were observed during an 18 September 1981 investigation of the marsh blockage (Brunton 1981), such rafting could be responsible for the periodic downstream transport of *Azolla* plants.

It seems unlikely that the dumping of aquarium waste could explain recurring, independent populations of *A. cristata* across five subwatersheds in this lightly or uninhabited Canadian Shield landscape of L & G County. Indeed, *A. cristata* appears to be infrequently or rarely cultivated as a water garden or aquarium species in Canada, even in heavily urbanized areas. An online survey of 365 nurseries and aquaria active in the Greater Toronto Area (GTA) between 2011 and 2013 found that only 17 (4.6%) offered this species (L. Erdle pers. comm. 2017). Azan *et al.* (2015) reported that of 331 857 individual plant sales in one year by 20 stores in the GTA, only 931 (or 0.003%) consisted of *A. cristata* (as *A. caroliniana*).

Extent and persistence of populations

Some of the newly discovered L & G County *Azolla* populations were found to be immense, covering many hectares (Figure 3), in one case extending for kilometres. In 2016, we conservatively estimated a density of 13.5 *Azolla* plants/m^2 in a typical *Wolffia–Lemna* mat at the Maple Grove settlement (n = 20 randomly chosen, 1-m^2 plots). Thus, this 2.6-km stretch of the Gananoque River that includes about 36 ha of apparently suitable habitat (identified from satellite images), supports about 485 000 plants. Extrapolating to the entire 10.8-km section of the Gananoque River along which *Azolla* was found implies an *Azolla* population of about two million plants. Even this large number, however, reflects only a portion of the total population that year because it excludes smaller sites off the Gananoque River. Despite that impressive estimate, in 2014 our field observations indicate that *Azolla* populations were even larger near the town of Gananoque—likely 200–300% more dense.

Azolla cristata has been considered short lived in the north of its range (Crow and Hellquist 2000). Populations in upstate NY appear to follow that pattern, persisting for several years in a given location, then disappearing for at least a period of years (A. Nelson pers. comm. 23 December 2014). Our finding that *A. cristata* has persisted at individual sites in L & G County for several years and probably even decades (R. Griffin pers. comm. 27 September 2016) is therefore notable. The Knight's Creek population, for example (Figure 5), has been known from its present location since at least 1981 (Cody and Schueler 1988; F.W. Schueler pers. comm. 6 November 2016). Despite periodic inspection in the intervening years (D.F.B. pers. obs.), *Azolla* was not observed again until 2016 (H.J.B. pers. obs.).

Overwintering capacity

The existence of these recurring *A. cristata* populations strongly suggests persistence over winter, either as dormant plants from the previous year or through the survival of propagules. This is consistent with observations near Lake Erie where a population believed to be *A. cristata* persisted over at least two growing seasons (2006 and 2007) in Black Creek (Fort Erie, ON; A. Garofolo pers. comm. 19 December 2016) and along the Rideau River in Ottawa in the late 1990s (Darbyshire 2002). Eric Hellquist (pers. comm. 28 May 2018) reports that *Azolla* plants in central NY were evident in May 2018 at a site where the species is reliably found; this is too early in the growing season for these plants to represent growth from the current year.

Azolla cristata was presumed unable to endure Canadian winter conditions, based on its apparent lack of persistence in ON (Darbyshire 2002). Because the −11°C average lowest winter temperature of Gananoque (Weather Spark 2018a) is only 3°C below the −8°C average lowest winter temperature of Oswego, NY (Weather Spark 2018b) where *A. cristata* is common (E. Hellquist pers. comm. 28 May 2018), "Canadian winter conditions" may not actually present a significant constraint to *Azolla* population sustainability in L & G County. The lower section of the Gananoque River where *Azolla* has been abundant in recent years was unfrozen on 2 March 2019 (D.F.B pers. obs.), also implying that aquatic temperature conditions are relatively moderate here.

Wong Fong Sang *et al.* (1987) found that *A. filiculoides* plants, frozen in a wild state between −10°C and −1°C for at least two weeks and then transferred to a 25°C growth chamber, started to grow again. Fronds of *A. filiculoides* are reportedly able to withstand hard frosts (−5°C) and prolonged ice cover (Lumpkin and Plucknett 1980). Janes (1998) found that although mature *A. filiculoides* plants in England died following a short (18 h) exposure to −4°C temperatures, they were capable of surviving encasement in ice for at least a week and only those plants that protruded above the ice were killed at sub-zero temperatures. Because *Azolla* can survive indefinitely at 4°C, Janes (1998) suggested that plants are capable of survival in fresh water below the ice where the temperature does not reach 0°C.

Azolla cristata is thought to be among the most cold-tolerant members of its genus (Lumpkin 1993). Consistent with that, in this study mats of apparently healthy *A. cristata* were evident at Knight's Creek on 9 November 2016 in 6°C water. Robust populations also were noted at Kinsman Park in Gananoque even later into that year on 19 November 2016 (K.L. McIntosh pers. comm. 19 November 2016).

We found no reference to turion-like structures in *A. cristata* in the botanical literature, although based on the growth observed in our cultivated sample (Figure 6; also see Results), these appear to exist. Eric Hellquist (pers. comm. 28 May 2018) also observed what appears to be perennating bud tips in *Azolla* populations in central NY in early May.

Conclusions

There is substantial evidence that *A. cristata* is naturally occurring in the Frontenac Axis of L & G County, ON. Large populations have persisted for 20+ or even 50+ year periods in lightly settled, rural locations there far removed from urban and suburban centres. Our observations, along with a reinterpretation of the earlier eastern ON and western QC data of Darbyshire (2002) and Darbyshire and Thomson (2004), imply that human-facilitated introductions are unlikely here. Interpretation of the likely origins of populations in the western Lake Ontario area is less clear because of their frequent occurrence in disturbed areas with high population densities.

The long period between observations of *Azolla* at some L & G County sites may not represent true absences, but may reflect periods when poorer growing conditions result in smaller, inconspicuous populations. The tiny population along the Gananoque River in 2015 between two "bumper" years, for example, could be a reflection of the documented ephemeral nature of *A. cristata* (Svenson 1944; Cranfill 1980; Lumpkin 1993). Small, inconspicuous populations may be normal in ON and elsewhere, with extensive populations such as those noted along the Gananoque, Ottawa, and Rideau Rivers, appearing only in years of especially favourable growth.

The occurrence of apparently self-sustaining *A. cristata* populations in eastern ON has phytogeographic and conservation implications. These occurrences are located within suggested plant migration routes of other uncommon plants with southern affinities. The Frontenac Axis area has long been recognized as a centre for such diversity, including provincially rare plant taxa of conservation concern, such as Pitch Pine (*Pinus rigida* P. Miller), Deerberry (*Vaccinium stamineum* L.), Appalachian Polypody (*Polypodium appalachianum* Haufler & Windham), Rue-anemone (*Thalictrum thalictroides* (L.) A.J. Eames & B. Boivin), and *Azolla* associate *P. virginica* (Dore *et al.* 1959; Cody 1982; Keddy 1995; Oldham and Brinker 2009).

Warming weather conditions in recent decades may be encouraging the persistence of *Azolla* populations in ON, QC, and BC. Warmer winters with longer ice-free periods and slightly warmer water temperatures would be expected to suppress barriers to the establishment and persistence of particular populations. The increased number of potential animal vectors in recent decades (especially migratory Wood Ducks and Canada Geese; Hughes and Abraham 2007; Zimmerling 2007) also increases potential opportunities for *Azolla* to be repeatedly transported into southeastern Canada.

Author Contributions

Both authors contributed to the conceptualization of this article, investigation, methodology, formal analysis of the data, writing of the original draft, review and editing. Both authors approved the final version of the manuscript.

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Distribution and taxonomy of *Isoetes tuckermanii* subsp. *acadiensis*, comb. nov. (Isoetaceae) in North America

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Abstract

Isoetes acadiensis is an emergent aquatic lycophyte of freshwater shores found in a narrow range along the Atlantic coast of northeastern North America where it frequently coexists with *Isoetes tuckermanii* (*sensu stricto* [*s. str.*]). Apparently fertile plants with intermediate morphology occur commonly in mixed populations. No sterile hybrids between the two taxa have been detected. Although *I. acadiensis* maintains a distinctive geographic distribution (within and smaller than that of *I. tuckermanii* [*s. str.*]), exhibits molecular evidence of genetic distinctiveness, and has morphologically distinctive features in most populations, the weight of evidence suggests it is not distinct from *I. tuckermanii* at a species level. Accordingly, *I. tuckermanii* subsp. *acadiensis*, comb. nov. is proposed as the appropriate designation for this biogeographically important Acadian endemic.

Key words: *Isoetes tuckermanii* subsp. *acadiensis*; *Isoetes acadiensis*; *Isoetes tuckermanii*; taxonomy; distribution; Acadian endemic; lycophyte

Introduction

Interspecific relationships within the lycophyte group Quillworts (*Isoetes*; Isoetaceae) have received considerable attention in North America since the 1980s (Kott and Britton 1983; Taylor and Luebke 1988; Taylor *et al*. 1993; Brunton and Britton 1997; Musselman *et al.* 1997; Brunton and McNeill 2015). However, the infraspecific relationships of these *Isoetes* have received less attention because of the group's reputation for difficult identification (Tryon and Tryon 1982; Cody and Britton 1989). Subspecific classification is applied to separate the common North American *Isoetes echinospora* M. Durieu subsp. *muricata* (M. Durieu) A. Löve & D. Löve (Taylor *et al.* 1993) from Eurasian *I. echinospora* (*sensu stricto* [*s. str.*]) populations, but only one North American *Isoetes* subspecies has been described in recent years: *Isoetes melanopoda* M. Durieu subsp. *silvatica* D.F. Brunton & D.M. Britton in the southern United States (Brunton and Britton 2006; Troia and Rouhan 2018).

Acadian Quillwort, *Isoetes acadiensis* L.S. Kott, was separated from *Isoetes tuckermanii* A. Braun (Kott 1981) during a period of particularly dramatic re-evaluation of the genus in North America (Brunton and Troia 2018). Since that time, increases in the quantity and quality of *Isoetes* field data in North America have enhanced taxonomic clarity within the group in general and the *I. tuckermanii* – *acadiensis* complex in particular.

Recent distributional, morphological, and ecological evidence suggests that *I. acadiensis* may not be specifically distinct from *I. tuckermanii.* In some recent publications these taxa have been combined without nomenclatural distinction (Taylor *et al.* 2016). Based on extensive field and herbarium studies over several decades supported by enhanced and more abundant imagery than was available in the past, this study evaluates that concept and presents evidence for a reconsideration of the taxonomic status of *I. acadiensis*.

Methods

Kott (1981) identified three attributes that distinguish *I. acadiensis* from *I. tuckermanii*: megaspore and microspore ornamentation patterns and leaf colour. Over 300 herbarium specimens were examined for these and other definitive morphological and/or ecological attributes. Other features that have been useful in discriminating closely related *Isoetes* taxa, such as plant size, root and corm form and structure, spore size and colour, velum coverage of the sporangia, and sporangial pigmentation (Taylor *et al.* 1993, 2016; Brunton 2015), were found not to differ between *I. acadiensis* and *I. tuckermanii* (*s. str.*) (Kott 1981; Kott and Britton 1983; this study) and were not evaluated further.

Between 1989 and 2017, I examined 33 *Isoetes tuckermanii* (*sensu lato* [*s. l.*]) populations in the field in New Brunswick (NB), Newfoundland and Labrador (NL), Nova Scotia (NS), including the *I. acadiensis* type location, Ontario (ON), Connecticut, Maine (ME), Massachusetts (MA), and New Hampshire. These observations provide insight into the site ecology, population structure, and infraspecific abundance within individual populations throughout the range of the taxon.

Scanning electron microscope (SEM) images were taken of microspores and megaspores of selected specimens of *I. tuckermanii* (*s. l.*) from contemporary collections and herbarium specimens using the standard methods of Britton and Brunton (1992) and Brunton and Britton (2006). Herbaria reviewed for *I. tuckermanii* and related taxa include Acadia University (ACAD),

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Canadian Museum of Nature (CAN), Agriculture and Agri-Food Canada (DAO), Duke University (DUKE), University of Michigan (MICH), Milwaukee Public Museum (MIL), Missouri Botanical Garden (MO), Université de Montréal (MT), University of New Hampshire (NHA), Nova Scotia Museum of Natural History (NSPM), New York Botanical Garden (NY; selected specimens), New York State Museum (NYS), University of Guelph (OAC), Academy of Natural Sciences (PH), and author's private collection (DFB).

The concept of subspecies employed here is consistent with the traditional view of it as a geographically coherent component of a species with morphological distinctions that can intergrade (Davis and Heywood 1963; Kapadia 1963; Mayr and Ashlock 1991). This is more explicitly defined by USDA (2010) as "a grouping within a species used to describe geographically isolated variants, a category above variety".

The infraspecific term "variety" was used widely in earlier North American *Isoetes* literature (Engelmann 1867, 1882; Proctor 1949; Reed 1953). It was applied rather loosely however, to geographically randomized morphological variants; most of these have subsequently been synonymized or dismissed as forms. Article 25 of the International Code of Nomenclature (Shenzhen Code) states that varieties are components of subspecies but not equivalent to them (Turland *et al.* 2018).

Results

Isoetes tuckermanii is a locally common tetraploid ($2n = 4x = 44$), shallow-water aquatic/emergent of freshwater lake and river shores in northeastern North America (Taylor *et al.* 1993), growing in acidic or subacidic substrates. *Isoetes acadiensis* (also tetraploid) was distinguished from *I. tuckermanii* by Kott (1981) based on several key characters:

- megaspore ornamentation—lower, broader muri (Figure 1a) in a more open pattern than with *I. tuckermanii* (Figure 1b) and completely lacking the latter's equatorial band (girdle) of spines;
- microspore ornamentation—a densely echinate or coarsely papillate perispore (surface; Figures 2a,b) compared with a smooth to densely fine-papillate perispore in *I. tuckermanii* (Figures 2c,d);
- leaf colour—darker green, rarely exhibiting the reddish-brown colour typical of *I. tuckermanii*;
- restricted distribution—confined to a narrow band along the Atlantic coast (Figure 3).

Morphological variation and genetic distinction

Field and herbarium research undertaken in the current study indicates that several of the stated *I. acadiensis* attributes are also common in *I. tuckermanii* (*s. str.*) populations. Leaf colour, for example, was found to be uniformly reddish-brown in all 18 mixed populations (several thousand plants) examined *in situ* in NS and NB, including those at the type location for *I. acadiensis* in Halifax County, NS (Figure 4). Extensive examinations of SEM images obtained since 1981 have also determined that, although *I. acadiensis* plants routinely exhibit the densely echinate microspore ornamentation described in Kott (1981), such ornamentation is also frequently found on plants with typical *I. tuckermanii* megaspore ornamentation (e.g., Lake George, York County, NB, D.M. Britton and A. Anderson 11,915, [OAC]). Conversely, the smooth to papillate microspore ornamentation typical of *I. tuckermanii* is found on plants with typical *I. acadiensis* megaspore ornamentation (e.g., Uniake Lake, Hants County, NS, M.L. Fernald *et al.* 23,107 [GH] and Trefry Lake, Yarmouth County, NS, M.L. Fernald *et al.* 19,618, [NSPM]). Some *I. tuckermanii* (*s. l.*) specimens

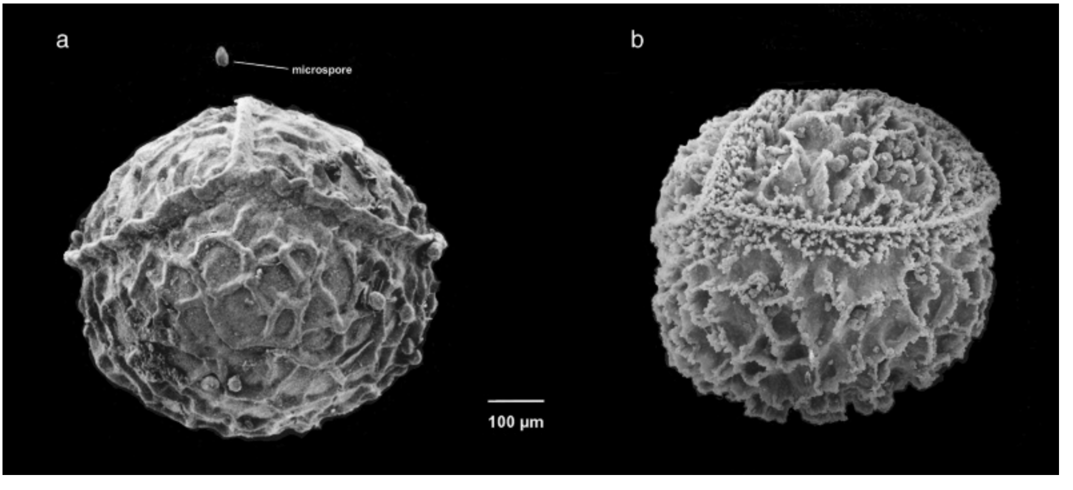

FIGURE 1. Typical megaspores of *Isoetes tuckermanii* (*s. l.*). a. *I. acadiensis*, Grand Lake Shubenacadie, Halifax County, Nova Scotia, R. Bidwell s. n., 11 August 1945 (Topotype) (NYPM); b. *I. tuckermanii* (*s. str.*), Taunton, Massachusetts, A.A. Eaton s. n., 15 September 1903 (MICH). Photos: Donald M. Britton.

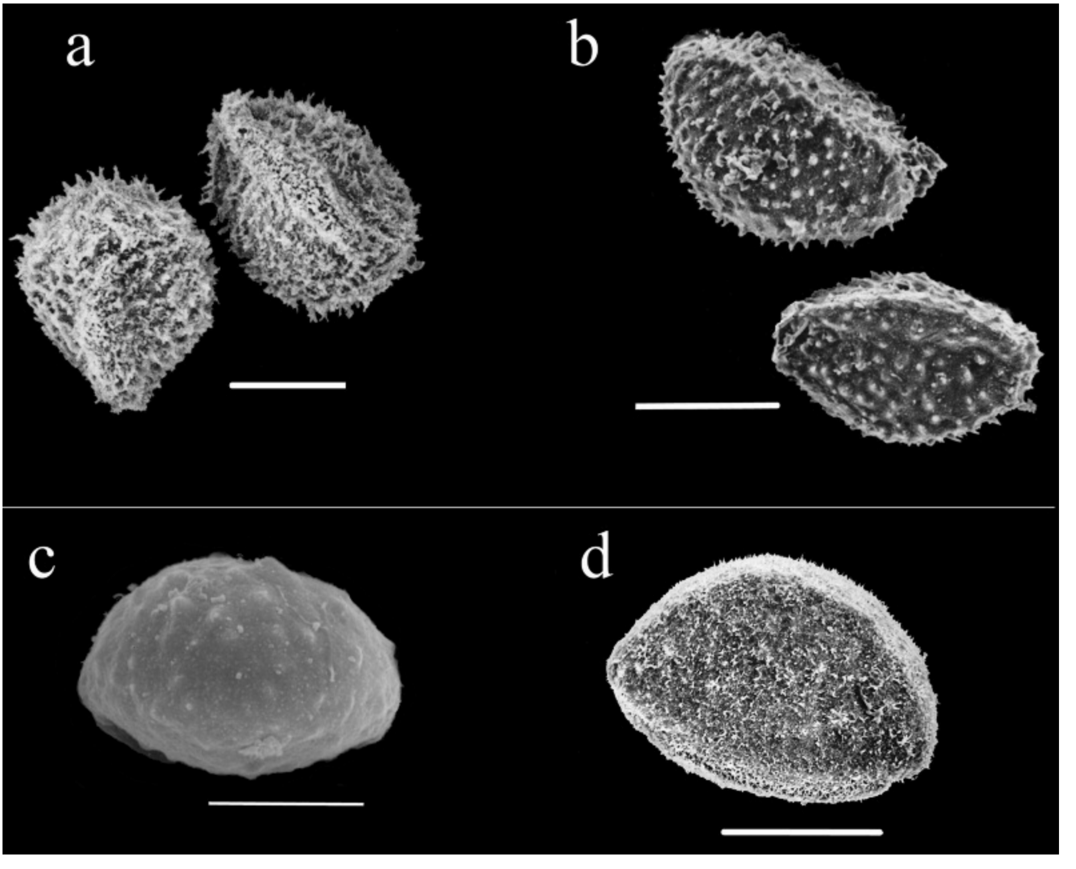

FIGURE 2. Typical microspores of *Isoetes tuckermanii* (*s. l.*). *I. acadiensis*: a. Short papillate–echinate type (Gavelton, Yarmouth County, Nova Scotia [NS], M.L. Fernald, B. Long & D.H. Linder 19,626, 4 August 1920 [NSPM]); b. Roughly echinate type (Grand Lake Shubenacadie, Halifax County, NS, R. Bidwell s. n., 11 August 1945 [NYPM]). *I. tuckermanii* (*s. str.*): c. Plain to smooth type (Taunton, Massachusetts, A.A. Eaton s. n., 15 September 1903 [MICH]); d. Densely fine-papillate type (Gray Lake, Muskoka District, Ontario, J. Goltz and P. Papoulidis 1,447, 11 August 1988 [OAC, DFB]). Scale bar = 10 µm. Photos: Donald M. Britton.

were found to contain microspores with both smooth to papillate and densely echinate ornamentation patterns (Figure 5). Consistent with most other polyploids in North America (Taylor *et al.* 1993; pers. obs.), no significant differences in megaspore or microspore size were detected between these two tetraploids (Kott and Britton 1983; this study).

That said, the extremes of megaspore ornamentation expression between *I. tuckermanii* (*s. str.*) and *I. acadiensis* can be dramatic, with the low, broad muri and a plain, unornamented equatorial band (girdle) typical of *I. acadiensis* (Figure 1b) contrasting sharply with the thin, high-walled muri and dense band of equatorial spines of *I. tuckermanii* (*s. str.*) (Figure 1a). Even this characteristic is ambiguous, however. I have found that many plants (a majority in some cases) in at least eight of 21 Canadian *I. acadiensis* populations considered to be that taxon on the basis of other characters to exhibit intermediate megaspore ornamentation (Figure 6).

No plants with the aborted megaspores indicative of sterile hybrids (Taylor and Luebke 1988; Britton and Brunton 1989, 1992) have been detected in mixed *I. acadiensis–I. tuckermanii* populations. Similarly, aborted megaspores have not been observed amongst the numerous (200+) plants with intermediate megaspore and/or microspore ornamentation observed in this study.

Strikingly, however, plants with typical *I. acadiensis* megaspore ornamentation as per Kott (1981) appear to be almost entirely confined to the Acadian region of northeastern North America (viz., the Maritime provinces of Canada and the adjacent northeastern United States; Figure 3).

Megaspore ornamentation patterns of particular populations remain true to form over many years. An example of this is provided by the consistent megaspore ornamentation pattern exhibited by *I. acadiensis* plants in Trefry Lake, Yarmouth County, NS, over the last century, starting in 1920 (M.L. Fernald & B. Long 19,614

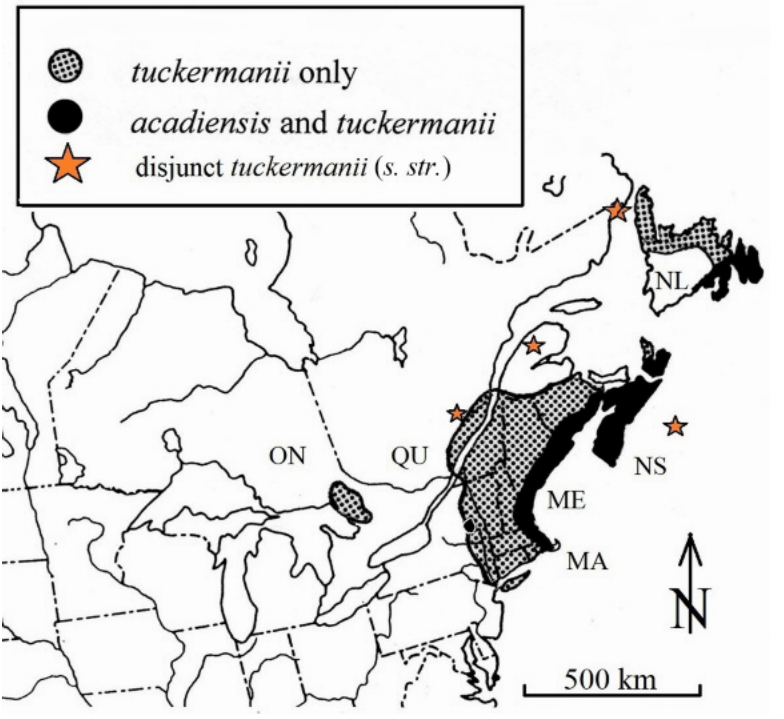

FIGURE 3. Distribution of *Isoetes tuckermanii* (*s. l.*) in North America (adapted from Taylor *et al.* 1993).

FIGURE 4. *Isoetes acadiensis* plants at type location, Grand Lake Shubenacadie, Halifax County, Nova Scotia, 18 July 2016. Coin is 27 mm across. Photo: D.F. Brunton.

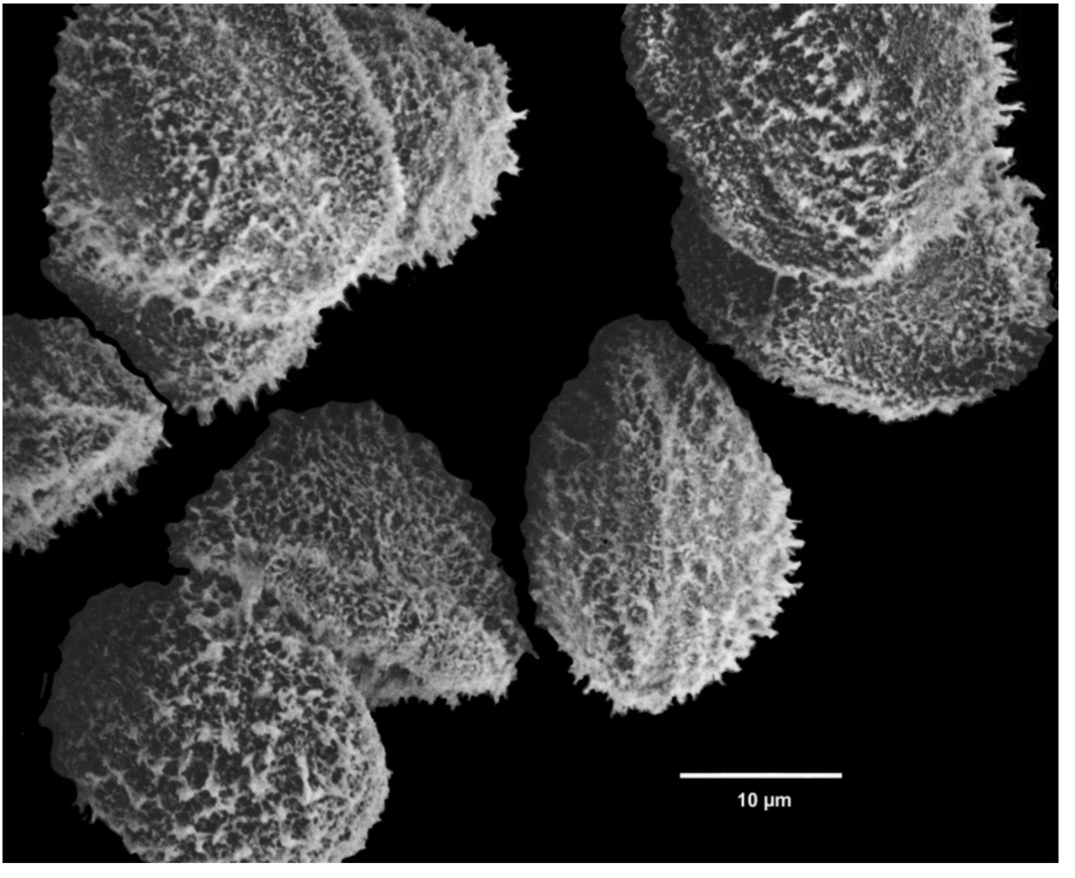

FIGURE 5. *Isoetes tuckermanii* (*s. l.*) microspores on a single plant with intermediate ornamentation ranging from finely papillate *I. tuckermanii* (*s. str.*) type (top left) to coarsely echinate *I. acadiensis* type (below, left, and right); Tusket River, Yarmouth County, Nova Scotia, J.S. Erskine 51.1436, 28 August 1951 [NSPM]). Photos: Donald M. Britton.

[NSPM]) through 1995 (D.F. Brunton and K.L. McIntosh 12,342 [OAC, DFB]) to 2015 (D.F. Brunton and K.L. McIntosh 19,400 [NY, DFB]). Currently however, plants showing megaspore ornamentation intermediate between "classic" *I. acadiensis* and *I. tuckermanii* (*s. str.*) appear to be the most commonly represented individuals at this site (pers. obs.).

Genetic evidence in support of particular taxonomic interpretations is unclear and perhaps contradictory. Based on DNA sequencing, Hoot *et al.* (2004) found a subtle but evident genetic distinction between *I. tuckermanii* (*s. str.*) and *I. acadiensis*. That study also found that despite a substantial (~800 km) oceanic gap between the two, genetic affinities (shared parental genomes) were evident between *I. acadiensis* and the European *Isoetes azorica* M. Durieu. Based on morphological characteristics, this relationship was alluded to earlier by Britton and Brunton (1996; see also Discussion, below). Recent data from contemporary Next Gen sequencing also suggests that insufficient justification exists for the treatment of *I. acadiensis* as specifically distinct from *I. tuckermanii* (P. Schafran pers. comm. July 2018). In contrast, however, the sequence data reported by Pereira *et al.* (2018) suggests species status distinctions based on different origins for *I. acadiensis* and *I. tuckermannii* (*s. str.*).

Isoetes acadiensis is reported as being of disjunct occurrence in brackish marshes in eastern Virginia, there providing the tetraploid parent for the sterile triploid ($2n$ = 3x = 33) hybrid *I. ×carltaylorii* L.J. Musselman (*I. acadiensis* × *engelmannii* A. Braun). The tetraploid taxon involved in this hybrid, however, appears to be *Isoetes riparia* M. Durieu var. *reticulata* A.A. Eaton, a rare Atlantic coastal taxon with atypically subdued megaspore ornamentation which mimics that of *I. acadiensis* (Brunton 2015). *Isoetes acadiensis* has not otherwise been reported south of MA, 650 km to the north.

Decaploid ($2n$ = 10x = 110) *Isoetes lacustris* L. forma *hieroglyphica* (A.A. Eaton) W.N. Clute is confused with *I. acadiensis* as well. It has megaspores ornamented with low, broad muri and a plain, unornamented equatorial band (Kott and Britton 1983; Tryon and Moran 1997; Haines 2011). The former is identical in all other respects to *I. lacustris* (*s. str.*) however. Most importantly,

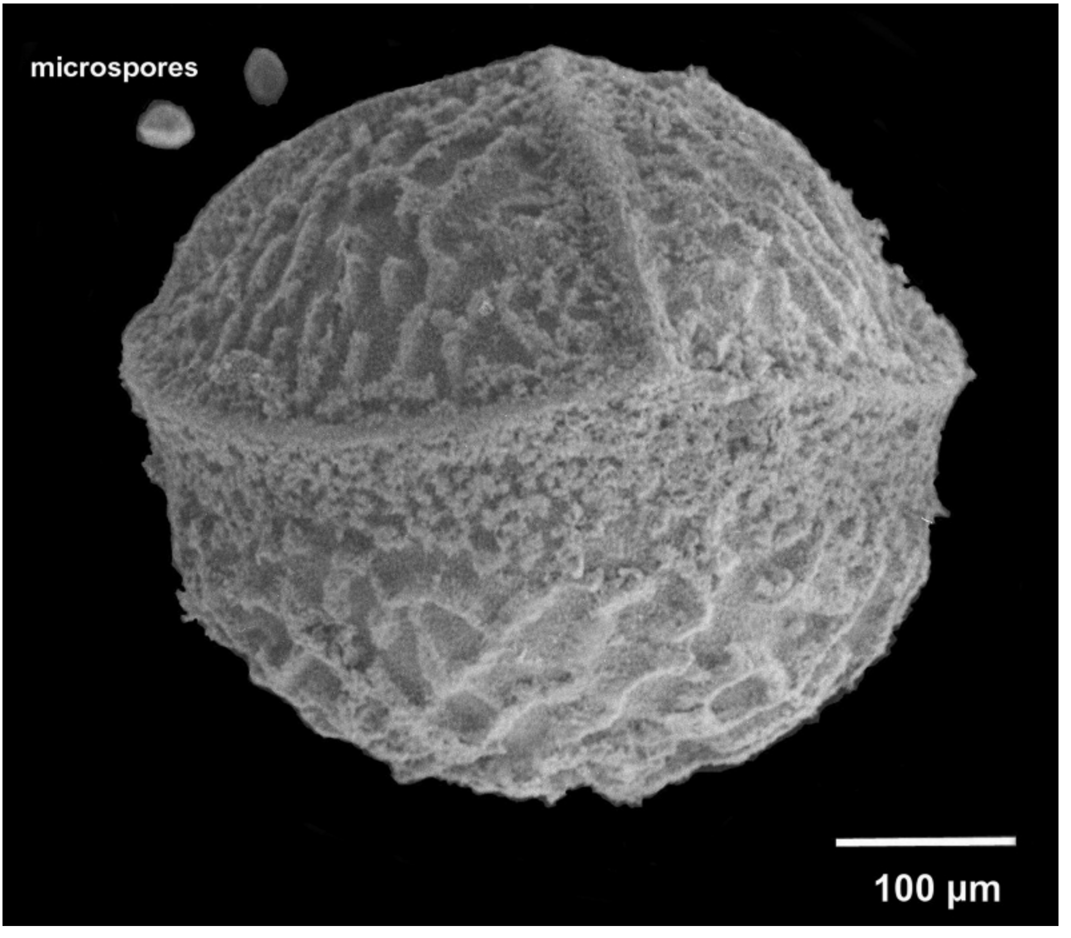

FIGURE 6. *Isoetes tuckermanii* (*s. l.*) with intermediate megaspore ornamentation, exhibiting the equatorial band of spines of *I. tuckermanii* (*s. str.*) and the lower, broader, less congested distal muri of *I. acadiensis* (Jassy Lake, Yarmouth County, Nova Scotia, R.C. Bean, D. White and D.H. Linder 19,615, 29 July 1920 [NSPM]). Photos: Donald M. Britton.

decaploid forma *hieroglyphica* has much larger (≥650 µm) megaspores than those (~520 µm) of tetraploid *I. tuckermanii* (*s. l.*) (Kott and Britton 1983; Taylor *et al.* 2016). Although found predominately in the Maritime provinces of Canada and adjacent New England, forma *hieroglyphica* rarely if ever forms pure populations and is found randomly across most of the range of *I. lacustris* (*s. l.*) as far west as central ON (Boshkung Lake, Stanhope Township, Haliburton County, ON, D.F. Brunton, K.L. McIntosh, W.C. Taylor & C.A. Caplen 13,349C, 9 August 1997 [OAC]).

Ecological segregation

Although plants of *I. acadiensis* and *I. tuckermanii* (*s. str.*) were most often found randomly in the 18 mixed populations examined in this study, some habitat differentiation has been noted. Transects conducted across large mixed populations in Yarmouth County, NS, in 1990, for example, indicated that plants with *I. acadiensis* megaspore ornamentation patterns occurred disproportionately in very shallow water or on emergent shores, while those with *I. tuckermanii* megaspore ornamentation patterns most commonly occurred in deeper water (0.5–1 m; pers. obs.). However, an exactly reversed situation was observed along similar transects conducted in mixed populations in Barnstable and Plymouth Counties, MA, in 1989 (pers. obs.). Accordingly, while some ecological segregation appears to be occurring within individual populations, no consistent pattern has been established.

Discussion

The herbarium, SEM, and field investigations described above, as well as most of the molecular evidence noted here, suggest that *I. acadiensis* constitutes a genetically distinct taxon (with European affinities) within *I. tuckermanii* (*s. l.*) and is almost exclusively confined within a restricted geographic range. A collection from Stoner Lake, Fulton County, New York (R.T. Clausen 5518, 17 August 1941 [NYS]) represents the only significantly inland report of this taxon (Figure 3). This distributional evidence, the absence of diagnostic morphological characters, ambiguous genetic evidence, and the apparent absence of sterile hybrids within populations that frequently (more than 60%) are mixed, indicate that *I. acadiensis* is not specifically distinct from the more wide-ranging *I. tuckermanii* (*s. str.*). The available evidence suggests that a subspecific ranking is the most appropriate designation for this taxon; that is proposed here.

Isoetes tuckermanii A. Braun **subsp. *acadiensis*** (L.S. Kott) D.F. Brunton, **comb. et stat. nov.**

Basionym: *Isoetes acadiensis* L.S. Kott; Canadian Journal of Botany 59: 2592. 1981.

Isoetes tuckermanii subsp. *acadiensis* may represent a relatively recent evolutionary "experiment" dating from the Wisconsinan or middle Sangamonian continental glaciation period (<110 000 years before present). During this period, extensive areas of the now-submerged continental shelf were exposed and available for colonization by coastal plain taxa (Fulton 1989). The identification of genetic affinities of *I. tuckermanii* subsp. *acadiensis* with *I. azorica* by Hoot *et al.* (2004) supports this, suggesting the former might once have occurred across a much larger area of the exposed continental shelf coastal plain. Accordingly, it likely was considerably more common at that time than it is today. Comparably, the rare Acadian quillwort endemic *Isoetes prototypus* D.M. Britton (Britton and Goltz 1991), may also have been more widely distributed across that larger glacial era Atlantic coastal plain.

Individual *I. tuckermanii* subsp. *acadiensis* populations are large—often consisting of hundreds or even thousands of plants (pers. obs.)—but it is found in relatively few individual populations overall. It is accordingly designated to be of conservation concern in NL (S1), NB (S2S3), NS (S3), ME (S2), and MA (S1) (NatureServe 2019). In addition to this significance, the taxon presents considerable potential for evolutionary and biogeographic research.

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Seasonal and temporal variation in scaled mass index of Black-capped Chickadees (*Poecile atricapillus*)

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Abstract
Avian body mass reflects a trade-off between risk of starvation and predation, and may vary with ambient temperature, age, and time of day. Seasonal variability in body mass is a common occurrence in northern temperate regions, including adaptive fattening. Previous evidence suggests that seasonal variability is less pronounced in tree-feeding bird species, as their food sources during winter are less limited and variable compared to ground-foraging species. We determined fat scores of tree-feeding Black-capped Chickadees (*Poecile atricapillus*) captured year-round between 2004 and 2015 (n = 4248) in southern Quebec, to test the relative strength of possible drivers of variability in chickadee body mass, including time, date, and year of capture, age, and temperature. First, we demonstrated that scaled mass index (SMI) was the body condition index, out of four possible indices tested, which most strongly correlated with fat scores measured in the field. We used SMI subsequently as our estimator of body condition to avoid observer effects associated with fat scores. Similar to other studies, time of capture significantly affected SMI, in which birds captured later were heavier, indicating that chickadees experience overnight weight loss and subsequent weight gain from foraging throughout the day. SMI was constant from April to November, then peaked in late winter, but was not influenced by daily temperature after accounting for month and year. SMI was not significantly affected by age. We concluded that adaptive fattening is an evolutionary response to risk of starvation in winter, rather than a proximal response to immediate ambient temperature.

Key words: Black-capped Chickadee; condition index; fat stores; scaled mass index; temperature; temporal; body mass

Introduction
Body mass varies greatly within bird species, often representing variation in lipid mass, and reflecting costs and benefits to high lipid stores (Lindstedt and Boyce 1985; Cresswell 1998). Higher lipid deposits may increase survival during periods of food shortage because fatter individuals have more endogenous energy stores (Thomas 2000; Krams *et al.* 2009; Ratikainen and Wright 2013). In winter, these energy stores may also act as buffers against cold temperatures, as birds expend more energy for thermoregulation, as well as against short winter days when reduced foraging increases the risk of starvation (Brodin *et al.* 2017; Da Silva *et al.* 2017). However, costs to higher body mass due to higher lipid deposits may include reduced takeoff ability and more time spent foraging to maintain a high body mass, both of which can increase chances of predation (Gosler *et al.* 1995; MacLeod *et al.* 2005, 2008; Rogers 2015). Alternatively, variation in lipid deposits may be stress-induced rather than adaptive; a lower average body mass may reflect low food availability rather than a fitness optimum (Ketterson *et al.* 1991; Kitaysky *et al.* 1999).

In northern temperate regions with large climate ranges, the effect of seasonality on body mass is especially pronounced (Haftorn 1992; Rogers 1995; Cooper 2007; Polo *et al.* 2007). The concept of adaptive winter fattening, in which small birds residing in cold habitats build up large fat reserves in response to low temperatures, has been widely studied (Haftorn 1989; Rogers 1995; Koenig *et al.* 2005; Merom *et al.* 2005) since its introduction by King and Farner in 1966. Weight gain in winter is caused by increased lipid deposits, which provide the metabolic fuel required to sustain an individual during winter fasts or food shortages (Lehikoinen 1987), as well as enlarged organs and muscles (Liu *et al.* 2008; Zheng *et al.* 2008, 2010; Liknes and Swanson 2011). Body mass tends to peak in midwinter and decline thereafter (Haftorn 1989). Lower body mass in spring and summer may be attributed to physiological stress during the breeding season or adaptive reduction in wing-loading to ease the labour of feeding nestlings (Freed 1981; Nagy *et al.* 2007). Other temporal factors that affect body mass include diurnal variation and migration (Winker *et al.* 1992; Cresswell 1998; Schaub and Jenni 2000).

Black-capped Chickadee (*Poecile atricapillus*), a tree-foraging species, overcomes the hardships of winter by caching its resources (Sherry and Vaccarino 1989), relying on micro-climates (Cooper and Swanson 1994), undergoing facultative diurnal hypothermia (Lewden *et al.* 2014), and increasing breast muscle size and enzymatic activity to improve shivering thermogenesis (Liknes and Swanson 2011). In ground-foraging birds, the trend of adaptive winter fattening holds true for several species, including juncos and sparrows (King and Farner 1966; Newton 1969; Rogers 1995), which those authors argued was exacerbated in ground-foragers because snowfall could limit access to ground-borne resources, resulting in food shortages. In comparison, tree-foraging species have more predictable resources, and as such do not need to build up as large a fat supply (Rogers 1987; Rogers and Smith 1993; Graedel and Loveland 1995). The body mass of tree-feeding species varies diurnally and seasonally, although the role of adaptive winter fattening is less prominent (Dawson and Marsh 1986; Silverin *et al.* 1989; Koivula *et al.* 1995; Cooper 2007).

There are several challenges associated with measuring size-corrected body mass in a non-destructive manner, such that ecologists have created various "condition indices" (Sears 1988; Redfern *et al*. 2000; Stevenson and Woods 2006; Jacobs *et al.* 2012). Some of the first indices involved using the ratio of body mass to a metric of body size, such as wing length. However, that method is often inaccurate because body size is seldom directly proportional to body mass (Peig and Green 2009). Calculating residuals from ordinary least squares regression (OLS) is one of the most popular methods, although several have argued that OLS violates key assumptions, leading to Type I and Type II errors (Garcia-Berthou 2001; Green 2001; Peig and Green 2009, 2010). To counter the flaws in OLS, Peig and Green (2009) developed the scaled mass index (SMI), which accounts for covariation between body size and body mass components during calculations by correcting body mass by a relative measure of body length.

Black-capped Chickadees are generally a well-studied species, particularly for food-storing behaviours (Sherry and Vaccarino 1989; Hitchcock and Sherry 1990; Smulders *et al.* 2004), social behaviour (Otter *et al.* 1998; Mennill *et al.* 2003), and vocal communication (Otter *et al.* 1997; Christie *et al.* 2004; Mennill and Ratcliffe 2004). The overall aim of our research was to provide additional information on fat mass variation at short- and long-time scales in Black-capped Chickadees using a 12-year data set and build on previous work that had focussed primarily on changes in muscle mass throughout the year (Swanson and Olmstead 1999; Swanson and Liknes 2006; Petit and Vézina 2014). Although we have direct estimates of visual lipid deposits within our dataset, those visual estimates are subjective and likely influenced by observer bias. Consequently, we elected to use a size-corrected mass index to estimate lipid levels in chickadees, with fat being the major cause of variation in body mass mediating a trade-off between higher reserves (longer fasting duration) and lower load (quicker predator escape). Thus, our first goal was to identify which condition index (body mass only, body mass/wing length, OLS, and SMI), is the most accurate predictor of lipids (as estimated by fat scores) in wild Black-capped Chickadees. We predicted that SMI would be the most reliable predictor of fat scores, as SMI accounts for proportions relative to the individual and overcomes the flaws found in OLS. Our second goal was to determine the trends in size-corrected body mass using the available data, through the comparison of the most reliable condition index with various predictors, including mean temperature, time of day, and age. As chickadees are an overwintering species, we predicted that at longer time-scales (months) they undergo adaptive winter fattening. Specifically, we predicted that chickadees would have a higher relative body mass in winter and lower relative body mass in summer. We also predicted that at shorter time scales (hours) chickadees would be lightest in the morning after a night of fasting and would increase in relative body mass through the day due to foraging (Bednekoff and Krebs 1995; Cresswell 1998; Kullberg 1998). Lastly, we predicted that older chickadees, which are more experienced at finding food, and typically of higher rank with better access to food, would need smaller fat reserves (Daunt *et al.* 2007; Marchetti and Price 2008).

Methods

Data were collected in southern Quebec, Canada, at the McGill Bird Observatory from September 2004 until December 2015 as part of banding operations. The bird banding station is located adjacent to the Morgan Arboretum in Sainte-Anne-de-Bellevue, Quebec (45.43ºN, 73.94ºW), in an open mixed deciduous/coniferous forest. Black-capped Chickadees were caught in a total of 16 mist nets to be weighed, measured, aged, sexed, and banded by trained individuals. Mist nets (110d/2 thread, 30 mm, 4 shelf passerine nests from SpiderTech, Helsinki, Finland) measured 8–12 m in length, 3 m in height, with a mesh size of 30 mm. During the spring and fall migration monitoring period, mist nets were open for five hours daily, starting 30 minutes before dawn except during rain. During the summer, chickadees were captured during MAPS (Monitoring Avian Productivity and Survivorship) operations, with mist nets open for six hours daily, starting 30 minutes before sunrise for each 10-day period (DeSante *et al.* 2016). During the non-standard winter banding, mist nets were employed opportunistically based on the weather conditions. Birds were collected from nets every 30 minutes, or more often during windy days. To reduce the impact on the birds, we did not net in the rain or in very poor conditions, and consequently we may be unable to detect the effect of extreme conditions. Further information about the banding process appears in Gahbauer and Hudson (2014).

The resulting dataset contains 4459 observations from 1866 individuals with outliers (outliers = body weight or wing chord ± 4 SD) removed over the 12-year period. Outliers were likely due to human error during the recording of data. Black-capped Chickadees were aged by variation in their plumage. Not all individuals were reliably aged, depending on the time of year and the plumage characteristics, and in these cases the birds were recorded as unknowns (Pyle 1997). Chickadees were assigned "young" and "old" age classifications. Birds of unknown age were excluded from the analysis. Fall hatch-year and spring second-year birds were categorized as "young" and fall after hatch-year and spring after second-year were considered "old", for a total of 4248 observations that were of known age (Table 1). We did not determine the sex of the birds outside of the breeding season, so it was excluded from the analyses. Birds were weighed on an electronic balance (iBalance 700, My Weight Canada, Vancouver, British Columbia, Canada; accuracy of 0.1 g), and wing length was measured with a ruler (accuracy of 1 mm). Each bird was released shortly after the banding process was completed.

Subcutaneous fat was visually estimated using standard protocol and codes from the MAPS program (DeSante *et al.* 2016). As described by Rogers (1991: 351):

> Each bird was held in the left hand, ventral side up, with the first two fingers of the left hand on the ventral (first finger) or dorsal (second finger) side of the neck. The first finger pressed against the base of the bill so that the bill pointed forward at approximately 45° above the extended longitudinal axis of the bird. The first finger of the right hand was held lightly against the left side of the pectoral musculature while the right thumb lightly held the tail in its natural position. Birds were held gently to avoid injury, but firmly to avoid escape. With the bird held in the above position, the ventral contour feathers were blown aside and the subcutaneous fat observed in the two defined areas was classified as follows (after Nolan and Ketterson 1983). 0 = no visible fat on abdomen (A) or in furcular depression (F). 1 = F < 33% full, A < 50% covered. 2 = F 33–66% full, A 50–100% covered but fat layer not even with pectoral region. 3 = F filled and fat flush with pectoral musculature, A completely covered, fat layer flush with pectoral musculature, thus neither F nor A bulging outward from pectoral musculature. 4 = as in 3 with F or A bulging. 5 = both F and A bulging. Subcutaneous fat was recognized by its yellow or orange-yellow color, which contrasts with the dark red color of muscle.

Temperature data were collected from the Sainte-Anne-de-Bellevue climate station, located 1.5 km away from the banding sites (45.25ºN, 73.55ºW), in Sainte-Anne-de-Bellevue, Quebec, Canada. As temperature data were occasionally missing from the local climate station, missing data were replaced using an equation (Sainte-Anne-de-Bellevue Temperature = 0.9987 × Airport Temperature – 0.2886, $R^2 = 0.99$) based on available data from the next closest climate station, at the Pierre Elliott Trudeau Airport (16 km away from banding sites; 45.28°N, 73.45°W) in Montréal, Quebec, Canada (Environment Canada 2015).

TABLE 1. Number of captures of Black-capped Chickadees (*Poecile atricapillus*) across a 12-year period in southern Quebec, Canada. Only those used in the analyses are included (*n* = 4248). Seasonal captures across all years were: 332 in late winter (January–March), 297 in spring (April–May), 542 in summer (June–August), 2277 in fall (September–October), and 800 in early winter (November–December).

Year	Number of captures
2015	393
2014	379
2013	272
2012	551
2011	342
2010	711
2009	331
2008	164
2007	307
2006	229
2005	442
2004	127

Comparing condition indices

The regressions of the log-transformed body mass and wing length were taken to determine the slope of the regression (1.105), which was used later during the SMI calculations. We used a linear mixed-effects model (R package nlme; function lme; Pinheiro *et al.* 2016) to compare four different measurement methods: body mass only, body mass/wing length, OLS, and SMI, all of which act as predictors of fat. The data included only the individuals that had been captured at least three times over the duration of the study (2787 observations from 360 individuals) and using a linear mixed-effect model reduced pseudo-replications associated with recaptures. "Body mass only" used the actual weight (g) of each bird recorded by banders. We calculated the "weight/wing length" for each individual by dividing body mass (g) by wing length (mm). We obtained OLS values by calculating the residuals of body mass on wing length using the ordinary least squares regression. SMI was calculated using the formula

$$\widehat{M_i} = M_i\left[\frac{L_0}{L_i}\right]^{b_{SMA}}$$

where slope (1.105) of the body mass ~ wing length regression acted as the scaling exponent, b_{SMA}, and M_i and L_i were the observed values, L_o was the average length value for the entire population, and $\hat{M}_i$ was the predicted value for mass (Peig and Green 2009). Prior to using parametric statistics, we tested for normality in the data (Shapiro-Wilks; cut-off of W > 0.95; R package stats; function shapiro.test; R Core Team 2015).

We excluded fat scores of 4, 5, or 6 due to very small sample sizes, and because the average mass for 4, 5, and 6 were lower than the average fat score of 1, thereby implying they were likely erroneous (i.e., chickadees are never fatter than a 3). The excluded values were distributed randomly throughout the year, and showed no pattern (and were rare), so excluding these values had no impact on our results. Because fat scores do not linearly translate into body mass, we first converted fat into body mass using the same model with fat score as a function of body mass (fixed effect) and individual (random effect), only including those individuals with at least three measurements. Setting a fat score of zero equal to 0 g, based on the linear effects model, a fat score of one was equal to 0.14 g, a fat score of 2 was equal to 0.39 g, and a fat score of 3 was equal to 0.54 g. Next, for each condition index, we calculated a linear mixed-effect model of fat score (converted to mass as above and with fat scores greater than 3 excluded) as a function of condition (fixed effect) and individual (random effect). We used Pearson's product-moment correlation test (R package stats; function cor; R Core Team 2015) to determine whether wing length is independent of body mass. We used a significance test with alpha set at 0.05 to determine which variables to include in the linear mixed-effect models.

Predictors of variation in size-corrected body mass

We calculated SMI for all 4248 observations for further analyses to test various predictors: temperature, age, and time of capture as time of day, and time of capture in month and years. We corrected for the time of day of capture by sunrise, using the formula: (time of capture – time of sunrise)/day length. Sunrise and day length data were collected from the National Research Council's sunrise database (National Research Council Canada 2016), using Montréal as the closest available city. Time of capture in month and year for all analyses were treated as categorical variables.

We first explored the relationships between the five possible drivers of SMI individually using univariate tests. For age (old versus young) we ran an unpaired, one-sample t-test (R package stats; function t.test; R Core Team 2015). For temperature and relative time capture we used linear regression (R package lm; function t.test; R Core Team 2015). For month and year of capture we use an analysis of variance (R package aov; function t.test; R Core Team 2015).

Next, we determined the relative strength of each driver, or biologically relevant combination of drivers, using mixed-effect linear models (R package lme4; function lmer; Bates *et al.* 2017), with individual as a random effect. We framed our *a priori* candidate models to test the following hypotheses: (1) including all drivers (temporal, temperature, age) effects additively (global model), (2) average hourly temperature of the capture time alone (temperature model), (3) age of the individual at the time of capture alone (age model), (4) shorter time-scale temporal effects only as capture time of day alone (time of day model), (5) longer time-scale temporal effects including additive effects of month and year of capture (month/year model), (6) longer time-scale temporal effects including additive and interaction effects of month and year of capture (interaction month/year model), (7) short and long time-scale effects together additively (time of day/month/year model), and (8) short and long time-scale effects together additively, and interaction of month and year of capture (interaction day/month/year model). We evaluated all nine models (including a null model with random effect of individual only) using Akaike Information Criterion adjusted for small sample sizes (AICc; Hurvich and Tsai 1989). Models were ranked according to the strength of support of each model, as determined by the difference in AICc between a given candidate model and the model with the lowest AICc (ΔAICc; Anderson *et al.* 2001). AICc is a measure of model performance, which compares the maximum-likelihood estimates of the models, while penalizing for increasing complexity. Ranking was corroborated with the conditional R^2 of the models (R package piecewiseSEM; function sem.model.fits; Lefcheck 2016).

Results

Comparison of condition indices

SMI was the best predictor for subcutaneous fat measured in Black-capped Chickadees (t_{2423} = 5.05; $P <$ 0.0001), followed by body mass only, body mass/wing length, and OLS (Table 2). Pearson's product-moment correlation test showed that wing length correlated positively with body mass (t_{2423} = 43.7, $P <$ 0.0001, R = 0.55).

Predictors of SMI in Black-capped Chickadees

We found no significant difference between the SMI of young versus old Black-capped Chickadees (Figure 1a), with older birds having an average SMI of

TABLE 2. Simple regression statistical output for four different body condition indices as predictors of fat in Black-capped Chickadees (*Poecile atricapillus*) captured across a 12-year period in southern Quebec, Canada. Shown are the computed standard error, *t*-value, and *P*-value from a linear mixed effects model.

Model	df	*t*-value	*P*-value
Body mass only	2423	4.04	0.0001
Body mass/wing length	2423	−1.67	0.1000
Ordinary least squares regression	2423	1.59	0.1100
Scaled mass index	2423	5.05	<0.0001

10.90 ± 0.62 (SD) g, and young birds having an average of 10.92 ± 0.60 g. While both regressions of temperature and the relative time of capture to SMI were significant ($P < 0.001$), both model fits were low (Adjusted $R^2 = 0.03$, 0.005, respectively; Figure 1). Overall, SMI of Black-capped Chickadees decreased with increasing temperature (Figure 1b) and increased with relative time of capture (Figure 1c). SMI of Black-capped Chickadees also significantly differed across the 12 months of the year, and the 12 years of the study (Figures 1d,e).

Of the nine models tested, the model that included all the temporal variables (time of day of capture, month, and year) explained the most variation in the SMI of Black-capped Chickadees (Table 3). The next best model (month/year of capture, as determined by AICc) was >8 AICc from the top model, thus it was significantly weaker than the top model (Anderson 2008). Thus, SMI variation in Black-capped Chickadees was primarily driven by temporal factors. We found a significant and positive effect of the time of day, with birds increasing in SMI later in the day (Table 4). Chickadees varied in their SMI across the year, with birds later in the winter (February and March) having significantly greater SMI, and birds in the later summer and fall (July–November) having significantly lower SMI, compared to a January baseline (Table 4). SMI also varied across the 12-years of study, with certain years (e.g., 2013–2015) having chickadees with significantly higher SMI on average (Table 4).

Discussion

SMI as an indicator of fat stores in Black-Capped Chickadees

As predicted, SMI was the most accurate predictor of subcutaneous fat stores in Black-capped Chickadees, followed by body mass only, and body mass/wing length. OLS correlated the least to fat stores. Our results support our prediction that SMI, which corrects body mass by relative wing length, would be the most accu-

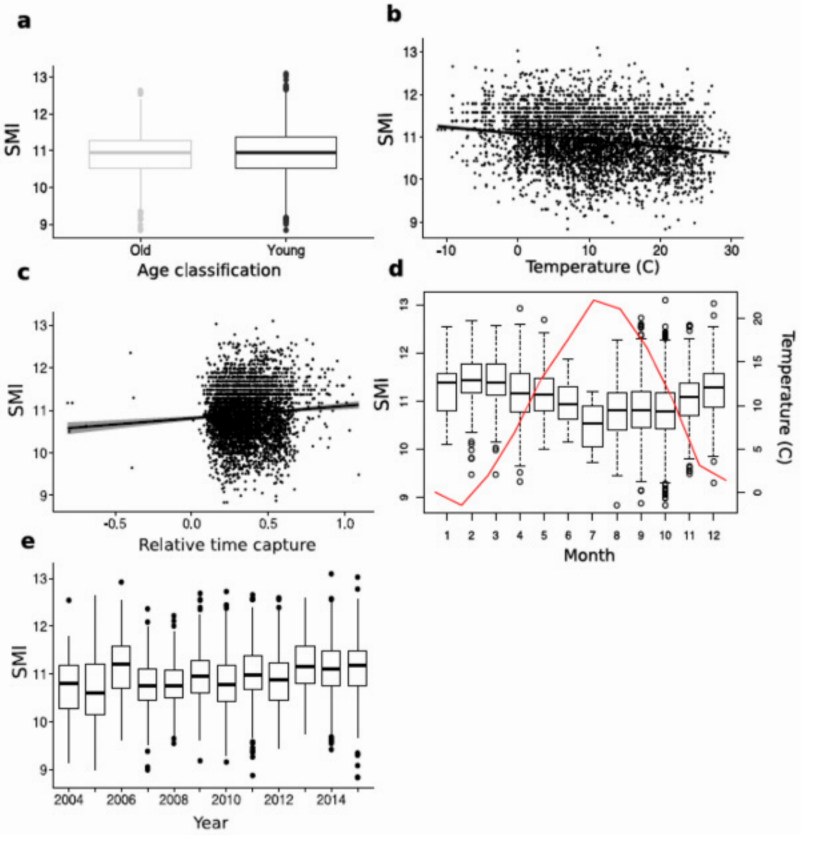

FIGURE 1. a. Boxplot of scaled mass index (SMI) of young and old Black-capped Chickadee (*Poecile atricapillus*); b. scatterplot of SMI versus mean temperature of day of capture for Black-capped Chickadees with linear regression line and 95% confident region in grey; c. scatterplot of SMI versus relative time of capture for Black-capped Chickadee; d. boxplots of SMI of Black-capped Chickadee across 12 months of the year, averaged across all years of study, with line graph of the average monthly temperature for each month across the study period in red; e. boxplots of mean SMI of Black-capped Chickadees across 12 years of the study.

TABLE 3. Summary of rankings of candidate models using Akaike Information Criterion for small sample sizes (AICc) from linear mixed-effects models assessing the variation of scaled mass index (SMI) in Black-capped Chickadees (*Poecile atricapillus*) captured across a 12-year period in southern Quebec, Canada.

Model	df	ΔAICc	Conditional R^2
Time of day/month/year	26	0.0	0.67
Month/year	25	53.9	0.67
Global	113	151.7	0.69
Interaction time of day/month/year	111	182.7	0.69
Interaction month/year	110	232.2	0.68
Temperature	4	509.2	0.61
Time of day	4	577.3	0.62
Age	4	646.2	0.60
Null	3	663.7	0.59

TABLE 4. Parameter estimates from the time of day/month/year linear mixed-effects models assessing the variation of scaled mass index (SMI) in Black-capped Chickadees (*Poecile atricapillus*) captured across a 12-year period in southern Quebec, Canada. Model output for month effects are relative to January, and year effects relative to 2004. Significant parameter estimates are bolded.

Model parameters	Estimates	SE	Df	*t*-value	*P*-value
Time of capture	0.36	0.04	3268	7.80	<0.001
Month of capture					
February	0.15	0.07	3423	2.07	0.040
March	0.15	0.06	3397	2.36	0.020
April	−0.03	0.07	3410	−0.49	0.630
May	0.06	0.07	3324	0.84	0.400
June	−0.13	0.11	3763	−1.12	0.260
July	−0.75	0.09	3587	−8.45	<0.001
August	−0.42	0.06	3492	−6.83	<0.001
September	−0.37	0.06	3502	−6.12	<0.001
October	−0.36	0.06	3561	−6.16	<0.001
November	−0.21	0.06	3436	−3.55	<0.001
December	−0.06	0.06	3323	−0.89	0.370
Year of capture					
2005	−0.08	0.05	3930	−1.54	0.120
2006	0.20	0.06	4036	3.10	<0.001
2007	0.02	0.06	4227	0.31	0.760
2008	0.05	0.07	4200	0.67	0.510
2009	0.14	0.06	4218	2.30	0.020
2010	−0.02	0.06	4161	−0.41	0.690
2011	0.13	0.06	4228	2.03	0.040
2012	0.10	0.06	4149	1.72	0.090
2013	0.28	0.07	4202	4.23	<0.001
2014	0.26	0.06	4123	4.05	<0.001
2015	0.18	0.07	4029	2.75	0.010

rate condition index out of the four methods for Black-capped Chickadees. Similar to our findings, SMI was found to be a good predictor in another passerine species, European Starling (*Sturnus vulgaris*; Peig and Green 2009), while being a poor predictor of fat stores in non-passerine birds (Jacobs *et al.* 2012).

The use of OLS as a measure of body condition has been contested in recent years (Labocha and Hayes 2012). Peig and Green (2009) argued that OLS favours large individuals, as OLS measures absolute rather than relative fat (see Blackburn and Gaston 1997). Moreover, OLS may lead to Type I and Type II errors via violations of key assumptions—that the body size indicator (BSI) length (in this study: wing length) is independent of mass, and that BSI length does not have error (Green 2001). The result from the Pearson's product-moment correlation test demonstrates that our data violates the first assumption. Conversely, Schulte-Hostedde *et al.* (2005) compared OLS to major axis and reduced major axis regression and found OLS to be the suitable choice. Likewise, Jacobs *et al.* (2012) found that OLS outperformed SMI in predicting lipid stores in seabirds. While "body mass only" was the second most reliable option, we do not recommend using body mass alone as a predictor of fat *in lieu* of other methods, as it is necessary to account for relative proportions of each individual.

Temporal drivers as strongest predictors of SMI variation in Black-Capped Chickadees

Temporal variables at both short time-scales (hours of the day) and long time-scales (months and years), were the strongest predictors of SMI variation in the Black-capped Chickadees in our study area. SMI was lowest in the morning and higher later in the day, which supports our prediction. Black-capped Chickadees spend several hours in the morning foraging to compensate for the energy lost the previous night. As hours go by, mass will increase until nightfall arrives again and body mass drops (Brittingham and Temple 1988). As shown in other studies, plasma triglycerides, indicative of fattening, are also high through mid-morning before dropping off in the afternoon, implying that most fattening occurs in the early morning (Mandin and Vézina 2012; Devost *et al.* 2014). Triglyceride levels, and therefore fattening, are highest in mid-winter (Mandin and Vézina 2012), consistent with our study.

SMI was, averaged across years, lowest from July to November, and highest in January to March suggesting that Black-capped Chickadees undergo adaptive winter fattening, although seasonal variation in body mass may be stress-induced or adaptive in other ways (Ketterson *et al.* 1991; Cresswell 1998; Kitaysky *et al.* 1999; Thomas 2000; Krams *et al.* 2009; Ratikainen and Wright 2013). Lower body mass in summer may be attributed to the stress of breeding season (Nagy *et al.* 2007), or reduction in energetic demands when flying to facilitate delivery of food to nestlings (Freed 1981; Croll *et al.* 1991). However, as we found low SMI from July–November, including the period well outside of the breeding season, we suggest that changes in SMI are mostly associated with winter fattening. Interestingly, we found that mean temperature did not significantly affect SMI in chickadees despite the seasonal variation in body mass. This discrepancy suggests that fat mass is programmed to increase during winter, rather than in response to immediate ambient temperature, although other factors, such as food availability and predation risk, may play important roles. These results are similar to other studies on tree-foraging species, including American Goldfinch (*Spinus tristis*; Dawson and Marsh 1986), Great Tit (*Parus major*; Silverin *et al.* 1989), and Willow Tit (*Poecile montanus*; Silverin *et al.* 1989; Koivula *et al.* 1995).

Age did not significantly affect SMI. In other species, weight generally increases with age due to growth and perhaps an improvement in feeding efficiency (Brooke 1978; Weimerskirch 1992). However, previous work on chickadees has demonstrated that birds of higher rank, which tend to be older (3.2 y compared to 1.5 y for subordinates), are often lighter with lower fat scores, presumably because they have better access to food sources (Schubert *et al.* 2007). We expected younger birds, presumably of lower rank, to have a higher SMI to buffer against the risk of starvation, a threat which might be greater for younger birds, but our data do not reflect this.

Black-capped Chickadees are often the focus of food-caching research, but there are few data on predictors and mechanisms behind body mass variation in this species. Although chickadees demonstrated winter fattening, it remains to be seen if temperature acts as a proximal or ultimate cause of weight gain/loss. The next step is to undertake experimental manipulations of temperature to determine how that influences avian body mass. Past studies have demonstrated that temperature, when measured over a longer period of time (e.g., several days to a month), acts as a proximal influence on metabolic rate in chickadees (Swanson and Olmstead 1999; Dubois *et al.* 2016). This current study used a much smaller window (time of capture) to assess the impact of temperature, and thus future research may wish to examine longer temporal variables as potential proximate factors.

Author Contributions

Writing – Original Draft: E.N.; Writing – Review & Editing: K.E. and B.F.; Data Collection: B.F.; Formal Analysis: E.N., B.F., and K.E.

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Note

New size record for Snapping Turtle (*Chelydra serpentina*) in southern Quebec, Canada

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Abstract
We report a new size record for a Snapping Turtle (*Chelydra serpentina*) in Quebec, Canada. We captured an adult male in good general condition in the Rivière du Sud in the southern Montérégie region. Its straight midline carapace length was 43.2 cm (maximum carapace length 45.1 cm), and it weighed 19.8 kg. This record contributes to our understanding of the maximum size of this species at the northeastern part of its range. More intensive effort will be necessary to document the Snapping Turtle population structure in Quebec to allow for sound comparisons with other populations, as well as a better understanding of the effects of elevation, latitude, and local habitat on Snapping Turtle growth and size.

Key words: Snapping Turtle; *Chelydra serpentina*; size record; Rivière du Sud; northeastern range; Quebec; Canada

Résumé
Nous rapportons un nouveau record de taille pour une tortue serpentine (*Chelydra serpentina*) au Québec, Canada. Nous avons capturé un mâle adulte en bonne condition générale dans la rivière du Sud dans le sud de la Montérégie. La longueur standard de la carapace était de 43,2 cm (longueur maximale de la carapace 45,1 cm) et il pesait 19,8 kg. Ce record contribue à une meilleure connaissance sur les tailles maximales de l'espèce dans le nord-est de son aire de répartition. Des efforts plus importants seront nécessaires pour documenter la structure de population de la tortue serpentine au Québec afin de permettre des comparaisons fiables avec d'autres populations, ainsi qu'une meilleure compréhension des effets de l'altitude, de la latitude et de l'habitat local sur la croissance et la taille de la tortue serpentine.

Mots-clés: tortue serpentine; *Chelydra serpentina*; record de taille; rivière du Sud; nord-est de l'aire de répartition; Québec; Canada

Finding the largest individuals of a turtle species in a given region requires perseverance and good data collection methods. Since 1992, we have been conducting research and managing an observation network to gather information related to herpetofauna distribution, reproduction, road mortality, and abnormal colouration and morphology among other topics. Observations from the public often consist of female turtles seen crossing a road or digging a nest in a garden during nesting season or turtles captured accidentally during sport fishing (Galois and Ouellet 2007a,b; Amphibia-Nature Observation Network unpubl. data). Reported size is usually a visual approximation, especially when the subject is an impressive Snapping Turtle (*Chelydra serpentina*). Despite the limited number of this species, occasional captures made during our biodiversity projects provide reliable and precise data. Here, we report the largest Snapping Turtle documented in Quebec, Canada.

The observation was made during a biodiversity survey in the Rivière du Sud, a tributary of the Rivière Richelieu, in Quebec's southern Montérégie region. After capturing the Snapping Turtle from a boat using a dip net, we examined it for general condition, measured it, and documented the observation using digital photography.

We used a forestry caliper (Dendrotik, Quebec, Canada) to measure to the nearest millimetre the straight midline carapace length (CL_{mid}), maximum carapace length (CL_{max}), maximum shell width (SW), straight midline plastron length (PL_{mid}), posterior lobe length of the plastron (middle scales suture of the plastron to the posterior end), precloacal length (posterior end of the plastron to the centre of the cloaca), and posterior end of the plastron to the tail extremity. To weigh the turtle, we used a 22.0-kg spring scale (Matzuo America, Illinois, USA) with 0.2-kg gradation. We released the turtle at the point of capture immediately after the measurements were made.

We searched the literature to obtain published information on Snapping Turtle size in North America. We also checked our own database for information we collected in the field and obtained through our observation network (https://www.amphibia-nature.org).

We captured the adult male Snapping Turtle on 3 July 2016 in the Rivière du Sud, Quebec (45°05'N, 73°13'W; datum WGS84). At the capture location, the river was characterized by slow moving water and shallow river-

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ine marsh, with the navigable open section limited to a narrow channel (Figure 1). The turtle was lying in shallow water on a muddy substrate. As we approached at reduced speed, the turtle started to move slowly beside the boat, allowing capture.

The turtle's dimensions were: CL_{mid} 43.2 cm (Figure 2), CL_{max} 45.1 cm, SW 36.0 cm, and PL_{mid} 30.2 cm. The distance between the posterior end of the plastron and the tail extremity was 42.4 cm. Total weight was 19.8 kg. With a morphological ratio of precloacal length (17.8 cm) to plastron posterior lobe length (12.8 cm) of 1.39, the turtle was determined to be male (Ernst and Lovich 2009; Dustman 2013). The turtle was in good general condition with no apparent injuries. Five leeches (*Placobdella parasitica*) were present on the carapace.

To our knowledge, the carapace length of this Snapping Turtle is the longest measured and reported in Quebec. In June 1939, a large turtle was captured on a road near Van Bruyssel, a hamlet in the Mauricie region, and brought to the Jardin zoologique de Québec (Bernard 1948). Reported measurements were: CL 18 inches (45.7 cm) and weight 30 pounds (13.6 kg). Unfortunately, it was not specified whether the carapace measurement was taken as a straight line or along the carapace curvature, and no picture was provided. Moreover, the weight of this turtle was abnormally low in relation to the carapace length based on data from other studies (Lagler and Applegate 1943; Hammer 1969; Johnston *et al.* 2012); therefore, the measurements are considered questionable. Two other well documented large male Snapping Turtles found in Quebec each had a CL_{max} of 43.0 cm (Desroches 2007), 2.1 cm shorter than our record. One of these was found dead in 2003 in the same area as our observation in the Rivière du Sud.

Large male Snapping Turtles have been reported in the literature from various locations in North America. Snapping Turtle males grow larger than females, and female size tends to increase with increasing latitude and elevation (Moll and Iverson 2008). In Minnesota, at 47°37'N, further north than our observation area, a male Snapping Turtle had a CL of 49.4 cm (not specified whether straight midline or maximum; Gerholdt and Oldfield 1987). In comparison with our observation, this conforms to the latitude trend of larger individuals in the north. However, in Ontario's Algonquin Park, a latitude (45°35'N) close to that of our area, the largest male captured had a CL_{mid} of 39.5 cm (Obbard 1977), i.e., smaller than our record. In Massachusetts (Middlesex County centroid 42°28'N), a male turtle's unspecified CL was 50.7 cm (Hunter *et al.* 1992), and, in Nebraska (41°44'N), the largest individual captured in Island Lake had an unspecified CL of 46.4 cm (Iver-

FIGURE 1. Adult Snapping Turtle (*Chelydra serpentina*) captured in the Rivière du Sud in southern Quebec, Canada. Photo: È.-L. Grenier.

FIGURE 2. The observed Snapping Turtle (*Chelydra serpentina*) was a male with a straight midline carapace length of 43.2 cm and a maximum carapace length of 45.1 cm. Photo: P. Galois.

son *et al.* 1997). The largest males in Florida populations in the Santa Fe River (29°52'N) and in Wekiwa Springs State Park (28°43'N) had CL_{max} of 45.0 cm (Johnston *et al.* 2012) and 44.8 cm (Walde *et al.* 2016), respectively. These measurements are only a few millimetres smaller than our record, but they are also smaller than some CL_{max} reported in other northern latitudes (Gerholdt and Oldfield 1987; Hunter *et al.* 1992).

Thus, these size records for male Snapping Turtles do not support the suggested relation between latitude and maximum size. The same discrepancies can also be found for females. A large female (CL_{mid} 37.3 cm, CL_{max} 39.9 cm) was found dead in Parc National des Îles-de-Boucherville (45°36'N) near Montréal, Quebec (Desroches 2007). In 2015, we captured a female with CL_{mid} 37.0 cm in Parc-nature du Bois-de-l'Île-Bizard (45°30'N) near Montréal, Quebec (P.G. and M.O. unpubl. data). A large female with CL_{mid} 35.8 cm was captured in Algonquin Park (Obbard 1977), and a female with unspecified CL 38.4 cm was captured in South Dakota (43°09'N; Hammer 1969). The largest female in a Florida population had a CL_{mid} of 38.0 cm (Johnston *et al.* 2012), close or even larger than female CL_{mid} reported in some northern populations. Thus, the relation between latitude and both male and female Snapping Turtle size needs further investigation.

Although size records are of interest, they remain anecdotal until ample data are collected to verify whether these large individuals are exceptional or relatively common in their populations. More intensive effort is necessary to document Snapping Turtle sizes and population structure in Quebec, at the northeastern limit of the species range, to allow more useful comparisons with other northern and southern populations. These studies would allow for a better understanding of the effects of elevation, latitude, and local habitat on Snapping Turtle growth and size. They would also provide data relevant to investigations of the effect of climate change on Snapping Turtle population structure over time.

A climate warming trend at northern latitudes could favour an extension of the species range toward the northeast by providing a long enough period for successful egg incubation. We already know that Snapping Turtle reproduction occurs as far north as 48°19'N in Abitibi, western Quebec (Lapointe 2018). In Canada, Snapping Turtle observations range northward to 51°N in western Ontario and 52°N in Manitoba (COSEWIC 2008). Therefore, additional information on Snapping Turtle distribution and population structure at northern latitudes is particularly important to allow for the documentation of potential changes over time in response to climate change. Our turtle observation network is an effective tool to obtain information from remote locations. Details, including date and location, and photos can be submitted online (https://www.amphibia-nature.org) or sent to info@amphibia-nature.org. With or without measurements, this information might help in identifying sites where more intensive surveys could eventually be undertaken to improve knowledge of Snapping Turtle populations at the northern limit of their range.

Author Contributions

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Predation on Caribou (*Rangifer tarandus*) by Wolverines (*Gulo gulo*) after long pursuits

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Abstract
Ungulates are an important source of food for Wolverines (*Gulo gulo*), especially in winter when scavenging on carcasses is a primary means of obtaining food. However, Wolverines are also known to prey on ungulates. We followed fresh tracks of Wolverines pursuing Caribou (*Rangifer tarandus*) on six occasions on the tundra of northern Alaska in 2011, 2015, 2017, and 2018; all ended in a predation event after pursuits of 4−62 km. Exhaustion of the Caribou after long pursuits appeared to contribute to the success of predation attempts. Snow conditions appeared to be a factor in only one of the six cases.

Key words: Alaska; Caribou; *Gulo gulo*; predation; *Rangifer tarandus*; Wolverine

Introduction
Ungulates are an important source of food for Wolverines (*Gulo gulo*), especially in winter when scavenging on carcasses is a primary means of obtaining food (Banci 1994; Copeland and Whitman 2003). However, Wolverines are capable of killing ungulates, including Moose (*Alces americanus*; Haglund 1974), Caribou/Reindeer (*Rangifer tarandus*; Burkholder 1962; Lofroth *et al*. 2007; Mattisson *et al*. 2017), Mountain Goats (*Oreamnos americanus*; Lofroth *et al*. 2007), Dall's Sheep (*Ovis dalli*; Gill 1978), and Elk (*Cervus canadensis*; Inman and Packila 2015). In Scandinavia, Wolverines are one of the main predators of unattended, free-ranging, semi-domestic Reindeer. While tracking Wolverines in snow and locating Reindeer carcasses fed on by Wolverines, both Haglund (1966) and Bjärvall (1982) stated that Wolverines were responsible for killing at least 30% of the Reindeer at the carcass sites they found. Mattisson *et al*. (2017) reported average individual kill rates for Wolverines ranging from less than one to five Reindeer per month depending on season and area, with as many as 15 during a single month.

Predation on ungulates by Wolverines is thought to occur opportunistically, with vulnerability of prey being a key factor determining the success of predation attempts (Haglund 1966; Banci 1994; Mattisson *et al*. 2017). Factors affecting vulnerability of prey include deep or crusted snow (Haglund 1966; Bjärvall 1982), poor body condition (Lofroth *et al*. 2007; Mattisson *et al*. 2017), and age of prey (Gustine *et al*. 2006; Inman and Packila 2015; Mattisson *et al*. 2017).

We are not aware of published reports of Wolverines pursuing Caribou over long distances in predation attempts. Haglund (1966) stated that no pursuits of Reindeer by Wolverines were more than 1 km. However, Reindeer herders and field personnel of the Norwegian Environment Agency in Scandinavia have reported long chases by Wolverines (J. Mattisson pers. comm. 9 January 2018). Here we report six occurrences of Wolverines killing Caribou after pursuits of 4–62 km on snow-covered tundra in northern Alaska.

Methods
We documented Wolverines killing Caribou by following Wolverine and Caribou tracks from a PA-18 Super Cub aircraft (Piper Aircraft, Vero Beach, Florida, USA). We made opportunistic observations on the Alaska North Slope between 68°N and 70°N and between 147°W and 155°W, while primarily engaged in Wolverine surveys and, in one case, during a Caribou telemetry flight. Poley *et al.* (2018) have presented details of the Wolverine survey methods.

Habitat in the study area consisted of snow-covered tundra with gentle relief, small drainages with shrubs protruding above the snow, and occasional ridges blown free of snow. Except for observation 4 below, snow conditions were similar throughout the track sequences and consisted of relatively firm, windblown snow, in which Wolverine tracks penetrated 0.5−10.0 cm and Caribou tracks perhaps slightly more, depending on conditions.

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Observations

(arranged chronologically within year from most recent year)

Kill 1

On 8 April 2018, while conducting a survey for Wolverine tracks in the Arctic National Wildlife Refuge in northern Alaska, P.V. and A.J.M. came across the tracks of a Wolverine and a Caribou that led to a Caribou carcass, near which a Wolverine was seen running at the approach of the aircraft. The Caribou kill was very fresh with the head only partly removed by the Wolverine. The Caribou had hard antlers, indicating it was a pregnant cow. The tracking team back-tracked the pair of footprints for 18 km before returning to the carcass where the Wolverine had just finishing removing the head.

At about the same time, M.A.K. and C.R.L. were tracking a Wolverine and Caribou ~50 km away (straight-line), where a Wolverine had encountered a small herd of Caribou and began pursuing one of them. They tracked the animals for 20 km to where the tracks disappeared in a windblown area. At that point, they returned to their survey route but, later that day, picked up the back-tracking effort from where the first team had stopped and followed the Wolverine and Caribou for an additional 22 km to within 2 km of where their forward-tracking session had ended earlier in the day, and the tracks again disappeared in the windblown area.

Piecing together the tracking sessions, the teams calculated that the total distance of the Wolverine's pursuit of the Caribou was 62 km. For most of the track sequence, the Wolverine tracks were a typical three by three pattern with spacing that indicated a fast and steady lope but not a full run, closely following the route of the Caribou. There were shorter sections of tracks where patterns indicated increases or decreases in speed, perhaps associated with changes in slope, snow conditions, or distance between the animals. There were occasional divergences between the two sets of tracks where the Wolverine took a more direct line to try to intersect the Caribou. The Caribou tracks indicated a similar strategy of an overall fast pace but not a full run, except near the end of the pursuit when both the Wolverine and Caribou appeared to run full speed. Along the chase route and at the kill site, there were no tracks of Wolves (*Canis lupus*), the only other Caribou predator in the study area in winter.

Kill 2

On 3 April 2017, M.A.K. and C.R.L. came across Wolverine tracks following the trail of a single Caribou and tracked the animals for 31 km to a freshly killed Caribou with the Wolverine resting next to the carcass. We estimated that the Caribou had been killed within an hour before our arrival based on the freshness of blood in the snow and the lack of feeding or caching activity by the Wolverine. We also returned to the point where we first found the tracks and traced them 4 km back to the point where the Wolverine started following the Caribou. The entire distance travelled by the Caribou and Wolverine was ~35 km, and the tracks roughly formed a large loop.

There was no indication that the Caribou floundered in snow while the Wolverine travelled on the snow surface. Throughout the track sequence, we did not observe anything to indicate that the Caribou or Wolverine tried to take advantage of any particular snow type or topographic feature (e.g., staying on the crest of a ridge where snow was hardest or following tracks from other groups of Caribou). Based on the tracks, covering distance seemed to be the strategy of the Caribou. With the exception of the last 100 m, there appeared to be no direct interactions between the Caribou and Wolverine (i.e., the Wolverine did not try to jump on or attack the Caribou during the pursuit). We suspect that the Wolverine simply followed closely behind the Caribou, eventually exhausting it. In the last 100 m, tracks showed that the Wolverine attempted to jump on the Caribou several times. Tracks at the kill site indicated relatively little struggle. No other predator tracks were observed during the tracking session.

Kill 3

On 5 April 2017, M.A.K. and C.R.L. found Wolverine tracks along with the tracks of two Caribou and tracked the animals for 31 km to the kill location. The Wolverine was not in sight when we arrived. Pursuit behaviour was similar to that in kill 2. We estimated that the Caribou had been killed approximately two days earlier based on the age of snow, the freshness and amount of blood in the snow, the nearly complete caching of the carcass in the vicinity of the kill site, and the amount of tracking at the kill site. We did not return to where we initially intersected the tracks to back-track to the beginning of the pursuit, so the entire length of the pursuit is unknown.

In this track sequence, the Caribou and Wolverine generally stayed on the crest of a ridge, where perhaps snow conditions were firmer than in the valley bottoms. As with kills 1 and 2, the Caribou did not flounder in snow or break through crust into deep snow. Except in the last 400 m, there appeared to be no direct interactions between the two Caribou and the Wolverine. Starting ~400 m from the kill site, both the Caribou and the Wolverine made a loop of about 100 m, at which time the two Caribou separated. The Caribou that was still being pursued by the Wolverine then travelled a short distance before making several rough figure eights ~100 m long before the Wolverine caught and killed it. The site of the kill did not indicate a long struggle between the Caribou and Wolverine once the Wolverine had overtaken the Caribou. The second Caribou was not pursued by the Wolverine once it separated from the other. We observed no Wolf tracks at the kill site or along the chase route.

Kill 4

On 9 April 2017, while searching for fresh Wolverine tracks, P.V. and A.J.M. saw a Wolverine sitting beside a Caribou carcass with fresh blood in the snow. We back-tracked the Wolverine and Caribou tracks to determine how the kill was made. The Wolverine had apparently spotted a group of about eight Caribou feeding on the bank of a large lake and ran toward them. The Caribou ran down onto the wind-hardened, snow-covered lake, where both the Wolverine and Caribou were able to stay on top of the snow. The Caribou ran across the lake and started up the bank on the far side, at which point they broke through the snow crust covering shrubs bordering the lake. Before the Caribou reached the hard-packed snow at the top of the bank, a 10-month-old calf veered from the group and was quickly subdued by the Wolverine. The entire chase sequence covered 4 km. We landed the ski plane on the frozen lake and walked to the kill site. The Wolverine had eaten off the nose of the calf and had chewed into the throat and back of the head. No other wounds were evident and the calf was not yet fully frozen. We observed no wolf tracks in the area.

Kill 5

On 25 March 2015, M.A.K. and C.R.L. found the tracks of a Wolverine and a Caribou, which appeared to be less than 24 h old, and followed them for 9 km to where the Wolverine had killed the Caribou and apparently cached parts of it nearby. We saw the Wolverine as it ran from the kill site on our approach. We did not back-track to determine the total length of the pursuit. Track patterns of the pursuit were similar to those of kills 2 and 3. The only other tracks in the area were of Red Fox (*Vulpes vulpes*).

Kill 6

On 7 April 2011, L.S.P. encountered the tracks of a Wolverine following the trail of a Caribou and followed the tracks for ~26 km, mostly along a creek bottom. We did not back-track to determine the total length of the pursuit. There was no evidence of interaction along the route. We could not tell whether the Caribou knew the Wolverine was following it. Eventually, the Caribou climbed a hill overlooking the creek and bedded down on a slope. The tracks indicated that the Wolverine approached the hill outside the view of the Caribou, came over the crest, bounded a short distance to the Caribou, and then both animals apparently rolled together to the bottom of the hill. The Wolverine had just begun dismembering the carcass when we arrived at the site.

Discussion

In these accounts, the vulnerability of the Caribou to predation was only evident in kill 4 (i.e., crusted snow that broke under the weight of the Caribou). In the other five cases, lack of evidence of extended struggles at the kill sites suggests that exhaustion of the Caribou ended the pursuit. Both Wolverines (Haglund 1966; Bjärvall 1982) and Caribou (Pritchard *et al*. 2014) are capable of sustained, long-distance movements, but physical endurance will determine the outcome of long pursuits when movement rates are rapid. During 1-h continuous observations of Wolverines travelling (but not pursuing prey at maximum speed), Magoun (1985) documented speeds of up to 8.0 km/h for female Wolverines and up to 10.6 km/h for males in summer on tundra. If we consider 8−10 km/h to be the maximum sustained speed for Wolverines on firm snow in winter, the long pursuit in kill 1 could have lasted ≥6 h.

Pritchard *et al*. (2014) documented a maximum movement rate for a Caribou in our study area of 13.8 km/h (straight line winter movement of a female wearing a GPS collar with a 2-h fix interval), but this rate of movement was rare in their study. If sustained for 62 km, a pursuit at this speed would have lasted 4.5 h. Although the speeds of Wolverines and Caribou seem well-matched, the persistence of the Wolverines was likely key to predation success in the long pursuits we documented.

We did not determine the frequency of successful predation attempts. We only followed very fresh tracks when we were reasonably confident that we could find the Wolverine, and long pursuits had a better chance of being detected by us during our survey flights. Also, we cannot conclude that longer pursuits result in more successful predation attempts or that all pursuits under similar winter conditions are as successful as those we observed.

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Note

Swimming as a potentially important emergency capability of White-throated Swifts (*Aeronautes saxatalis*) engaged in aerial mating

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Brunton, D.F. 2018. Swimming as a potentially important emergency capability of White-throated Swifts (*Aeronautes saxatalis*) engaged in aerial mating. Canadian Field-Naturalist 132(4): 386–388. https://doi.org/10.22621/cfn.v132i4.2034

Abstract

It seems reasonable that birds that court or mate in the air over lakes or rivers should be capable of taking off from water or be able to swim, as they might find themselves in the water as a result of this activity. Nonetheless, interaction with water has rarely been documented in the wild and has not been reported for any species of swift in Canada. I report an incident of such activity, however, from Oliver, British Columbia. In this case, I observed a White-throated Swift (*Aeronautes saxatalis*) swimming vigorously for over 10 minutes before reaching dry land approximately 85 m away. The bird likely fell into the water as a result of flight miscalculations during aerial courtship or mating. I speculate that its swimming capability was aided by the long, narrow, flipper-like wings of the species. I did not observe the bird take flight from the water surface. From these observations, it is evident that White-throated Swifts are relatively strong, capable swimmers, at least for short periods.

Key words: White-throated Swift; *Aeronautes saxatalis*; swimming; aerial mating; British Columbia

McGuire and Brigham (2017) reported seeing Common Nighthawks (*Chordeiles minor*) taking wing immediately after rare incidents of the birds hitting the surface of a water body. The recovery flight was immediate in one case and somewhat delayed in the other, occurring after several seconds of the bird drifting (not swimming) on the surface. Jackson (1970) reports almost identical behaviour of a Barn Swallow (*Hirundo rustica*) immediately following its release from banding. McGuire and Brigham (2017) logically imply that a capacity for swimming is important for species that are active over water, especially those twisting and turning rapidly in their aerial pursuit of insect prey. In the case of Common Nighthawk, such activity would also be undertaken in poor light conditions. Individuals unable to respond successfully to occasional "ditchings" likely have a higher probability of mortality.

McGuire and Brigham (2017) document a number of other passerine bird species capable of taking off from water and/or swimming for short distances. They further note that, although several swallow species have been observed swimming, observations are lacking for other aerial insectivores, such as swifts. Indeed, they cite Lowther and Collins (2002) as stating that Black Swifts (*Cypseloides niger*) do not swim, although no particular evidence or qualifications of that statement are offered. McGuire and Brigham (2017: 126) go on to conclude: "there are no reports [of swimming] for other swifts found in Canada". The following provides documentation of such behaviour by a swift in Canada. This report is based on field notes made by the author at the time of the original observations.

White-throated Swift (*Aeronautes saxatalis*) is found in Canada only in southern British Columbia where it nests in large colonies in crevices of high bedrock cliffs or on conglomerate bluffs (Godfrey 1986). Some of the colonies in the Okanagan Valley are situated over water. Aerial courtship and mating activity at and about the nesting colony require swifts to spend considerable time in extraordinarily complicated and seemingly perilous flight over water. This aerial mating behaviour was beautifully described at a breeding colony over Vaseux Lake in the Okanagan Valley in May 1922:

> [T]hey copulate in the air. At least several times I saw two meet, apparently face to face high in the air, cling together as though embracing for a moment through which they drop down hundreds of feet, there to separate and catch themselves on their wings (Percy A. Taverner, as cited by Cannings *et al.* 1987).

On 10 June 1982, I and several others witnessed an apparent malfunction of this aerial mastery at a large White-throated Swift breeding colony 6 km north of Oliver, Okanagan Valley, British Columbia (49.2413°N, 119.5182°W). This is only a few kilometres south of Taverner's observations of 60 years earlier. The 250-m tall, west-facing nesting cliff here towers over Gallagher Lake, a small (5.3 ha) pond situated in semi-arid Ponderosa Pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson) forest (Figure 1). Numerous individual swifts as well as pairs were observed performing spectacular aerial feats over a 2-h period before sunset. At least 50 instances of pairs involved in "courtship falls" (Ryan and Collins 2000) were noted during that time. Much as described by Taverner (above), these courtship falls involved pairs of birds tumbling through the air for 150–200 m and then veering off from seemingly cer-

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tain contact with the lake surface. It was not possible to measure how close to the water surface the birds came but it appeared to be less than a metre. Remarkably, no contact with the water was witnessed in any of these displays.

Near sunset at 2100, we observed a bird floating and flapping in the middle of the lake ~150 m away (Figure 1). None of us in a group of six observers (all birders) had noticed it hit the water. Observation through a 30–60× zoom spotting scope confirmed that it was an adult White-throated Swift (sex undetermined); no juveniles are present at this date, well before nestling hatching in the Okanagan Valley (Cannings *et al.* 1987). Observation conditions were excellent on this calm, warm, clear evening and our consensus was that a bird flapping on the still water could not have avoided detection for more than about five minutes.

Over the following 10 minutes we observed the swift through the spotting scope as it swam toward the shore of the lake ~85 m away. It did this by rapidly stroking both wings in unison, with a brief (~1 s) pause between strokes. After a series of 10–20 such quick strokes, it floated quietly for 5–10 s, then proceeded to swim further. The bird was quite buoyant and held its head distinctly above the water throughout, both during active swimming as well as during the brief pauses.

At one point, it attempted to climb onto a swim raft anchored near the lakeshore (Figure 1), but could not scale the ~40 cm vertical sides of the raft. The bird abandoned that effort after a minute or two of unsuccessful scrambling and resumed its open-water swimming. When the bird reached the lakeshore and crawled onto a stranded log, it was trembling strongly and appeared exhausted. It made no attempt to fly and offered no resistance when approached and picked up by one of our group of observers. It was clear-eyed, alert, and silent. After two minutes the trembling stopped but the bird remained placidly perched in hand, with its toes wrapped firmly around the finger of the observer. Although its body feathers were wet (soaked virtually to the skin), its head was completely dry.

The bird remained quiet and completely inactive over the next 45 minutes as it began to dry off. It did not attempt to preen or aid in drying its feathers. As it was now almost completely dark, we placed the bird on dry towels in a cardboard box covered lightly by a cloth and left it in a quiet corner of a residential room overnight. The box was taken outside the following morning about 0700 (10 h later) and uncovered. The bird made no attempt to fly from the box. It was picked up (again offering no resistance), held up toward the open sky and released from the hand. It flew directly

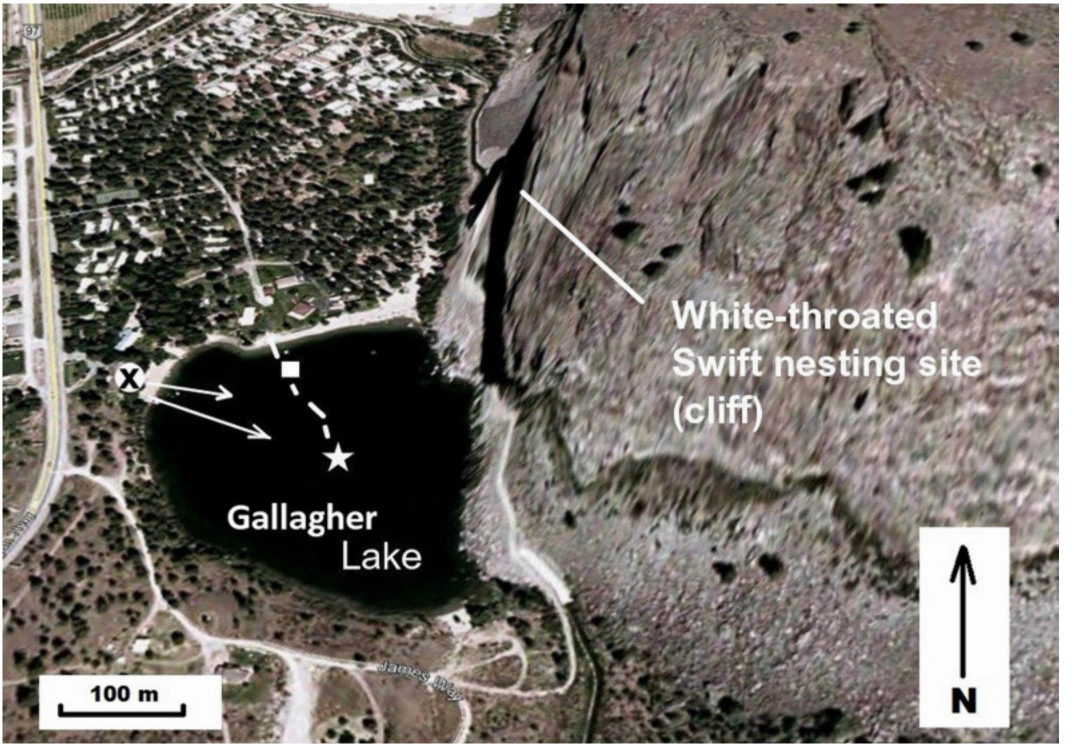

FIGURE 1. Location of observations of a swimming White-throated Swift (*Aeronautes saxaltis*), Gallagher Lake, British Columbia. X and arrows = observers' position and viewpoints; star = first noted location of swift on the water; dash line = approximate route of swim; square = approximate location of swim raft. Base image: GoogleEarth, 25 August 2016.

and strongly across the pond and back to the nesting cliff.

Given their propensity for high-speed acrobatic flying while over water bodies, it is not surprising that White-throated Swifts might, at least occasionally, hit the surface of the water. That such impacts occur, at least rarely, is also implied by historical references to White-throated Swifts striking the ground during courtship fall behaviour. Shufeldt (1887) describes two such entangled birds in New Mexico hitting the ground in a cloud of dust and, after several seconds, flying off separately. More dramatically, Van Tyne and Sutton (1937: 42) reported that White-throated Swifts at Emory Peak in western Texas "were often seen mating, and fierce aerial battles (between rival males?) sometimes persisted until the combatants struck the talus slope below and rolled down the steep declivity, still locked in bitter struggle". They do not state whether the "combatants" were able to fly off after such groundings.

Less foreseeable than the occasional occurrence of water ditchings was the fact that the Gallagher Lake swift could swim so adeptly for about 85 m and stay afloat for a considerable time. It had no evident difficulty maintaining a head-high profile throughout its swim. McGuire and Brigham (2017) noted that the Common Nighthawks they observed to land accidentally on a water surface also appeared buoyant. That ability would presumably reduce energy requirements and improve the bird's chances of a successful landfall (in the case of a swift) or flight from the surface (with the nighthawks). In comparison to the broader wings of most passerine species, the long, narrow, flipper-like wings of White-throated Swift also may assist in swimming efficiency and reduce the energy demands of that activity.

The Gallagher Lake bird showed no outward signs of injury from its ordeal and was seemingly able to recover its pre-ditching vigour within 10 h. It did not experience the feather loss from physical contact that McGuire and Brigham (2107) observed in Common Nighthawks with wet plumage. No loose feathers were noted in the box in which the swift was confined overnight.

Unlike Shufeldt's (1887) report of White-throated Swifts being able to rise from the ground, I saw no evidence that the Gallagher Lake bird was capable of flying directly from the surface of the water. Its inability to surmount the short vertical wall of the swim platform despite expending substantial effort in the attempt, suggests that its lift capacity had been reduced by the wetting of its plumage. These observations demonstrate, however, that, at least under emergency conditions, White-throated Swifts do have the advantageous ability to swim for a considerable distance.

Acknowledgements

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Note

Round-fruited St. John's-wort (*Hypericum sphaerocarpum*, Hypericaceae) in Canada

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Oldham, M.J., W.D. Van Hemessen, and S. Blaney. 2018. Round-fruited St. John's-wort (*Hypericum sphaerocarpum*, Hypericaceae) in Canada. Canadian Field-Naturalist 132(4): 389–393. https://doi.org/10.22621/cfn.v132i4.2055

Abstract
Round-fruited St. John's-wort (*Hypericum sphaerocarpum*), a native North American herbaceous, perennial vascular plant, is reported from four sites in southern Ontario, Canada. All four sites are along abandoned railway lines. Although the rich association of native flora suggests native status at one site, *H. sphaerocarpum* is believed to be introduced elsewhere in its Canadian range in Ontario.

Key words: Round-fruited St. John's-wort; *Hypericum sphaerocarpum*; Hypericaceae; Ontario; Canada; range extension; railway

Round-fruited St. John's-wort (*Hypericum sphaerocarpum* Michaux) is native to the midwestern and southern United States from Oklahoma east to southeastern Ohio and from southern Wisconsin south to Mississippi and Alabama (Robson 1996, 2015). Here, we report four records of *H. sphaerocarpum* from southern Ontario, Canada (Figure 1; see "Voucher specimens" below), representing a northeastern extension of the species' range. *Hypericum sphaerocarpum* is not listed for Canada by Scoggan (1978–1979) or Gillett and Robson (1981), and its inclusion in later publications, e.g., Morton and Venn (1990), Newmaster *et al.* (1998), and Robson (2015), is based on the records reported here.

Hypericum sphaerocarpum can be distinguished from other Ontario *Hypericum* species by the combination of its being herbaceous, 10–30 cm tall, having pinnately veined leaves 3.5–7 cm long, flowers <3 cm broad with more than 20 stamens and lacking black spots or streaks on the petals, and styles joined to form a beaked fruit (Robson 1996, 2015).

It was first discovered in Ontario and Canada on 19 September 1983 by M.J.O. along the then-active Canada Southern Railway (CSR), near Essex, Essex County. The species was well established, locally common along the edge of the tracks, and spreading to the adjacent ditch edge. Associates were mainly typical weedy species for this location and habitat: Spreading Dogbane (*Apocynum androsaemifolium* L.), Common Milkweed (*Asclepias syriaca* L.), Wild Carrot (*Daucus carota* L.), Common Teasel (*Dipsacus fullonum* L.), Slender Cottonweed (*Froelichia gracilis* (Hooker) Moquin-Tandon), Butter-and-eggs (*Linaria vulgaris* Miller), Kentucky Bluegrass (*Poa pratensis* L.), Prickly Russian-thistle (*Salsola tragus* L.), Bouncing-bet (*Saponaria officinalis* L.), goldenrod (*Solidago* sp.), and Yellow Goatsbeard (*Tragopogon dubius* Scopoli). The discovery of *F. gracilis* (Amaranthaceae) at this location also represented an addition to the Canadian flora (Oldham and Sutherland 1988). The CSR was abandoned between 2000 and 2010 (C. Cooper pers. comm. 28 January 2018). The site was revisited by M.J.O. on 24 July 1984 and 16 August 2012 and *H. sphaerocarpum* was found to be still present.

The second discovery of *H. sphaerocarpum* in Ontario was on 17 September 1992 by M.J.O. and J.M. Bowles along the Sydenham River near Arkona, Middlesex County. The population was locally common and growing in a moist prairie remnant along an embankment of the abandoned Grand Trunk Railroad (GTR) Sarnia line with a variety of habitat-specific, provincially and regionally rare native species (Oldham and Brinker 2009; Oldham 2017). These included Big Bluestem (*Andropogon gerardii* Vitman), Prairie Straw Sedge (*Carex suberecta* (Olney) Britton), Stiff Gentian (*Gentianella quinquefolia* (L.) Small), Fringed Gentian (*Gentianopsis crinita* (Froelich) Ma), Sharp-fruited Rush (*Juncus acuminatus* Michaux), Wiry Panicgrass (*Panicum flexile* (Gattinger) Scribner), Old Switch Panicgrass (*P. virgatum* L.), Little Bluestem (*Schizachyrium scoparium* (Michaux) Nash), Carpenter's Square Figwort (*Scrophularia marilandica* L.), Small Skullcap (*Scutellaria parvula* Michaux var. *parvula*), Yellow Indiangrass (*Sorghastrum nutans* (L.) Nash), Prairie Cordgrass (*Sporobolus michauxianus* (Hitchcock) P.M. Peterson & Saarela), and Nodding

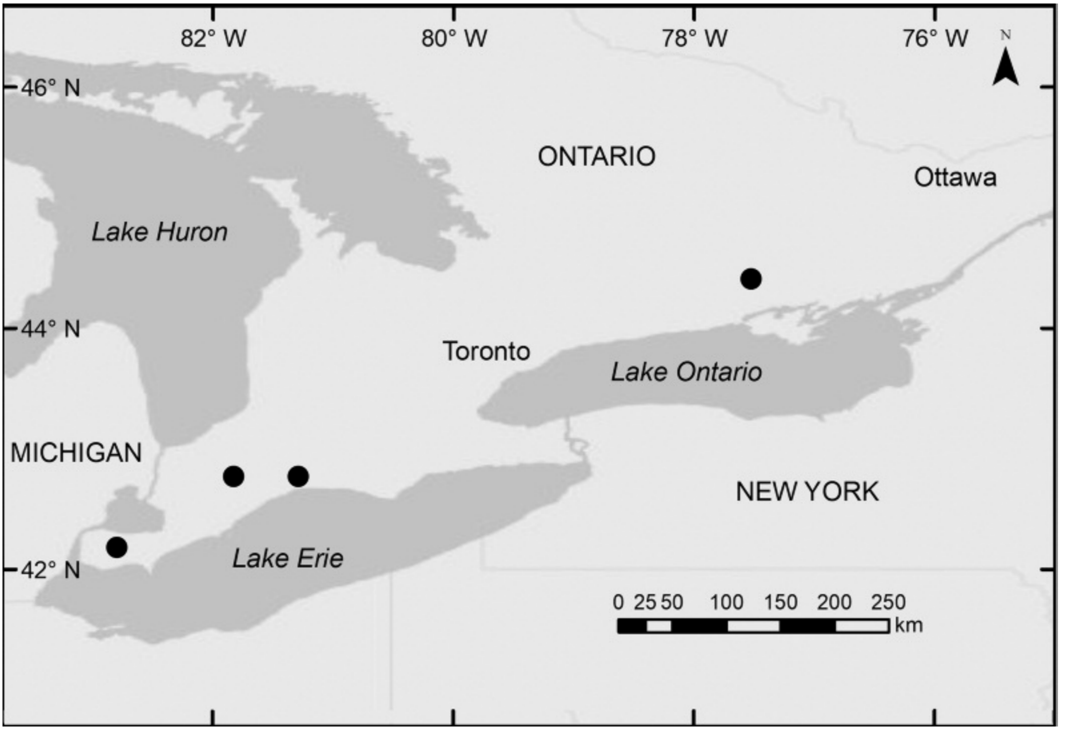

FIGURE 1. New locations for Round-fruited St. John's-wort (*Hypericum sphaerocarpum*) in Ontario, Canada.

Ladies'-tresses (*Spiranthes cernua* (L.) Richard). This population of *H. sphaerocarpum* was considered potentially native to the province by Oldham and Brinker (2009) based on its association with rare and ecologically conservative native species (Oldham *et al.* 1995) of prairie and southern affinity; its location adjacent to a rich floodplain woods containing many other rare native species (Bowles 1992); and its relative proximity (about 175 km) to a presumed native population in southeastern Michigan (Voss and Reznicek 2012).

The third Ontario population to be discovered was found on 27 June 2015 by S. and J. Blaney along a recreational trail occupying the former Pere Marquette Railway near Ivanhoe Station, Hastings County. The site was visited by M.J.O. on 8 July 2015, when the plants were in bud and on 26 July 2015 when they were in flower (Figures 2 and 3). This population was associated with weedy and primarily non-native species typical of the area and habitat, including Yarrow (*Achillea millefolium* L. *sensu lato*), Wild Carrot, Common St. John's-wort (*Hypericum perforatum* L.), Oxeye Daisy (*Leucanthemum vulgare* Lamarck), Garden Bird's-foot Trefoil (*Lotus corniculatus* L.), Tall Goldenrod (*Solidago altissima* L.), Panicled Aster (*Symphyotrichum lanceolatum* (Willdenow) G.L. Nesom), Colt's-foot (*Tussilago farfara* L.), and Tufted Vetch (*Vicia cracca* L.). The Hastings County population is located more than 350 km from the next nearest occurrence and is the most northern and eastern known population of the species (Robson 1996).

The most recent Ontario discovery of *H. sphaerocarpum* in Ontario was made on 1 September 2017, by W.D.V. along the former Canadian Pacific Railway Ontario and Quebec line near Paynes Mills, Elgin County. The site was revisited on 3 September 2017, when fruiting material was collected. This population consisted of approximately 100 plants and was growing directly in railway ballast on the bed of a decommissioned railway. Associated species were typical of similar decommissioned railways and common in the area; they included knapweed (*Centaurea* spp.), Wild Carrot, Small-flowered Evening Primrose (*Oenothera parviflora* L.), Wild Red Raspberry (*Rubus idaeus* L. ssp. *strigosus* (Michaux) Focke), and Tall Goldenrod.

In the core of its native range, *H. sphaerocarpum* occurs in a variety of habitats including wet and dry prairies, forest openings, roadsides, streambanks, cliffs, and fens (Steyermark 1963; Utech and Iltis 1970; Mohlenbrock 1978; Yatskievych 2006; Wilhelm and Rericha 2017). Some sources indicate an association with calcareous substrates (Svenson 1940; Adams 1962; Cooperrider 1989). The only known Michigan population, which is located in Monroe County, occurs in "openings of shrub thickets on the upper banks of a stream" (Voss and Reznicek 2012).

Some authors (e.g., Steyermark 1963; Mohlenbrock and Evans 1972; Mohlenbrock 1978) have recognized

FIGURE 2. Round-fruited St. John's-wort (*Hypericum sphaerocarpum*) along the former Pere Marquette Railway, now a recreation trail, on 26 July 2015. Photo: M.J. Oldham.

a more southern and eastern, bushy-branched variant of *H. sphaerocarpum*, named var. *turgidum* by Svenson (1940). The variety is characterized by having narrower leaves without lateral veins and with revolute margins. More recent authors have generally not recognized varieties in *H. sphaerocarpum*. Robson (2015) suggests that the narrow-leaved, bushy form from eastern parts of the range (var. *turgidum*) merges with the typical form, and he does not recognize infraspecific taxa. Ontario plants are variable with respect to leaf width, venation, and whether the margins are revolute, which could suggest multiple origins for the Ontario populations.

Adventive populations of *H. sphaerocarpum* can apparently persist for some time. The Elgin County population was discovered 46 years after abandonment of the associated rail line and the Hastings County population was discovered 27 years after abandonment of that line. The Essex County population persisted for at least 29 years after its original discovery and for 2–12 years after abandonment of the CSR line. The Middlesex County population persisted for at least seven years after abandonment of the GTR Sarnia line. Some of these rail lines and their embankment habitat date back to the early 1850s (C. Cooper pers. comm. 28 January 2018) and, thus, assuming that *H. sphaerocarpum* and other prairie-affinity species were not already present in nearby remnant prairie areas no longer extant, they could have become established at any time over the last 180–200 years. Whether *H. sphaerocarpum* is native to Canada may never be fully known. Although some evidence (noted above) suggests that the Middlesex County population is native, the presence of three of the four known populations in weedy situations along railway embankments suggests that the other populations are adventive in Canada.

Voucher specimens

Canada, Ontario, Essex Co., Canada Southern Railway line, 2 km northeast of Essex, 42.181°N, 82.799°W, 19 September 1983, *M.J. Oldham 4087* (TRTE; identified by A.A. Reznicek); 24 July 1984, *M.J. Oldham 4390* (MICH, NHIC 03481); 16 August 2012, *M.J. Oldham 40456* (NHIC 03586, TRT).

Canada, Ontario, Middlesex Co., Sydenham River, 5.7 km south-southeast of Alvinston, 42.772°N, 81.835°W, along an embankment of the abandoned Grand Trunk Railroad Sarnia line, 17 September 1992, *M.J. Oldham and J.M. Bowles 14419* (MICH, NHIC

FIGURE 3. Close-up of flowers of Round-fruited St. John's-wort (*Hypericum sphaerocarpum*). Photo: M.J. Oldham.

03535); 13 July 1993, *M.J. Oldham and J.M. Bowles 15136* (NHIC 03484).

Canada, Ontario, Hastings Co., former Pere Marquette Railway now recreation trail, 5 km west of Ivanhoe Station, 44.413°N, 77.528°W, 27 June 2015, *S. Blaney and J. Blaney* (photos iNaturalist: https://www.inaturalist.org/observations/4621216); 8 July 2015, *M.J. Oldham 43039* (CAN, TRT); 26 July 2015, *M.J. Oldham 43092* (CAN, DAO, MICH, NHIC 03379, TRT).

Canada, Ontario, Elgin Co., 2 km southwest of Paynes Mills, along the former Canadian Pacific Railway Ontario and Quebec line, 42.773°N, 81.294°W, 1 September 2017, *W.D. Van Hemessen* (photos iNaturalist: https://www.inaturalist.org/observations/7747872); 3 September 2017, *W.D. Van Hemessen 114* (NHIC 03430).

Acknowledgements

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Diversity and conservation status of lichens and allied fungi in the Greater Toronto Area: results from four years of the Ontario BioBlitz

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Abstract
Bioblitzes are typically 24-hour biological surveys of a defined region carried out by taxonomic specialists, citizen scientists, and the general public. The largest in Canada is the Ontario BioBlitz, an annual event held in the Greater Toronto Area (GTA). Between 2013 and 2016, we examined the feasibility of including lichens and allied fungi in the Ontario BioBlitz. These taxa are often overlooked, understudied, and taxonomically difficult. We completed a bioblitz in each of the four major watersheds in the GTA and recorded 138 species in 72 genera which, combined with all previous collections, totals 180 species in 88 genera in the area. Thirteen of the species we collected are provincially ranked as S1 (critically imperilled), S2 (imperilled), or S3 (vulnerable). We collected *Lecanora carpinea* for the first time in Ontario. Our results provide a baseline list of GTA lichens that can be used for monitoring. This is one of the first detailed lichen surveys of a major North American urban area and it demonstrates that rapid bioblitz surveys are proficient in capturing lichen diversity despite their inconspicuous nature and the advanced microscopy and chemical analyses required for their identification.

Key words: Biogeography; biodiversity; conservation; citizen science; rare species; BioBlitz Canada

Introduction
Bioblitzes are biological surveys that are spatially defined and temporally limited, usually within a 24-hour period. The term bioblitz was introduced in 1996 by the United States National Park Service and popularized by Edward O. Wilson in 1999 (Shorthouse 2010). Bioblitzes are designed to document all living things in a particular area, and to include taxonomic specialists with the general public or citizen scientists in a meaningful and educational experience (Holden 2003; Scanlon *et al.* 2014). The value of a bioblitz to the understanding and conservation of biodiversity was described by Silvertown (2009) and Donnelly *et al.* (2014). Since 2003, at least 85 peer-reviewed articles mention the term bioblitz, with the vast majority lauding the method as a needed component for future biodiversity monitoring projects (Wheeler *et al.* 2012; Laforest *et al.* 2013; Telfer *et al.* 2015; Wei *et al.* 2016). Data gathered at a bioblitz are important for developing the biological knowledge of an area and they provide a baseline that can be used to monitor changes. For example, species have been discovered at bioblitzes that are new to science (Strongman and White 2011; Bird and Bamber 2013), represent major range extensions (McAlpine *et al.* 2012; Miller *et al.* 2012; Ridling *et al.* 2014; McMullin *et al.* 2015; Ratzlaff *et al.* 2016; Tucker and Rehan 2017; McMullin 2018), and have provided new information on the spread of invasive species (Miller 2016). In honour of the 2009 Saint Mary's University Bioblitz held in the Blue Mountain-Birch Cove Wilderness Area (Nova Scotia), a new species of fungus found in the stomach of a mayfly was named *Trifoliellum bioblitzii* (Strongman and White 2011).

The Ontario BioBlitz Program, led by the Royal Ontario Museum, has held six annual events since 2012 in the Greater Toronto Area (GTA). The GTA is the largest urban area in Canada with a population of almost 6.5 million (Statistics Canada 2017). Each major watershed in the GTA, delineated by ravine system and river complex, was surveyed. Approximately 3500 species have been identified including two species of spider that are new to Canada (*Myrmarachne formicaria* de Geer and *Pholcus opilionoides* Schrank) and over 40 species assessed by the Committee on the Status of Endangered Wildlife in Canada (Ontario BioBlitz 2017). Each event included between 200 and 300 taxonomic specialists, and an equal number of citizen scientists. To increase the scope of taxonomic expertise, the Ontario BioBlitz Program leverages partnerships among academic institutions (e.g., University of Toronto and the University of Guelph), non-government organizations (e.g., Ontario Nature), and governmental agencies (e.g., Canadian

Museum of Nature, Parks Canada, and the Toronto Zoo). All events include some component of public engagement, whether it is direct mentorship by taxonomic specialists or more general information provided at base camp by partner organizations. All data collected during the Ontario BioBlitz Program are made available on the iNaturalist Canada platform (www.inaturalist.ca) and, via Canadensys, to the Global Biodiversity Information Facility. Based on the number of volunteers and the number of species documented, the Ontario BioBlitz Program is one of the largest bioblitz initiatives in the world. The program includes taxonomic specialists in as many fields as possible, including those focussed on uncommonly studied groups such as lichens.

Lichens are composite organisms comprised primarily of a mycobiont (fungus) and photobiont (an alga or a cyanobacterium or both; McMullin and Anderson 2014). Unlike vascular plants, they lack a protective cuticle that allows them to acquire nutrients directly from the atmosphere and precipitation that washes over them (Richardson 1975; Richardson and Cameron 2004). As a result, airborne chemicals are also taken in by lichens, which have a range of tolerances, making it possible to correlate air quality with the presence of particular species (Richardson 1992; Cameron *et al.* 2007; McMullin *et al.* 2017). A study in three cities in southern Ontario showed that urbanization is negatively correlated with lichen diversity (McMullin *et al.* 2016). The GTA is the largest urbanized area in Canada, which has likely had a considerable impact on lichen diversity. Nevertheless, no baseline data exist for lichens, other than a small number of scattered historical collections (Wong and Brodo 1992), so changes cannot be ascertained. Bioblitzes are a way to quickly develop baseline data for a region. Once a baseline is established for lichens, it can be an efficient way to monitor air quality and the effects of urbanization on biodiversity.

Lichens and allied fungi, however, are often poorly represented at bioblitzes. They are typically overlooked because many species are minute and inconspicuous. Lichenology has also traditionally been an academic pursuit that limited the number of people with access to the resources and skills required for lichen identification. It was only recently that the first detailed identification guide with colour illustrations of North American lichens was published (Brodo *et al.* 2001), with more regional illustrated guides produced in the years that followed (e.g., Hinds and Hinds 2007; McCune and Geiser 2009; McMullin and Anderson 2014). Nonetheless, difficulty in locating smaller species plus the advanced microscopy and chemical analyses required for lichen identification (Brodo *et al.* 2001) continues to limit their inclusion in rapid surveys such as bioblitzes.

The aim of our study was to target lichens during the Ontario BioBlitz over four years in each of the four major watersheds in the GTA. Our objectives were to identify the areas most likely to contain a rich lichen biota, collect all species encountered, reliably identify specimens in a laboratory, deposit specimens in a public herbarium, and compare our findings with species that have been historically collected in the GTA. The results will provide the first baseline list of lichens in the GTA, one of the first detailed urban lichen surveys in North America, and demonstrate the ability of a 24-hour bioblitz to capture lichen diversity.

Study Area

The GTA is located in southern Ontario, Canada on the north shore of Lake Ontario (Figure 1). It covers 7127 km^2 and includes the City of Toronto surrounded by the four Regional Municipalities of Durham, York, Peel, and Halton. With a total human population of 6 417 516 (2016 figures), the GTA is the most populous region in Ontario (total population 13 448 494) and Canada (35 151 728; Statistics Canada 2017). Population densities range from 255.9 people/km^2 in the Durham region to 4334.4 people/km^2 in the City of Toronto (Statistics Canada 2017). The GTA is bordered by (from east to west) the Kawartha Lakes, Lake Simcoe, and the Niagara Escarpment. This area is sometimes referred to as the Greater Toronto Bioregion (Shoreline Regeneration Work Group 1991). Despite being a dense urban centre, it contains a number of conserved parks and natural areas as well as farmland, and overlaps with a portion of the Oak Ridges Moraine as part of the Greenbelt (Milne *et al.* 2006). Rouge National Urban Park for example, found at the intersection of the City of Toronto, York, and Durham, is one of the largest urban parks in the world, and aims to conserve both natural areas and agricultural lands. Of the 80 km^2 of parks within the City of Toronto, about 50% are naturalized areas (J. Weninger pers. comm. 2017). Within Toronto, there are 307 km of creeks and rivers, over 200 km of trails, and an estimated 10 million trees in the city core (Johnson 2012).

The Oak Ridges Moraine was exposed when the Late Wisconsin glacier retreated about 12 000 years ago (Barnett *et al.* 1998). The bedrock of the GTA however formed about 450 million years ago, and is comprised mainly of shale, dolomitic siltstone, and limestone. Outside of the densely urbanized zones, the soil is mostly clayey or sandy silt, and is often designated as till due to recent agricultural activities. In the most populous areas, the soil type varies widely, from gravel and sand to silty clay depending on location and proximity to large bodies of water (Sharpe 1980). The drainage and pH of the soil ranges broadly as well, and this variety leads to many different biological community types throughout the city (Smith *et al.* 2015). The mean annual temperature is 9.4°C with a mean monthly low of −3.7°C in January and a high of 22.3° in July. The mean annual precipitation is 831.1 mm, with rainfall constituting 86% of the total (Government of Canada 2017). Most of the rain falls in May, August, and September, while most of the snow falls between Decem-

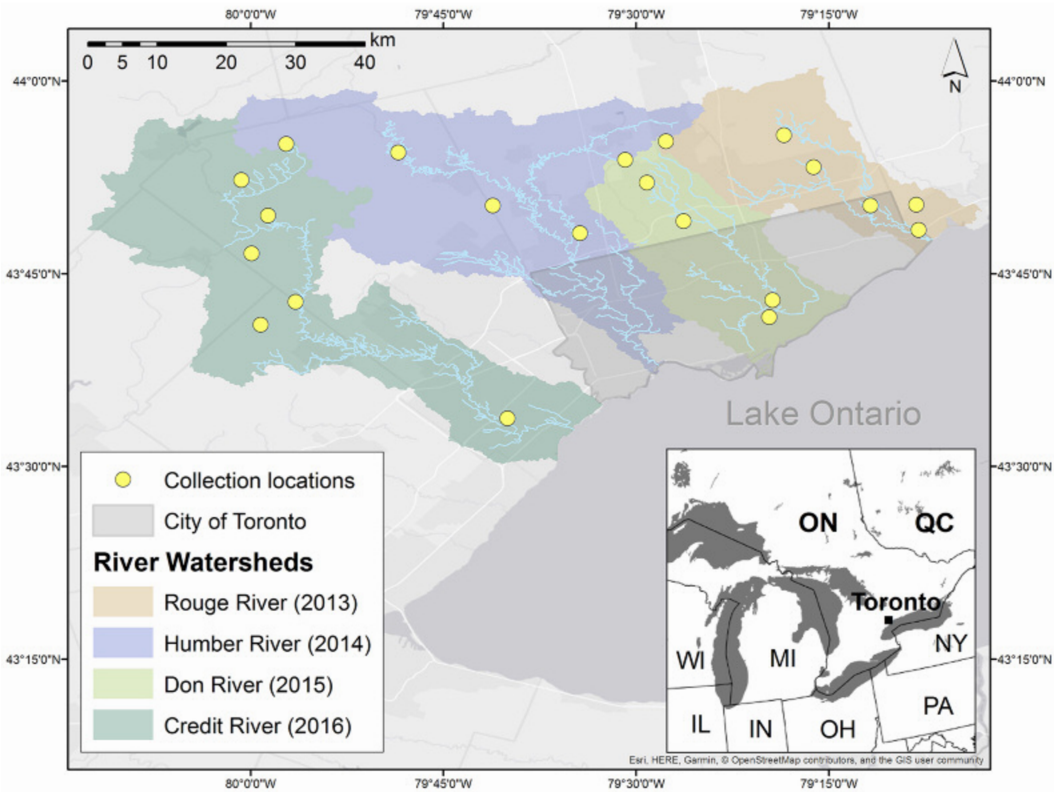

FIGURE 1. Lichen collection sites in the four watersheds surveyed in the Greater Toronto Area, Ontario, Canada.

ber and March (Government of Canada 2017). The province of Ontario has been improving air quality in recent decades, and there has been a considerable improvement since 2008, as well as fewer smog advisories (Government of Ontario 2014). Nitrogen oxides, sulphur dioxide, carbon monoxide, and fine particulate matter have decreased in concentration and emission by over 10% between 2006 and 2015, while ozone increased 3% (Government of Ontario 2015a). Some areas of the GTA with high vehicular traffic have poorer air quality than areas outside the city (Government of Ontario 2015a). Overall, air quality in the GTA is highly variable depending on proximity to highways, industrial sectors, and other point sources of pollution (Government of Ontario 2015a).

The southern edge of the GTA is Carolinian forest which is dominated by trees such as American Beech (*Fagus grandifolia* Ehrhart), hickory (*Carya* spp.), maple (*Acer* spp.), and oak (*Quercus* spp.). The tree communities in the GTA are also influenced by the Great Lakes-St. Lawrence forest to the north, which includes species such as Red Pine (*Pinus resinosa* Aiton), Eastern White Pine (*Pinus strobus* L.), and Yellow Birch (*Betula alleghaniensis* Britton; Government of Ontario 2015b; Smith *et al.* 2015). Prior to logging and urbanization, grasslands were present in the area. Today, the only remaining oak savannah grassland in the GTA is located in High Park in the west end of Toronto. The anthropogenic impacts on the land combined with the variety of soil types, slight changes in topography, and influences of the watersheds has meant that the GTA is a hotspot for biodiversity with many habitats and microhabitats supporting a wide range of wildlife (Smith *et al.* 2015).

Methods

Sampling and storage

We sampled each of the four major watersheds in the GTA over a 24-hour period in June, 2013 (Rouge River), 2014 (Humber River), 2015 (Don River), and 2016 (Credit River; Figure 1). The areas we visited were selected because they were among the least disturbed or developed in each watershed and they appeared to have a comparatively high diversity of ecosystems and habitat types, based on satellite images and ecosystem classification maps. To maximize the area covered, we split into two groups each year, one lead by R.T.M. and the other by K.D. Our sampling protocol followed the methods of Newmaster *et al.* (2005), who showed that examining large areas (referred to as floristic habitat sampling) captures cryptogam diversity more effectively than establishing smaller representative plots. Using floristic habitat sampling, we attempted to examine all distinct restricted mesohabitats in each area (e.g., streams, rock outcrops, cliffs, swamps) as well as many microhabitats (e.g., snags, tree bases, different rock types). This method was also used by Selva (1999, 2003) to sample lichens. He refers to it as an "intelligent meander" as it allows more time to be spent in areas that are likely to have a higher number of lichen species. We collected specimens on trees, wood, and soil with a knife and those on rock were collected with a 1.8 kg hammer and cold chisel. Our wet specimens were air dried for three days and then stored in acid free packets. All specimens were identified in the lichen laboratory at the Biodiversity Institute of Ontario in Guelph or the Canadian Museum of Nature in Ottawa.

Identification

We used standard microscopy and chemical spot tests to identify specimens following Brodo *et al.* (2001). We also used an ultraviolet light chamber to examine secondary metabolites. Using thin-layer chromatography, we further assessed chemical properties in solvents A, B′, and C (Culberson and Kristinsson 1970; Orange *et al.* 2001). We deposited our specimens at the Canadian Museum of Nature (CANL) and the Biodiversity Institute of Ontario Herbarium (OAC) at the University of Guelph (see Appendix S1 for collection and accession details).

Historical records

We obtained data on lichens and allied fungi previously collected in the GTA from various sources: Wong and Brodo (1990, 1992), a physical search of the national herbarium at the Canadian Museum of Nature, and an electronic search of five botanical databases (Canadensys, Canadian Museum of Nature, Consortium of North American Lichen Herbaria, Biodiversity Institute of Ontario, and the Global Biodiversity Information Facility). Reports of dubious species that we did not collect were borrowed and verified or revised, if they were available.

Conservation status

Ontario conservation status ranks (S-ranks) are nonlegal designations set by the Ontario Natural History Information Centre (NHIC) and are based on guidelines developed by NatureServe (NatureServe 2015). Species with distributions and frequencies that are believed to be well understood receive a rank between 1 and 5: 1 = critically imperilled, 2 = imperilled, 3 = vulnerable, 4 = apparently secure, 5 = secure. Other species receive one of the following designations: NR = not ranked, U = unrankable (due to a lack of information), ? = rank uncertain.

Results

We collected 138 lichen and allied fungus species in the GTA. These data, combined with all previous collections, total 180 species in 88 genera (see Annotated Species List). Ninety-five (51%) of these species are microlichens (crustose species that includes all allied fungi) and 85 (47%) are macrolichens (59 foliose and 26 fruticose). Green algae are the primary photobionts in 152 (84%) species, while 15 (8%) species have cyanobacteria as their primary photobiont, and 13 (7%) species are nonlichenized fungi traditionally treated with lichens. Four (2%) species are lichenicolous. Nine (5%) species are calicioids, six of which are nonlichenized, and one of which is lichenicolous, *Sphinctrina anglica* Nyl. *Lecanora carpinea* (L.) Vain. was collected for the first time in Ontario (McMullin 2018).

We located the highest number of lichens and allied fungi at the Forks of the Credit River Provincial Park (74 species), Glen Haffy Conservation Area (49 species), and the Belfountain Conservation Area (35 species; Figure 1).

Conservation status

One hundred and forty of the 180 species in the GTA have been assigned conservation ranks. Twenty-two species have a rank of S1 to S3—bolded species were collected during the bioblitzes and non-bolded are historical collections: S1. ***Acrocordia cavata* (Ach.) R.C. Harris** and *Gyalecta fagicola* (Hepp *ex* Arnold) Kremp.; S1S2. *Placidium lachneum*; S1S3. ***Melanelixia subargentifera* (Nyl.) O. Blanco, A. Crespo, Divakar, Essl., D. Hawksw. & Lumbsch**, *Phaeophyscia hirsuta* (Mereschk.) Essl., and *Scytinium teretiusculum* (Wallr.) Otálora, P.M. Jørg. & Wedin; S2. *Bacidia laurocerasi* (Delise *ex* Duby) Zahlbr.; S2S3. ***Chaenothecopsis debilis* (Turner & Borrer *ex* Sm.) Tibell**, *Coenogonium luteum* (Dicks.) Kalb & Lücking, ***Flavopunctelia soredica* (Nyl.) Hale, *Gyalecta jenensis* (Batsch) Zahlbr.**, ***Lecania naegelii* (Hepp) Diederich & v.d. Boom**, ***Phaeocalicium polyporaeum* (Nyl.) Tibell**, *Phaeophyscia ciliata* (Hoffm.) Moberg, and ***Viridothelium virens* (Tuck. *ex* E. Michener) Lücking, M.P. Nelsen & Aptroot**; S3. *Anaptychia palmulata* (Michx.) Vain., ***Catillaria nigroclavata* (Nyl.) Schuler**, ***Coenogonium pineti* Lücking & Lumbsch**, ***Placidium squamulosum* (Ach.) Breuss**, and ***Sphinctrina anglica***; and S3S4. *Bacidia bagliettoana* (A. Massal. & De Not.) Jatta and ***Phaeophyscia kairamoi* (Vain.) Moberg**. The remainder of the species are either secure, apparently secure, possibly extripated or are not ranked: S4 = 26, S4S5 = 13, S5 = 78, S5? = 1, SU = 6, SH = 1, and SNR = 33. The S-ranks presented here may have changed during a recent update for Ontario lichens by the NHIC (available at: https://www.ontario.ca/page/get-natural-heritage-information). These updates were not available in time to include in the present manuscript.

Annotated Species List

The list is arranged alphabetically by genus and species. Species authors are cited following Brummitt and Powell (1996) or the 21st edition of the North American Lichen Checklist (Esslinger 2016). Nomenclature mostly follows the 21st edition of the North American Lichen Checklist (Esslinger 2016). Deviance from

Esslinger's list represents the opinion of the authors. Names in bold represent collections made during the watershed bioblitzes while those not in bold represent previous collections made in the GTA by different collectors. Non-lichenized fungi traditionally treated with lichens are preceded by a dagger (†). New provincial records are preceded by an asterisk (*). Substrates follow species names, followed by watershed acronyms (CR = Credit River, DR = Don River, HR = Humber River, RR = Rouge River), and provincial conservation status ranks (*S-ranks*).

***Acarospora fuscata* (Schrad.) Arnold** – Saxicolous on non-calcareous rock. CR, HR, RR. *S5*.

***Acarospora glaucocarpa* (Ach.) Körb.** – Saxicolous on calcareous rock. CR. *S4S5*.

***Acarospora moenium* (Vain.) Räsänen** – Saxicolous on calcareous boulders and concrete. DR, HR. *SNR*.

***Acrocordia cavata* (Ach.) R.C. Harris** – Corticolous on a deciduous snag and *Populus*. CR, DR. *S1*.

***Alyxoria varia* Pers.** – Corticolous on a deciduous snag, *Acer*, and *Fraxinus*. CR, HR. *S4*.

***Amandinea dakotensis* (H. Magn.) P. May & Sheard** – Corticolous on a deciduous snag. DR. *S4*.

***Amandinea punctata* (Hoffm.) Coppins & Scheid.** – Corticolous on *Acer nigrum* and *P. strobus*. Lignicolous on exposed wood and a *Thuja* fence. CR, DR, HR, RR. *S5*.

Anaptychia palmulata (Michx.) Vain. – Terricolous. *White 316* (CANL) (Wong and Brodo 1992). *S3*.

†*Arthonia caudata* Willey – Corticolous on *P. strobus*. CR, DR, HR, RR. *SNR*.

***Arthonia helvola* (Nyl.) Nyl.** – Corticolous on *B. alleghaniensis* and *Betula papyrifera*. CR, HR, RR. *SNR*.

***Arthonia radiata* (Pers.) Ach.** – Corticolous on *Acer*. CR. *S5*.

Arthothelium spectabile (Flot.) A. Massal. – Corticolous on *Acer saccharum*. (Wong and Brodo 1992). DR. *SU*.

***Aspicilia cinerea* (L.) Körb.** – Saxicolous on an exposed boulder. HR. S*4S5*.

Bacidia bagliettoana (A. Massal. & De Not.) Jatta – Terricolous. (Wong and Brodo 1992). *S3S4*.

Bacidia laurocerasi (Delise *ex* Duby) Zahlbr. – Corticolous on *Thuja occidentalis*. *Cain s.n.* (F). DR. *S2*.

***Bacidia rubella* (Hoffm.) A. Massal.** – Corticolous on *T. occidentalis*. HR. *S4*.

Bacidia schweinitzii (Fr. *ex* Tuck.) A.Schneid. – Corticolous. (Wong and Brodo 1992). HR. *S5*.

***Bacidia* sp.** – Corticolous on *A. saccharum*. HR. *SNR*.

Bacidia suffusa (Fr.) A.Schneid. – Corticolous. (Wong and Brodo 1992). *S4*.

***Bilimbia sabuletorum* (Schreb.) Arnold** – Bryicolous; corticolous on *T. occidentalis*; saxicolous. CR, HR. *S5*.

***Caloplaca arenaria* (Pers.) Müll. Arg.** – Saxicolous on non-calcareous rock. CR, HR. *S5*.

***Caloplaca cerina* (Ehrh. *ex* Hedw.) Th. Fr.** – Corticolous on *Fraxinus*, *Populus, Populus balsamifera*, and *Populus tremuloides*. CR, DR, HR. *S5*.

***Caloplaca feracissima* H. Magn. –** Saxicolous on calcareous rock and concrete. CR, DR, HR, RR. *S5*.

***Caloplaca flavovirescens* (Wulfen) Dalla Torre & Sarnth. –** Saxicolous on a calcareous boulder and a rock wall. CR. *S5*.

***Caloplaca holocarpa* (Hoffm. *ex* Ach.) A.E. Wade –** Saxicolous on a calcareous rock. CR, HR. *S5*.

***Caloplaca pyracea* (Ach.) Th. Fr.** – Corticolous on *Fraxinus*, *Populus, P. balsamifera, P. tremuloides*. CR, DR, HR, RR. *SNR*.

***Candelaria concolor* (Dicks.) Stein** – Corticolous on *Acer, A. saccharum*, a deciduous snag, and *Fraxinus americana*. CR, DR, HR, RR. *S5*.

***Candelariella aurella* (Hoffm.) Zahlbr.** – Saxicolous on calcareous rock and concrete. CR, DR, HR, RR. *S5*.

***Candelariella efflorescens* R.C. Harris & W.R. Buck** – Corticolous on *B. papyrifera*; lignicolous on an exposed fence and a *T. occidentalis* snag. CR, DR, RR. *S5*.

***Candelarie1lla vitellina* (Hoffm.) Müll. Arg.** – Saxicolous on non-calcareous rock. HR. *S5*.

***Catillaria nigroclavata* (Nyl.) Schuler** – Corticolous on *Elaeagnus angustifolia,* a fallen branch, *P. strobus,* and a snag. CR, DR, HR, RR. *S3*.

***Chaenotheca* sp.** – Lignicolous (stump). DR. *SNR*.

***Chaenotheca balsamconensis* J.L. Allen & McMullin** – Fungicolous on *Trichaptum abietinum*. CR. *SNR*.

†*Chaenothecopsis* sp. – Lignicolous on a snag. HR. *SNR*.

†*Chaenothecopsis debilis* (Turner & Borrer *ex* Sm.) Tibell – Lignicolous on a stump. CR. *S2S3*.

***Chrysothrix caesia* (Flot.) Körb.** – Corticolous on *A. saccharum, E. angustifolia, Fraxinus*, and *Quercus rubra*. CR, DR, HR, RR. *S5*.

Cladonia cariosa (Ach.) Spreng. – Terricolous. (Wong and Brodo 1992). *S5*.

***Cladonia cenotea* (Ach.) Schaer.** – Lignicolous on an old stump. HR. *S5*.

***Cladonia chlorophaea* (Flörke *ex* Sommerf.) Spreng.** – Corticolous; lignicolous on a log; saxicolous on a mossy rock. CR, HR, RR. *S5*.

***Cladonia coniocraea* (Flörke) Spreng.** – Lignicolous on a log. RR. *SU*.

***Cladonia crispata* (Ach.) Flot.** – Lignicolous on a stump. HR. *S5*.

***Cladonia cristatella* Tuck.** – Lignicolous on a log and a stump. HR, RR. *S5*.

***Cladonia cryptochlorophaea* Asahina** – Saxicolous. HR. SU.

***Cladonia decorticata* (Flörke) Spreng.** – Lignicolous on a log. *S4*.

***Cladonia digitata* (L.) Hoffm.** – Lignicolous on a stump. HR. *S4S5*.

***Cladonia fimbriata* (L.) Fr.** – Lignicolous on a log. CR. *S5*.

Cladonia furcata ssp. *furcata* (Huds.) Schrad. – Terricolous. (Wong and Brodo 1992). *S5*.

Cladonia gracilis ssp. *turbinata* (Ach.) Ahti – Terricolous. (Wong and Brodo 1992). CR. *S5*.

Cladonia humilis (With.) J.R. Laundon – Terricolous. (Wong and Brodo 1992). *S4*?

***Cladonia incrassata* Flörke** – Lignicolous on a stump. HR. *S4*.

***Cladonia macilenta* var. *bacillaris* (Genth) Schaer.** – Lignicolous on a log, a stump, and a *Thuja* fence. CR, HR, RR. *S5*.

***Cladonia ochrochlora* Flörke** – Corticolous on the base of a tree; lignicolous on a stump; saxicolous on a mossy rock. CR, HR. *S5*.

***Cladonia pocillum* (Ach.) Grognot** – Terricolous on thin soil over rock. CR, RR. *S4S5*.

***Cladonia pyxidata* (L.) Hoffm.** – Lignicolous on a log. RR. *S5*.

Cladonia ramulosa (With.) J.R. Laundon – Corticolous on a *Pinus* stump. (Wong and Brodo 1992). *SNR*.

***Cladonia rei* Schaer.** – Terricolous and on soil on a fence rail. CR, HR. *S5*.

***Cladonia scabriuscula* (Delise) Nyl.** – Lignicolous on an old stump. HR. *S5*.

†*Clypeococcum hypocenomycis* D. Hawksw. – Lichenicolous on *Hypocenomyce scalaris*. HR. *SNR*.

Coenogonium luteum (Dicks.) Kalb & Lücking – Corticolous on *Thuja*. (Wong and Brodo 1992). *S2S3*.

***Coenogonium pineti* Lücking & Lumbsch** – Lignicolous on a charred stump and a log; terricolous. CR, RR. *S3*.

***Cyphelium tigillare* (Ach.) Ach.** – Lignicolous on an old *Thuja* fence. CR. *S4*.

***Dictyocatenulata alba* Finley & E.F. Morris** – Corticolous on *B. alleghaniensis* and a *B. papyrifera* snag. CR, HR, RR. *SNR*.

***Dimelaena oreina* (Ach.) Norman** – Saxicolous on non-calcareous rock. HR. *S4*.

***Diplotomma venustum* (Körb.) Körb.** – Saxicolous on a rock wall. CR. *SNR*.

Enchylium tenax (Sw.) – Terricolous. (Wong and Brodo 1992). *S4*.

***Evernia mesomorpha* Nyl.** – Corticolous on a dead *Rhus typhina* branch, a deciduous snag, and *Larix laricina*. CR, HR. *S5*.

***Flavoparmelia caperata* (L.) Hale** – Corticolous on *Acer, A. saccharum*, a fallen deciduous tree, an unknown ornamental tree, a snag, and *Ulmus*; lignicolous on fence rails. CR, DR, HR, RR. *S5*.

***Flavopunctelia flaventior* (Stirt.) Hale** – Corticolous on *F. americana* and *Populus grandidentata*; lignicolous on a *Thuja* fence post. CR, DR, HR. *S5*.

***Flavopunctelia soredica* (Nyl.) Hale** – Corticolous on a deciduous tree, *F. americana,* and on *Fraxinus*. CR, HR. *S2S3*.

***Graphis scripta* (L.) Ach.** – Corticolous on *Acer*, *A. rubrum, A. saccharum,* and on *B. alleghaniensis*. CR, DR, HR. *S5*.

Gyalecta fagicola (Hepp *ex* Arnold) Kremp. – Corticolous on *Ulmus*. *Cain s.n.* (NY). CR. *S1*.

***Gyalecta jenensis* (Batsch) Zahlbr.** – Saxicolous on calcareous rock. CR. *S2S3*.

***Hyperphyscia adglutinata* (Flörke) H. Mayrh. & Poelt** – Corticolous on *Acer, A. saccharum*, *E. angustifolia,* and on *Quercus*. CR, DR, HR, RR. *S4*.

***Hypocenomyce scalaris* (Ach.) M. Choisy** – Corticolous on *P. strobus*; lignicolous on a stump. DR, HR. *S5*.

***Hypogymnia physodes* (L.) Nyl.** – Corticolous on a snag. HR. *S5*.

†*Illosporiopsis christiansenii* (B.L. Brady & D. Hawksw.) D. Hawksw. – Lichenicolous on *Physcia*, and *Physcia millegrana*. CR, HR. *SNR*.

†*Julella fallaciosa* (Arnold) R.C. Harris – Corticolous on *Acer, Acer saccharum*, *Betula,* and *B. papyrifera*. CR, DR, HR, RR. *SNR*.

***Lecania croatica* (Zahlbr.) Kotlov** – Corticolous on *Acer, Acer rubrum, A. saccharum*, a deciduous tree, *F. grandifolia,* and *Tilia*. CR, DR, HR. *SNR*.

***Lecania naegelii* (Hepp) Diederich & v.d. Boom** – Corticolous on *Fraxinus, F. americana*, and on *P. tremuloides*. DR, HR, RR. *S2S3*.

Lecanora albellula Nyl. – Corticolous. (Wong and Brodo 1992). *SNR*.

***Lecanora allophana* f. *sorediata* Nyl.** – Corticolous on *P. tremuloides*. HR. *S5*.

***Lecanora carpinea* (L.) Vain.** SNR – Corticolous. DR. *SNR*.

***Lecanora hybocarpa* (Tuck.) Brodo** – Corticolous on *A. rubrum* and a deciduous snag. CR, HR. *S4S5*.

Lecanora polytropa **(Hoffm.) Rabenh.** – Saxicolous on non-calcareous rock. HR, RR. *S5*.

Lecanora pulicaris **(Pers.) Ach.** – Corticolous on *P. strobus*. CR, HR. *S5*.

Lecanora sambuci **(Pers.) Nyl.** – Corticolous on *Fraxinus, F. americana*, *Populus,* and *P. tremuloides*. CR, DR, HR, RR. *SNR*.

Lecanora symmicta **(Ach.) Ach.** – Corticolous on *A. rubrum* and *P. strobus*; lignicolous on a *Thuja* fence rail. CR, DR, HR. *S5*.

Lecanora thysanophora **Harris** – Corticolous on *Acer*, a deciduous snag, and *Q. rubra*. CR, DR, HR, RR. *S5*.

Lecidella stigmatea **(Ach.) Hertel & Leuckert** – Saxicolous on concrete and a rock wall. CR, HR. *S5*.

Lepraria finkii **(B. de Lesd.) R.C. Harris** – Corticolous on *Salix* and *T. occidentalis*; lignicolous on a log and a stump. CR, DR, HR, RR. *SNR*.

Lepraria neglecta **(Nyl.) Erichsen** – Corticolous on *Tsuga canadensis*. HR. *S4S5*.

Leptogium byssinum (Hoffm.) Zwackh *ex* Nyl. – Terricolous on clay soil. (Wong and Brodo 1992). *SH*.

Lithothelium hyalosporum (Nyl.) Aptroot – Corticolous. (Wong and Brodo 1992). *S4*.

Lobaria quercizans Michx. – Corticolous. (Wong and Brodo 1992). CR. *S4S5*.

Megalaria laureri (Hepp *ex* Th. Fr.) Hafellner – Corticolous on *Fagus*. (Wong and Brodo 1992). *SNR*.

Melanelixia subargentifera **(Nyl.) O. Blanco, A. Crespo, Divakar, Essl., D. Hawksw. & Lumbsch** – Corticolous on *P. tremuloides*. HR. *S1S3*.

Melanelixia subaurifera **(Nyl.) O. Blanco, A. Crespo, Divakar, Essl., D. Hawksw. & Lumbsch –** Corticolous on a dead *R. typhina* branch, *F. americana,* a snag, and *T. occidentalis*; lignicolous on a *Thuja* fence rail; saxicolous on exposed boulders. CR, DR, HR, RR. *S5*.

Micarea prasina s. lat. **Fr.** – Corticolous on *T. occidentalis*. CR. *SNR*.

Micarea peliocarpa **(Anzi) Coppins & R. Sant.** – Lignicolous on a stump. HR. *S4S5*.

Montanelia sorediata **(Ach.) Goward & Ahti** – Saxicolous on an exposed boulder. HR. *S5*.

†***Mycocalicium subtile*** **(Pers.) Szatala** – Lignicolous on a decorticated stump and a snag. CR. *S4S5*.

Myelochroa aurulenta **(Tuck.) Elix & Hale** – Corticolous on *Acer*. CR. *S5*.

Myriolecis dispersa **(Pers.) Śliwa, Zhao Xin & Lumbsch** – Saxicolous on calcareous rock and concrete. DR, HR, RR. *SU*.

Myriolecis hagenii **(Ach.) Ach.** – Lignicolous on a *Thuja* fence and a wooden sign post. CR, HR. *S5?*

Myriolecis semipallida **H. Magn.** – Saxicolous on concrete. CR. *SNR*.

Ochrolechia arborea **(Kreyer) Almb.** – Corticolous on a living fallen *T. occidentalis* and a snag. CR, HR, RR. *S4S5*.

†***Ovicuculispora parmeliae*** **(Berk. & Curt.) Etayo** – Lichenicolous on *Physcia* and *Physcia stellaris*. CR, DR. *SNR*.

Parmelia sulcata **Taylor** – Corticolous on *A. saccharum, F. americana,* a snag, and *Ulmus*; lignicolous on a fence rail; saxicolous on exposed boulders. CR, DR, HR, RR. *S5*.

Peltigera canina (L.) Willd. – Corticolous on a rotting log. (Wong and Brodo 1992). HR. *S5*.

Peltigera didactyla (With.) Laundon – Terricolous. (Wong and Brodo 1992). *S5*.

Peltigera elisabethae Gyeln. – Terricolous. (Wong and Brodo 1992). HR. *S5*.

Peltigera evansiana **Gyeln.** – Terricolous. CR. *S4S5*.

Peltigera horizontalis (Huds.) Baumg. – Terricolous. (Wong and Brodo 1992). HR. *S4S5*.

Peltigera lepidophora (Nyl. *ex* Vain.) Bitt. – Terricolous on sandy soil. (Wong and Brodo 1992). *S4*.

Peltigera leucophlebia (Nyl.) Gyeln. – Terricolous. (Wong and Brodo 1992). *S4*.

Peltigera neckeri Hepp *ex* Müll. Arg. – Terricolous (Wong and Brodo 1992). *S5*.

Peltigera neopolydactyla (Gyeln.) Gyeln. – Terricolous. (Wong and Brodo 1992). *S5*.

Peltigera praetextata **(Flörke *ex* Sommerf.) Zopf** – Lignicolous on a moss-covered log; saxicolous on a mossy rock; terricolous on a moss-covered rock. CR, HR, RR. *S5*.

Peltigera rufescens **(Weiss) Humb.** – Terricolous on well-drained soil. CR. *S5*.

Pertusaria macounii **(Lamb) Dibben –** Corticolous on *F. grandifolia*. CR. *S4*.

†***Phaeocalicium curtisii*** **(Tuck.) Tibell** – Corticolous on *R. typhina*. CR, DR, HR. *S5*.

†***Phaeocalicium polyporaeum*** **(Nyl.) Tibell –** Fungicolous on *Trichaptum biforme*. DR. *S2S3*.

Phaeophyscia adiastola **(Essl.) Essl.** – Bryicolous. CR. *S4*.

Phaeophyscia ciliata (Hoffm.) Moberg – Corticolous on *Populus*. *Darker 5609* (FH). *S2S3*.

Phaeophyscia hirsuta (Mereschk.) Essl. – Corticolous on *Salix*. (Wong and Brodo 1992). CR. *S1S3*.

Phaeophyscia kairamoi **(Vain.) Moberg** – Corticolous on *A. nigrum*. RR. *S3S4*.

Phaeophyscia orbicularis **(Neck.) Moberg** – Lignicolous on a picnic table; saxicolous on a boulder. DR, HR, RR. *S5*.

Phaeophyscia pusilloides **(Zahlbr.) Essl.** – Corticolous on *Acer, A. saccharum*, a deciduous snag, *Fraxinus*, and *Q. rubra*. CR, DR, HR, RR. *S5*.

Phaeophyscia rubropulchra **(Degel.) Essl. –** Corticolous on *A. saccharum, Crataegus*, and a snag. CR, DR, HR, RR. *S5*.

Physcia adscendens **(Fr.) H. Olivier –** Corticolous on *Acer, A. saccharum*, *Malus*, *P. strobus*, a snag, and *Ulmus*. CR, DR, HR, RR. *S5*.

Physcia aipolia **(Ehrh. *ex* Humb.) Fürnr.** – Corticolous on *A. nigrum,* a deciduous snag, *Fraxinus,* and *F. americana*. CR, DR, HR, RR. *S5*.

Physcia dubia **(Hoffm.) Lettau** – Saxicolous on a boulder. CR, HR. *S5*.

Physcia millegrana **Degel. –** Corticolous on *Acer, A. saccharum*, *Fraxinus, F. americana, Malus*, and *Tilia*. CR, DR, HR, RR. *S5*.

Physcia stellaris **(L.) Nyl.** – Corticolous on a deciduous snag, *F. americana, P. strobus,* and *Q. rubra*; lignicolous on a *Thuja* fence. CR, DR, HR, RR. *S5*.

Physciella chloantha **(Ach.) Essl.** – Corticolous on *Acer*, a deciduous snag, *Fraxinus*, and *Ulmus*. CR, DR, HR. *S4*.

Physciella melanchra **(Hue) Essl.** – Corticolous on *Acer* and *F. americana*. HR, RR. *S4*.

Physconia detersa **(Nyl.) Poelt** – Corticolous on *B. papyrifera* and a snag. CR, DR, HR, RR. *S5*.

Physconia enteroxantha **(Nyl.) Poelt** – Corticolous on *Acer, A. nigrum*, *Fraxinus, F. americana*, and *Ulmus*; saxicolous on boulders. CR, HR, RR. *S4*.

Placidium lachneum (Ach.) B. de Lesd. – Terricolous. (Wong and Brodo 1992). *S1S2*.

Placidium squamulosum **(Ach.) Breuss** – Terricolous. CR. *S3*.

Placynthium nigrum **(Huds.) Gray** – Saxicolous on shoreline rocks. CR. *S5*.

Polychidium muscicola (Sw.) Gray – Corticolous on old *Ulmus* log. *Cain 25418* (Det. Hale) (US). HR. *SNR*.

Porpidia crustulata **(Ach.) Hertel & Knoph** – Saxicolous. CR. *S5*.

Porpidia macrocarpa **(DC.) Hertel & A.J. Schwab** – Saxicolous. CR. *S4*.

Protoblastenia rupestris **(Scop.) J. Steiner** – Saxicolous on calcareous rock. CR, RR. *S5*.

Protoparmelia hypotremella **Herk, Spier & V. Wirth** – Corticolous on a dead branch. CR. *SNR*.

Protoparmeliopsis muralis **(Schreb.) Rabenh.** – Saxicolous on concrete. CR, HR. *S5*.

Pseudoschismatomma rufescens (Pers.) Ertz & Tehler – Corticolous on *Tilia*. *Cain 26826* (det. Harris) (NY). *SNR*.

Punctelia caseana Lendemer & Hodkinson – Corticolous. *Cain 27122* (det. Lendemer) (CANL). HR. *SNR*.

Punctelia rudecta **(Ach.) Krog** – Corticolous on *Acer*, *Crataegus*, a deciduous snag, *T. occidentalis,* and *Q. rubra*; saxicolous on boulders. CR, DR, HR, RR. *S5*.

Pyrenula pseudobufonia (Rehm) R.C. Harris – Corticolous on *Acer.* (CANL) (Wong and Brodo 1992). HR. *S4*.

Pyxine sorediata (Ach.) Mont. – Corticolous. (Wong and Brodo 1992). CR. *S5*.

Ramalina americana Hale – Corticolous on *Picea.* (Wong and Brodo 1992). CR. *S5*.

Ramalina obtusata (Arnold) Bitter – Corticolous on *Ulmus.* (Wong and Brodo 1992). HR. *S4?*

Rhizocarpon reductum **(Ach.) A. Massal.** – Saxicolous on a non-calcareous boulder. HR. *SNR*.

Rinodina freyi **H. Magn.** – Corticolous on *Q. rubra.* CR. *SNR*.

Sarcogyne hypophaea **(Nyl.) Arnold** – Saxicolous on non-calcareous rock. RR. *SNR*.

Sarcogyne regularis **Körb.** – Saxicolous on calcareous rock. CR, DR, HR, RR. *S5*.

†***Sarea resinae*** **(Fr.) Kuntze** – Resinicolous on *Picea* and *Picea glauca*. HR, RR. *SNR*.

Scoliciosporum chlorococcum **(Stenh.) Vězda** – Corticolous on *P. strobus* and on a fallen deciduous branch. CR, HR. *S5*.

Scoliciosporum umbrinum **(Ach.) Arnold** – Corticolous on *Q. rubra.* CR. *S4*.

Scytinium lichenoides **(L.) Otálora, P.M. Jørg. & Wedin** – Saxicolous. CR. *S5*.

Scytinium teretiusculum (Wallr.) Otálora, P.M. Jørg. & Wedin – Saxicolous. (Wong and Brodo 1992). *S1S3*.

†***Sphinctrina anglica*** **Nyl.** – Lichenicolous on *P. hypotremella.* CR. *S3*.

†***Stenocybe pullatula*** **(Ach.) Stein** – Corticolous on *Alnus*. CR. *SU*.

Thelocarpon superellum Nyl. – Terricolous. *Cain 25720* (TRTC) (Wong and Brodo 1992). *SNR*.

Trapelia placodioides **Coppins & P. James** – Saxicolous. CR, HR, RR. *S5*

Varicellaria velata (Tuner) Schmitt & Lumbsch – Corticolous on *Fagus*. (Wong and Brodo 1992). *S4*.

Variolaria trachythallina (Erichsen) Lendemer, Hodkinson & R.C. Harris – Corticolous. (Wong and Brodo 1992). *S4*.

***Verrucaria calkinsiana* Servít** – Saxicolous on calcareous rock. CR, DR. *S5*.

***Viridothelium virens* (Tuck. *ex* E. Michener) Lücking, M.P. Nelsen & Aptroot –** Corticolous on *F. grandifolia* and *Tilia*. DR. *S2S3*.

***Xanthomendoza fallax* (Hepp *ex* Arnold) Søchting, Kärnefelt & S. Kondr.** – Corticolous on *Acer, A. rubrum, Fraxinus, F. americana*, and *Ulmus*. CR, DR, HR, RR. *S5*.

***Xanthomendoza hasseana* (Räsänen) Søchting, Kärnefelt & S. Kondr.** – Corticolous on *Populus* snag. DR. *S5*.

***Xanthomendoza ulophyllodes* (Räsänen) Søchting, Kärnefelt & S. Kondr.** – Corticolous on *A. nigrum,* a fallen deciduous tree, a snag, and on *T. occidentalis.* DR, HR, RR. *S4*.

***Xanthoparmelia cumberlandia* (Gyeln.) Hale** – Saxicolous on non-calcareous rock. CR, HR, RR. *S5*.

***Xanthoparmelia plittii* (Gyeln.) Hale** – Saxicolous on non-calcareous rock. HR. *S4S5*.

Xanthoparmelia viriduloumbrina (Gyaln.) Lendemer – Saxicolous. (Wong and Brodo 1992). CR. *SU*.

***Xanthoria elegans* (Link) Th. Fr. –** Saxicolous on a non-calcareous rock. CR, DR, HR. *S5*.

***Xanthoria parietina* (L.) Th. Fr.** – Corticolous on *Acer* and *P. balsamifera*; lignicolous on a *Thuja* fence rail. CR, DR, HR. *SNR*.

***Xanthoria polycarpa* (Hoffm.) Rieber** – Corticolous on *Acer* and a fallen deciduous tree. CR, HR. *S4*.

Discussion

Our results from the four bioblitzes brings the total number of lichens and allied fungi known from the GTA to 180. This is a relatively large number of species compared to other studies in southern Ontario, such as the Arboretum at the University of Guelph (104 species; McMullin *et al.* 2014), Awenda Provincial Park (203 species; McMullin and Lendemer 2016), Copeland Forest Resources Management Area (154 species; McMullin and Lendemer 2013), and Sandbanks Provincial Park (128 species; McMullin and Lewis 2014). The major difference between these studies and the GTA bioblitzes is that they were comprehensive surveys without time restrictions. We expect to find additional species in unexamined habitats and localities in the GTA region. The GTA also differs by encompassing a much larger area than that examined by these previous studies, which could allow for a greater number of microhabitats that could be colonized by a greater number of species. However, the GTA is also affected more by air pollution, agriculture, and other industries such as historical timber harvesting that are known to have detrimental affects on lichen communities (Lesica *et al.* 1991; Henderson 2000; McMullin *et al.* 2013). Locations within the GTA that contained the greatest number of species were among the furthest from the city centre (e.g., Forks of the Credit Provincial Park and Glen Haffey Conservation Area). This pattern has been observed with lichens in four other Canadian cities (Halifax, Hamilton, Niagara, and Owen Sound; Cameron *et al.* 2007; McMullin *et al.* 2016). Despite the negative anthropogenic effects on lichen diversity, the GTA contains 37% of the 482 lichens reported in southern Ontario by Wong and Brodo (1992). This new baseline for the GTA can be used to monitor the impact of future environmental changes on lichen diversity.

Forty-two lichen species collected previously in the GTA were not collected during our study (see the Annotated Species List). We may not have examined the same microhabitats, or alternatively air pollution, habitat loss, or climate change may have caused their extirpation in the area. Targetted searches of the locations where these 42 species were collected (if they are known) would provide stronger evidence of their presence or absence in the area. Locations where species we collected are recorded to faciliate ongoing monitoring.

We discovered 13 species that are listed provincially as S1 (critically imperilled), S2 (imperilled), or S3 (vulnerable). Nine additional S1, S2, and S3 species were collected historically that we did not find. These results suggest that the GTA is ecologically important for lichens in Ontario. The most notable species we found does not have a rank because it is new to Ontario, *L. carpinea* (Figure 2; McMullin 2018). *Lecanora carpinea* is typically a western species in North America with small disjunct and scattered populations in the east, the largest of which is in the United States on the southwestern shore of Lake Superior (McMullin 2018). The only S1 ranked species that we discovered was *A. cavata*. This species may need to be reranked as it was also discovered during other recent surveys in southern Ontario (McMullin and Lewis 2014; McMullin and Lendemer 2016). Additional notable species that are rarely collected in the province and that have low ranks include *M. subargentifera* (S2S3), which has been previously collected five times (Wong and Brodo 1992; McMullin and Lewis 2013), *G. jenensis* (S2S3), which is known from four other sites (Brodo *et al.* 2013; Lewis and Brinker 2017), and *P. kairamoi* (S3 S4), which is known from three previous collections (McMullin *et al.* 2015). Although the bioblitzes were not comprehensive surveys, they revealed a surprising number of rare species as well as high overall richness.

Bioblitz projects can contribute to our understanding and, as a result the conservation, of lichens and other biota (Shorthouse 2010; Foster *et al.* 2013). The num-

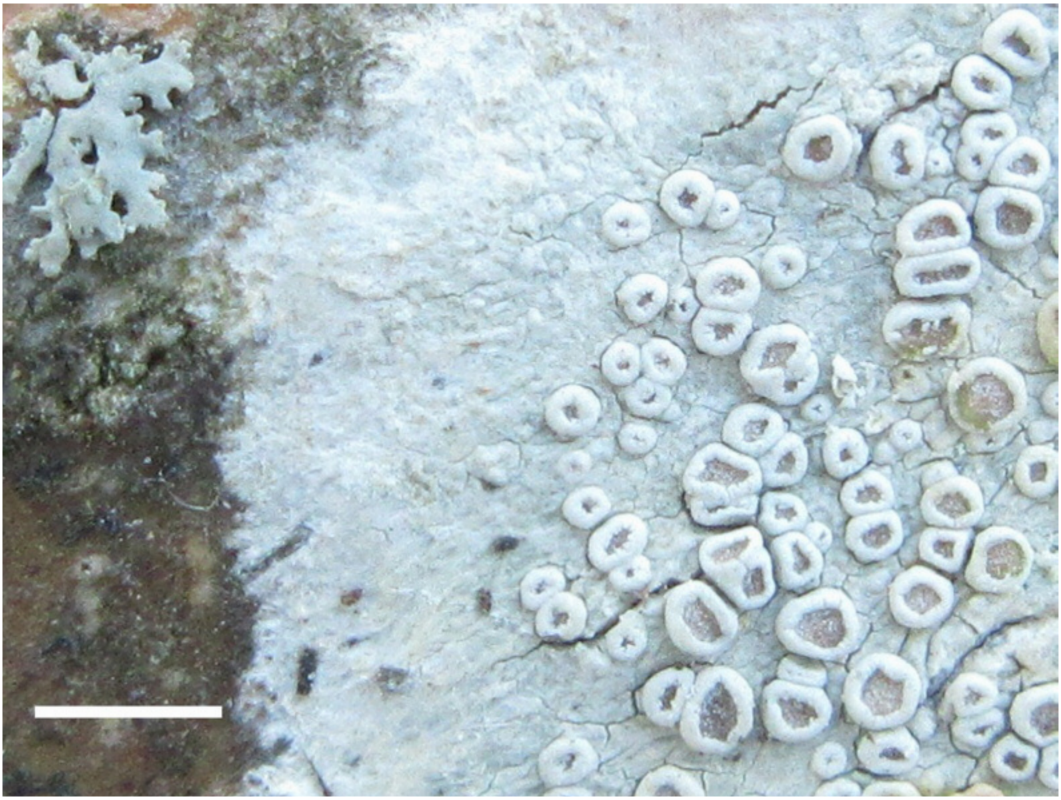

Figure 2. *Lecanora carpinea*, *McMullin 15729* (CANL), scale = 2.1 mm. A new record for Ontario. Photo: Troy McMullin.

ber of bioblitz projects globally has increased steadily since the term was introduced in 1996, and several countries now have their own national programs (Donnelly *et al.* 2014). National Geographic partnered with many United States-based environmental organizations to complete a 10-year bioblitz project in 2016 to celebrate the 100th anniversary of the United States National Parks Service. In the final year alone, more than 125 individual events occurred, with over 13 000 species recorded by some 6000 participants (www.nationalgeographic.org/bioblitz). Bioblitz projects that include non-scientists or other members of the general public lead to an increase in peoples' biodiversity knowledge (Pollock *et al.* 2015) and often encourages learning about the natural world (Bela *et al.* 2016), particularly for children (Himschoot 2017). Bioblitz events in or near large urban areas provide opportunities to teach people about the value of the urban biodiversity where they live (Wei *et al.* 2016). Technology is also an important driver of the success of the bioblitz movement; mobile applications and taxonomic identification software allow citizen scientists to crowd-source expertise. Online tools can have a positive impact on informal science learning (Scanlon *et al.* 2014; August *et al.* 2015) and can decentralize taxonomic expertise (Gardiner and Bachman 2016). High throughput DNA barcoding has also become more common at bioblitz events (Laforest *et al.* 2013; Telfer *et al.* 2015; Geiger *et al.* 2016) and has demonstrated that biodiversity surveys by non-experts can significantly increase overall species observations, especially when deliberately selecting diverse habitats.

Since 2012, the Ontario Bioblitz program has grown to be the largest and most robust (in terms of species documented and volunteers involved) bioblitz project in Canada. Although based in the GTA, the program has influenced province-wide action with many smaller communities adopting the program's core strategy of including taxonomic experts, citizen scientists, and general members of the public under one project delivery. The core strategy of the Ontario BioBlitz program was leveraged to propose a nation-wide bioblitz project to celebrate Canada's sesquicentennial in 2017. The project, titled BioBlitz Canada, was awarded $750K from the federal government to launch a series of bioblitz events across the country in 2017, including five flagship events in major urban areas (e.g., Halifax, Toronto, and Vancouver), 10 science-intensive events in ecosystems with taxonomic data gaps (e.g., Kluane National Park, Yukon and Big Trout Bay along the north shore of Lake Superior, Ontario), and 20 community-level bioblitz events in every province and territory (www.bioblitz canada.ca; Catling *et al.* 2017). The future of BioBlitz Canada rests with an advisory committee, which comprises 15 leading environmental groups and is currently facilitated by the Royal Ontario Museum.

The value of a bioblitz is multi-faceted and increasingly recognized in Canada, as it is in many other countries. The results from our study contribute to our understanding of this value. We show that, despite time restrictions, substantial scientific contributions can be made even with inconspicuous and understudied groups that are taxonomically difficult, such as lichens and allied fungi.

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SUPPLEMENTARY MATERIAL:

APPENDIX S1: Collection details of specimens examined.

Taxonomic survey of Agaricomycetes (Fungi: Basidiomycota) in Ontario tallgrass prairies determined by fruiting body and soil rDNA sampling

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Abstract
The fungal composition of North America's grasslands is poorly known, but an important area of study due to grassland conservation concerns and their close relation to agricultural lands. This study is a survey of Agaricomcyetes from fifteen diverse tallgrass prairies across southwestern Ontario, determined through fruiting body surveys (above-ground) and next-generation sequencing of soil ribosomal DNA (below-ground), and compares the results of these two techniques. The most species rich taxa were the Clavariaceae, Hygrophoraceae, and Entolomataceae, each detected by both techniques, with the addition of the Sebacinaceae and Polyporaceae *sensu lato* below-ground, and Hymenogastraceae (*Hebeloma* spp.) and Mycenaceae above-ground. Many of the most abundant species belonged to these species-rich taxa and were highly abundant by either technique. The above-ground surveys found at least 73 species and the below-ground technique 238 operatonal taxonomic units. Although many fine-scale taxa (species and approximate families) were unique to one technique or the other (only eight genetic species were shared between both), the below-ground technique uncovered a greater breadth of higher taxa (mostly equivalent to orders), including ones undetected by the above-ground technique. A review of grassland fungi surveys around the world shows many similarities and the potential for grassland fungal conservation in North America. Given current technological advancements and grassland conservation concerns, it is prudent to further study North America's grassland fungi.

Key words: Tallgrass prairie; grassland mycota; fungal conservation; mushrooms; next-generation sequencing; basidiomycetes; survey

Introduction
Worldwide, grasslands represent the largest terrestrial biome, covering approximately 40% of the earth's land surface, and are tremendously important for the development of crop and grazing agriculture and the biodiversity of natural grassland remnants (Gibson 2009). The prairies represent the large region of grasslands in central North America. They are characterized by low or no woody plant coverage, consisting mostly of grasses and a high diversity of sparse, broadleaved herbaceous species (Sims 1988). Tallgrass prairies comprise the eastern portion of the central grasslands and have more precipitation (mesic), than the drier mixed-grass and shortgrass prairies further west (xeric; Samson and Knopf 1996). Southwestern Ontario is classified as part of the Temperate Deciduous Forest biome (Whittaker 1975; Archibold 1995), and within that as Mixedwood Plains ecozone (Ecological Stratification Working Group 1995), so there is only a small amount of naturally occurring tallgrass prairie-oak savannah mosaic (Barcza and Lebedyk 2014). This study focussed on tallgrass prairie in southwestern Ontario, though pockets also exist in Ontario further northwest (Quinlan 2005) and northeast (e.g., the Rice Lake plains; Catling *et al.* 1992). Prairies, particularly tallgrass, are among the most depleted and imperilled ecosystems in the world (Noss *et al.* 1995; Samson and Knopf 1996; Koper *et al.* 2010) and tallgrass prairies in Ontario are no exception (Barcza and Lebedyk 2014). Consequently, tallgrass prairie is habitat to many plant and animal species at risk (Rodger 1998; Environment Canada 2014), and perhaps unexplored fungi at risk.

The Agaricomycetes are a class of fungi (phylum Basidiomycota) that include about one-fifth of all fungal species (Kirk *et al.* 2008) and diverse morphologies of mushrooms (fruiting bodies; Hibbett *et al*. 2014). Both globally in terrestrial ecosystems and within grasslands and shrublands specifically, Agaricomycetes comprise 50% of soil fungal diversity (Tedersoo *et al.* 2014). They include the dominant saprotrophs of plant litter and other species that are pathogens and mutualists—especially those forming ectomycorrhizal relationships with plant roots (Weiss *et al.* 2004; Smith and Read 2008; Hibbett *et al.* 2014). Some species belong to more

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than one of these categories or are opportunistic (Griffith and Roderick 2008).

Illuminating the fungal composition of ecosystems by producing species lists and collections of dried specimens is an important first step for fungal conservation by providing basic information to mycologists, conservationists, and governments (Arnolds 1989a; Keizer 1993; Courtecuisse 2001; Bruns 2012). Mushroom forays are often carried out by local naturalist groups, but lists are usually not documented with specimens kept in recognized fungaria, and when they are, identifications of many taxa may be suspect if applied without attention to microscopic characters and thorough consideration of species names outside of incomplete or outdated field guides. The majority of authoritative data are found in herbaria (fungaria), which are increasingly being digitized and compiled (e.g., http://www.MyCoPortal.org) but still require some care with interpretation of outdated taxonomy and confirmation of identifications (Redhead 1989). Available records reveal regional and ecological gaps where specimens have not been collected.

Given the global extent of grassland cover and the importance of fungi to grassland ecosystems, it is remarkable that no estimate of a grassland mycota has been compiled. Typically, wooded ecosystems are preferred over grasslands for forays and scientific surveys (noted in Griffith and Roderick 2008; e.g., Polach 1992; Castellano *et al.* 1999; Dewsbury *et al.* 2006). Grassland mushroom fungi are best known from extensive fruiting body surveys in Europe (e.g., various grasslands in England, Wilkins and Patrick 1939; forest meadow slopes in Poland, Gumińska 1976; and coastal grasslands in the Netherlands, Arnolds 1981). There are also records from soil culturing and fruiting body surveys in Australia (Warcup 1951, 1959; Warcup and Talbot 1962, 1963, 1965), and fewer in North America (shortgrass prairie dung cultures, Wicklow and Angel 1974; alvar grasslands surveys, Mycological Society of Toronto 2005a,b; and a mixedgrass prairie survey, Hay 2013). Many studies from Europe are specific to "waxcap" grasslands, which have received special attention and mycological study due to concerns over land management changes and loss of characteristic fungi in this habitat (Rotheroe *et al.* 1996; Rotheroe 2001; Newton *et al*. 2003; Mitchel 2010; Griffith *et al.* 2013). Other studies are focussed on producing national Red Lists of species potentially at risk (e.g., the Netherlands, Arnolds 1989a). Although there is anecdotal knowledge among mycologists and naturalists of which mushrooms are found in North American grasslands (such as in field guides, e.g., Arora 1986; Barron 1999), a lack of scientific data makes study of distribution and ecology difficult or impossible (Redhead 1989). Thus, syntheses and interpretation of the available data have not been attempted.

Next-generation sequencing (NGS) represents a major advancement in high-throughput sequencing technology and, with the development of taxon-specific DNA barcodes, has revolutionized biology (Shokralla *et al.* 2012; Lindahl *et al.* 2013; Bleidorn 2016). Communities of microorganisms can be characterized through collection of DNA sequences from environmental samples, a process termed "eDNA metabarcoding" (Taberlet *et al.* 2012). Continual growth of reference datasets such as GenBank and UNITE further facilitates more accurate and thorough classification of DNA sequences obtained through NGS, and improved primers have been developed to target specific fungal taxa based on amplification of ribosomal DNA (rDNA) regions (Asemaninejad *et al.* 2016; Taylor *et al*. 2016; De Filippis *et al.* 2017). Previously hidden fungal diversity is constantly uncovered by NGS when unclassifiable sequences are found (Hibbett *et al.* 2014; Nilsson *et al.* 2016). This has improved our understanding of the ecology and distribution of known species, particularly those that are difficult to find through culturing or fruiting body surveys. The "mycobiome" in soils and plants is often studied, albeit at taxonomic scales too coarse to uncover biodiversity at the species level (Peay *et al.* 2016). Microfungi (i.e., molds; Clarke and Christensen 1981; Maggi *et al*. 2005) and arbuscular-mycorrhizal fungi (Eom *et al.* 2000; Stover *et al.* 2012) have been surveyed in grasslands and many studies conduct microbial surveys from non-taxonomic, chemical perspectives (e.g., McKinley *et al.* 2005). Agaricomycetes in native grasslands of North America have been explored obliquely in the process of fulfilling other research objectives using NGS in tallgrass prairies of Oklahoma (Penton *et al.* 2013) and Kansas (Jumpponen *et al.* 2010; Jumpponen and Jones 2014).

The fungal taxa of a site may be uncovered using fruiting body surveys (or spores, hyphal sheaths on roots, etc.), culture-based approaches, or molecular methods (including NGS), and usually there are disparities among the results of each technique (Horton and Bruns 2001). Seeing differences among results is useful for determining limitations of any one technique and to gain a more accurate view of community composition. Results of molecular techniques have been compared with cultures of grassland or agroecosystem soil samples (Hunt *et al.* 2004; Lynch and Thorn 2006) and with fruiting body surveys of ectomycorrhizal species in treed ecosystems (Gardes and Bruns 1996; Smith *et al*. 2007; Porter *et al*. 2008; Dickie *et al.* 2009). The only mycological study we found comparing both of the above- and below-ground techniques that we use (specifically fruiting body surveys and NGS high-throughput sequencing) was of dead wood communities (Ovaskainen *et al.* 2013).

All things considered, the fungal composition of North American grasslands is a large research gap that can now readily be addressed. The objectives of this study are to survey the Agaricomycetes in selected Ontario tallgrass prairies by fruiting body and soil rDNA sampling, and to compare results of fruiting body and soil rDNA sampling techniques. These findings may yield new insights into prairie ecology and management in conservation and restoration initiatives, will contribute to better understanding mushroom species biogeography and surveying methods, and will serve as a foundation to inform future research.

Study Area

This study sampled from fifteen different tallgrass prairie sites across southwestern Ontario, Canada (Figure 1). The sites include prairie remnants and restorations (from agricultural fields) respresenting a diversity of soil types and vegetative cover. We have grouped them into geographic regions and described them from west to east.

Four sites were from the Herb Gray Parkway, a major highway construction project in Windsor, Ontario. Each of the four sites underwent restorative management to remove woody and invasive plants, and had species at risk transplanted from construction zones; hence, they were labeled as "Final Restoration Sites" (FRS; Balsdon and Snyder 2015). Two of these four sites were in west Windsor with loam to loamy sand soils (FRS #23: 42.273°N, 83.069°W and FRS #32: 42.272°N, 83.070°W). The other two were in east Windsor with silty clay soils (FRS #27: 42.229°N, 82.994°W and FRS #28: 42.228°N, 82.993°W). We also sampled from two sites in the Ojibway Prairie Provincial Nature Reserve (Ojibway prairie site #1: 42.263°N, 83.071°W and Ojibway prairie site #2: 42.261°N, 83.068°W). The reserve is a large area of tallgrass prairie and oak savannah ecosystems with silty sand to sandy soils in west Windsor near FRS #23 and FRS #32.

Five sites were located in Walpole Island First Nation (WIFN), north of Lake St. Clair, Ontario. Two sites were old agricultural fields that have revegetated after being abandoned in recent decades (WIFN sites #2 and #3) and three were chosen as representatives of high quality tallgrass prairies with minimal to no agricultural history (WIFN sites #1, #4, and #5). The soils range from silty sand to loam to silty clay. Details regarding these sites and their locations may be obtained through permission from the Nin.Da.Waab.Jig Heritage Centre.

Relatively centrally located in our survey region was the Dutton-Dunwich site (42.643°N, 81.536°W) located on a railroad line in Elgin County managed by the West Elgin Nature Club and Elgin County Stewardship Council. Despite gravel covering much of the soil and encroachment of woody vegetation, we found a diversity of quality native vegetation and pockets of undisturbed land.

On the southeastern edge of our survey area were two sites in Norfolk County, both restored tallgrass prairies with very sandy soils characteristic of the area: DeMaere prairie (42.685°N, 80.464°W), managed by the Nature Conservancy of Canada, and Mary & Peter's prairie (42.641°N, 80.572°W) managed by private landowners. Blair Flats (43.384°N, 80.373°W) sits on the north-eastern edge of our survey area, in the

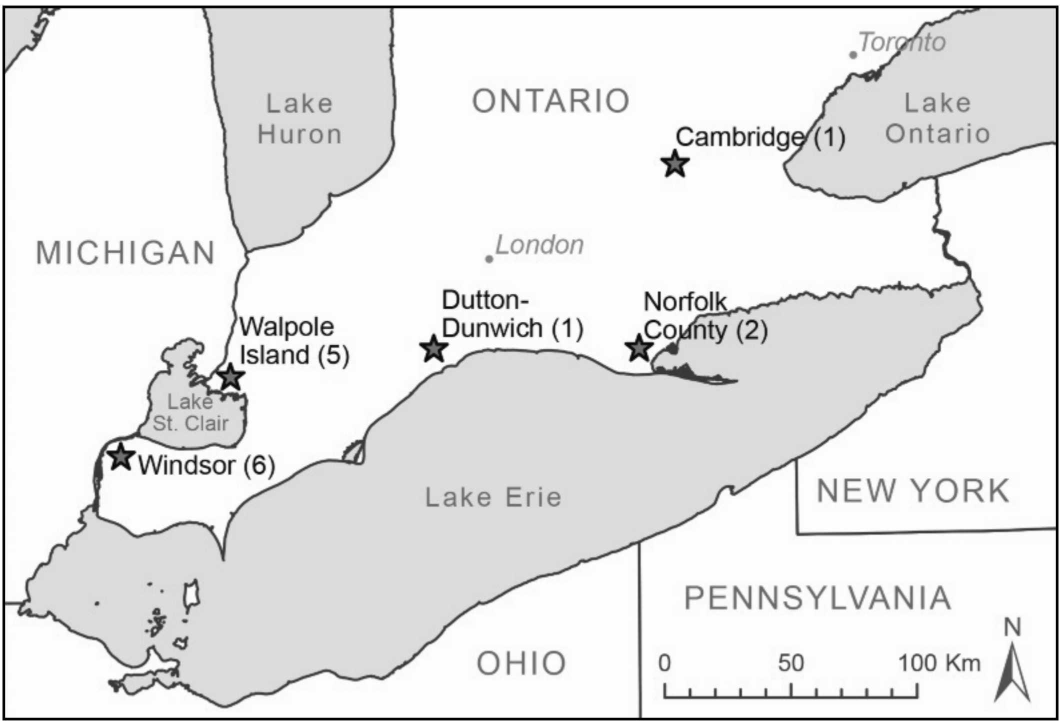

FIGURE 1. Map of 15 tallgrass prairie sites sampled across five regions in southwestern Ontario. Site abbreviations are listed in Table 1.

Township of North Dumfries near Cambridge, Ontario. It was one of our restored tallgrass prairie sites and is managed by the RARE Charitable Research Reserve. It had thick cover of native vegetation and silty clay loam soil.

Methods

Soil collection and sieving

Soil samples were collected for NGS. Six, 1 m square quadrats were sampled across each site to capture maximal variety across the landscape. Single soil cores, 20 cm deep and 2.5 cm diameter, were taken from each quadrat corner and from the quadrat centre. All five cores were mixed in one bag per quadrat. Above-ground vegetation and litter was removed from the top of each core. The soil corer was wiped clean using a cloth and 70% ethanol solution to prevent soil mixing between quadrats. Bags of soil were kept in a cooler with ice packs in the field and transferred to a −20°C freezer in the lab. Soil was collected from 2009 to 2014 at least once in June or July and once in October by investigators in previous studies (Table 1). Summer and fall samples were kept separate through the full sequencing protocol, yielding two to three timepoints of NGS data per site, though seasonal differences are not examined in the present study. Dutton-Dunwich and Mary & Peter's prairies were not sampled for soil.

Soil subsamples of 20 g from each quadrat were mixed with 100 mL of 0.1 M (moles/L) sodium pyrophosphate for 5–10 minutes to break apart soil colloids. The mixture was poured over stacked sieves with pore sizes 1.18 mm, 0.25 mm, and 0.053 mm, and washed with deionized water. The sieve washing technique allows for the capture of plant debris, fungal hyphae, rhizomorphs, and sclerotia, while removing spores, including abundant asexual spores of ascomycetous and zygomycetous molds (Thorn *et al.* 1996; Lynch and Thorn 2006).

Organic materials were extracted from the sieves and placed in Falcon tubes until ~5 mL was obtained for each sample. The organic materials included plant roots (and potential fungi on their surfaces) picked from the upper (coarse) sieve with forceps and dark organic matter separated from sand and silt in the middle and lower (fine) sieves, collected with a spatula and broad tip pipette, respectively. Sieves and collecting tools were thoroughly rinsed with deionized water and cleaned using 70% ethanol between each sample.

Soil DNA extraction, PCR procedures, and submission for NGS

To ensure cell wall lysis prior to DNA extraction, soil organic matter was lyophilized using a Virtis Bench Top 3.5 L Freeze Dryer (SP Scientific, Stone Ridge, New York, USA) and ground to a floury texture using liquid nitrogen in a sterile mortar and pestle for each sample. DNA extraction was carried out using a Soil Microbe DNA MicroPrep™ kit (Zymo Research, Irvine, California, USA) following standard protocols. This involved bead-beating samples using a FastPrep™ FP210 machine (Bio101, Qbiogene, Inc., Carlsbad, California, USA) set at a speed of 4.0 for 30 seconds. The concentration of eluted DNA was measured using a Nanodrop2000 Spectrophotometer (ThermoFisher, Mississauga, Ontario, Canada).

PCR was carried out by combining solutions to a total of 25 µL in microtubes: 3.0 to 5.0 µL molecular grade water (remaining difference), 3 µL each of forward and reverse primers, 12.5 µL ToughMix (Quanta Biosciences, Beverly, Massachusetts, USA), 1.0 to 3.0 µL template DNA (at ~20 ng/µL), and 0.5 µL loading dye. The primers used were LSU200-F and LSU481-R (AACKGCGAGTGAAGMGGGA and TCTTTCCCT-

TABLE 1. Site visits for soil and/or fruiting bodies at 15 tallgrass prairie sites across southwestern Ontario. Footnotes identify principal investigators associated with sampling.

Site	Abbreviation	Soil sampling	Fruiting body surveys
FRS #23	HA	July and October 2014‡	June, July and October 2015§
FRS #32	HB	July and October 2014‡	June, July and October 2015§
Ojibway prairie site #1	OA	July and October 2014‡	June, July and October 2015§
Ojibway prairie site #2	OB	July and October 2014‡	June, July and October 2015§
FRS #27	HC	July and October 2014‡	June, July and October 2015§
FRS #28	HD	July and October 2014‡	June, July and October 2015§
Walpole Site #1	WA	June and October 2009*, October 2014‡	October 2014, July and October 2015§
Walpole Site #2	WB	June and October 2009*, October 2014‡	October 2014, July and October 2015§
Walpole Site #3	WC	June and October 2009*	not sampled
Walpole Site #4	WD	June and October 2009*, October 2014‡	October 2014, July and October 2015§
Walpole Site #5	WE	June and October 2009*, October 2014‡	October 2014, July and October 2015§
Dutton-Dunwich	DD	not sampled	June and October 2015§
Mary & Peter's prairie	MP	not sampled	June and October 2015§
DeMaere prairie	DM	July and October 2014†	October 2014, July and October 2015§
Blair flats	BF	July and October 2014‡	October 2014, August and October 2015§

*Chokroborty-Hoque (2011).
†Catomeris (2015).
‡Allan (2017).
§The present study.

CACGGTACTTG, respectively), which target ~250 nucleotide bases at the D1 large subunit (LSU) region of ribosomal DNA (Asemaninejad *et al.* 2016). Barcodes were included with forward and reverse primers to discriminate among site visits. Soil templates were PCR-amplified using a Biometra T1 Thermocycler (Montreal Biotech, Dorval, Quebec, Canada) programmed as follows: 94°C 2 min, 30 cycles of 94°C 30 sec, 60°C 30 sec, 72°C 18 sec, and holding at 4°C after cycling. PCR products were checked for successful amplification by gel electrophoresis using 1.0% (w/v) agar-agar gels in 1× TAE buffer with 0.5 µg/mL ethidium bromide. PCR products from each of the six quadrats were pooled to one tube per site visit, lyophilized, and rehydrated before being submitted for paired-end Illumina MiSeq high-throughput sequencing using a 2×300 kit. Sequencing was conducted by the London Regional Genomics Centre (Robarts Research Institute, London, Ontario, Canada).

NGS data processing and taxonomic annotation

Raw soil sequence data following Illumina MiSeq were submitted to the European Nucleotide Archive (ENA) by sites, under project accession number PR JEB19932. The raw data were processed using a pipeline developed by Greg Gloor, Biochemistry, University of Western Ontario, London, Ontario, Canada which is available on GitHub (http://www.github.com/ggloor/miseq_bin/tree/Jean). PANDAseq overlapped forward and reverse sequence reads with a minimum overlap of 30 nucleotides (Andre *et al.* 2012). Sequence data from three Illumina MiSeq runs were processed separately until this stage when they were combined, using the script workflow_combined_runs.sh from the aforementioned GitHub. A number of programs are used in this workflow. UCLUST was used to create identical sequence unit clusters (ISUs, 100% similarity), then UCHIME was used to find and remove chimeric sequences (Edgar *et al.* 2011). This removed 22 600 possibly chimeric sequences from the 529 300 unique sequences. UCLUST was then used to further cluster ISUs into operational taxonomic units (OTUs, 97% similarity) with a most common, centroid seed OTU sequence (Edgar 2010). A 99% similarity cutoff has been used to delimit yeast species OTUs from sequences of the D1-D2 LSU(25S) region of rRNA (Peterson and Kurtzman 1991), but we chose 97% because our amplicons were from only the most variable (D1) part of this region. Our sequence clustering produced 14 300 OTUs. The read counts were attached to OTUs, using a 0.1% cutoff in any sample.

To capture Agaricomycete OTUs only, sequences were filtered using the Ribosomal Database Project (sequence classifier, gene database: fungal LSU training set 11; Wang *et al.* 2007) and a neighbour-joining tree to produce an Agaricomycete clade after alignment using MUSCLE (Edgar 2004) in MEGA6 (Tamura *et al.* 2013). Agaricomycete OTUs were annotated to a finer scale by querying through NCBI's GenBank database using the Basic Local Alignment Search Tool for nucleotide sequences (blastn) to find matches. Species-level names were applied only when query cover and percent identity were both greater than 97% and no competing species names were retrieved within this range. Filtering by taxonomic identity for Agaricomycetes left 281 OTUs. These Agaricomycete OTU sequences were submitted to GenBank under accession numbers KY353514–KY353794. OTUs were sorted into coarser taxonomic groups as minor (ca. family) and major (ca. order) clades based on their assigned taxonomic annotation and placement in a neighbour-joining tree.

Fruiting body field surveys and sequencing of specimens

Fruiting body collection allowed us to sample a larger area than soil coring and provided us with voucher specimens as tangible records for morphological and sequence-assisted identifications. Surveys were conducted at each site in a wandering design covering on average 2.2 ha and ranging from ~0.2 to 10 ha. A global positioning system (GPS) receiver was used to ensure soil sampling quadrats were surveyed and to evenly search remaining ground of each site. Fruiting bodies were counted, genetic individual counts estimated from clusters of fruiting bodies, and a voucher specimen collected for each morphospecies (conservatively estimated in the field). Each voucher was documented with a specimen code, photos, GPS coordinates, and habitat notes, and was preserved using a food dehydrator before being stored in a paper herbarium packet. We conducted fruiting body surveys two to three times for each site on dates ranging from October 2014 to 2015 (Table 1). WIFN site #3 was not sampled for fruiting bodies. Dried specimens were deposited at the University of Western Ontario herbarium (UWO) and associated photos and data (including which identification resources were consulted) are available online (http://www.mushroomobserver.org/species_list/show_species_list/652).

Genomic DNA was extracted from mushroom specimens using the GeneJET Plant Genomic DNA Purification Mini Kit (Thermo Fisher Scientific Inc., Mississauga, Ontario, Canada), starting with bead beating in a FastPrep™ FP120 machine (Bio101, Qbiogene Inc., Carlsbad, California, USA) set at 4.0 for 30 seconds. The concentration of eluted DNA was measured using a Nanodrop2000 Spectrophotometer. PCR was carried out by combining solutions to a total of 25 µL in microtubes: 9.0 to 9.5 µL molecular water (remaining difference), 1.25 each of forward and reverse primers, 12.5 FroggaMix (FroggaBio, Toronto, Ontario, Canada), and finally 0.5 to 1.0 µL template DNA (at ~20 ng/µL). We used the primers ITS8F and LR3-mod (AGTCGTA ACAAGGTTTCCGTAGGTG and GGTCCGTGTTT CAAGACGGG, respectively), which cover ~1300 bases, including partial SSU, complete ITS1, 5.8S, and ITS2, and partial LSU (Vilgalys and Hester 1990; Dentinger *et al*. 2010). This overlaps the region amplified by LSU200-F and LSU481-R for the soil samples (which is important for our later analyses comparing sequences between the above- and below-ground techniques). Fruiting body templates were PCR-amplified using a MWG Biotech Primus96 (Huntsville, Alabama, USA) thermocycler programmed as follows: 94°C 1 min, 30 cycles of 94°C 30 sec, 58°C 30 sec, 72°C 1 min 30 sec, an extension time of 72°C for 7 min, and finally holding at 4°C. Successful PCR products were cleaned using the EZ-10 Spin Column PCR Products Purification Kit (Bio Basic Canada Inc., Markham, Ontario, Canada) and submitted for Sanger sequencing (Sanger *et al.* 1977). Each PCR sample was submitted four separate times with different primers to cover the entire amplified length: ITS8F, LS1R-mod (CTTAAG TTCAGCGGGTAGTCC), LS1-mod (GGACTACCC GCTGAACTTAAG), and LR3-mod (Vilgalys and Hester 1990; Hausner *et al.* 1993; Dentinger *et al.* 2010). Sequencing was conducted by the London Regional Genomics Centre (Robarts Research Institute, London, Ontario, Canada).

Fruiting body sequences were assembled and checked for errors using Geneious 8.0.5 (Kearse *et al.* 2012). Assembled sequences were queried through GenBank to find matches that might help to inform identification of specimens. Fruiting bodies were identified using taxonomic keys, involving navigating through indicative macro- and micro-scopic features, chemical tests, and ecological context. Sequences were deposited in GenBank under accession numbers KX215469–KX215471 and KY706152–KY706198 (Supplementary Data Sheets A and E; Hay *et al.* 2018).

Statistical analyses

To compare soil rDNA sequencing and fruiting body surveys, data from WIFN site #3, Dutton-Dunwich prairie, and Mary & Peter's prairie were excluded because these sites were not sampled with both techniques. To ensure soil data were equally weighted across sites, two additional quadrats in DeMaere prairie were excluded to maintain consistency of six quadrats per site, and Walpole Island site samples from October 2009 were excluded to maintain two samples per site from each season (early summer and fall).

Average relative abundances of OTUs were calculated by dividing read values by the sum reads for each site visit (column) and averaging for each OTU (row) across all site visits. Shared genetic species were found by bringing OTU and fruiting body sequences into MEGA 6, aligning with MUSCLE, trimming to OTU length (the limiting factor), then using Microsoft Excel 2013 (version 15.0.4737.1001, Microsoft Corporation, Redmond, Washington, USA) to highlight duplicate sequences. Venn diagrams illustrating degrees of overlap at different taxonomic scales were created using the venneuler package (Wilkinson 2011) in RStudio (RStudio Team 2016). A map of site regions was produced using QGIS 2.18.15 (QGIS Development Team 2017) and open source boundary data (Statistics Canada 2011; United States Census Bureau 2016).

Results

Fruiting body survey totals and common taxa

From the 14 sites surveyed two to three times for fruiting bodies, at least 73 different species were found across 45 genera, of which 57 were identified to species level. Sequences were obtained from 50 collections representing at least 40 different species. The number of species found ranged from zero to 22, and was on average nine species per site (Supplementary Data Sheets A and B; Hay *et al.* 2018).

The most abundant species by counts of estimated genetic individuals (clusters of similar fruiting bodies) were *Entoloma sericeum* (Bull.) Quél. ("silky pinkgill"; note: because there are no standard common names for fungal species, including mushrooms, common names when they exist are included in quotation marks upon first occurrences), which was found covering a large proprotion of the ground at Blair Flats during a fall survey, unidentified white *Clavaria* species, *Cotylidia undulata* (Fr.) P. Karst. ("stalked rosette") found only at DeMaere prairie, and unidentified *Clitopilus* and *Mycena* (*sensu lato*, white) species (Table 2). The species occurring across the most (four) sites were *Entoloma* subgenus *Leptonia* (diaphanous, umbilicate), *Marasmiellus* sp., and *Vascellum curtisii* (Berk.) Kreisel (Table 2). The most species rich minor clades (ca. families) were the Entolomataceae, Hygrophoraceae, Hymenogastraceae (mostly *Hebeloma* spp.), Clavariaceae, and Mycenaceae, with 17 to five species each (Figure 2).

Soil rDNA sampling totals and common taxa

After quality filtering, removing rare OTUs, and removing sequences of non-agarics, 1 194 767 reads of 281 OTUs from 30 samples (site visits) remained, an average of 39 826 reads and 30 OTUs per sample (Supplementary Data Sheet D; Hay *et al.* 2018). Removal

TABLE 2. The 17 most abundant fruiting body species (four or more individuals), as measured by the number of individuals, estimated from groups or clusters of fruiting bodies.

Species	Individuals	Sites
Entoloma sericeum	17	2
Clavaria sp. (white)	12	2
Cotylidia undulata	12	1
Clitopilus sp.	10	3
Mycena sp. (*sensu lato*, white)	10	3
Entoloma subgenus *Leptonia* (diaphanous, umbilicate)	9	4
Marasmiellus sp.	9	4
Vascellum curtisii	9	4
Hygrocybe conica (group)	7	3
Mutinus cf. *elegans*	6	3
Tubaria furfuracea	6	3
Astraeus hygrometricus	6	1
Entoloma incanum	4	2
Hebeloma cf. *sporadicum*	4	2
Psathyrella ammophila	4	2
Hebeloma cf. *dunense*	4	1
Omphalina pyxidata	4	1

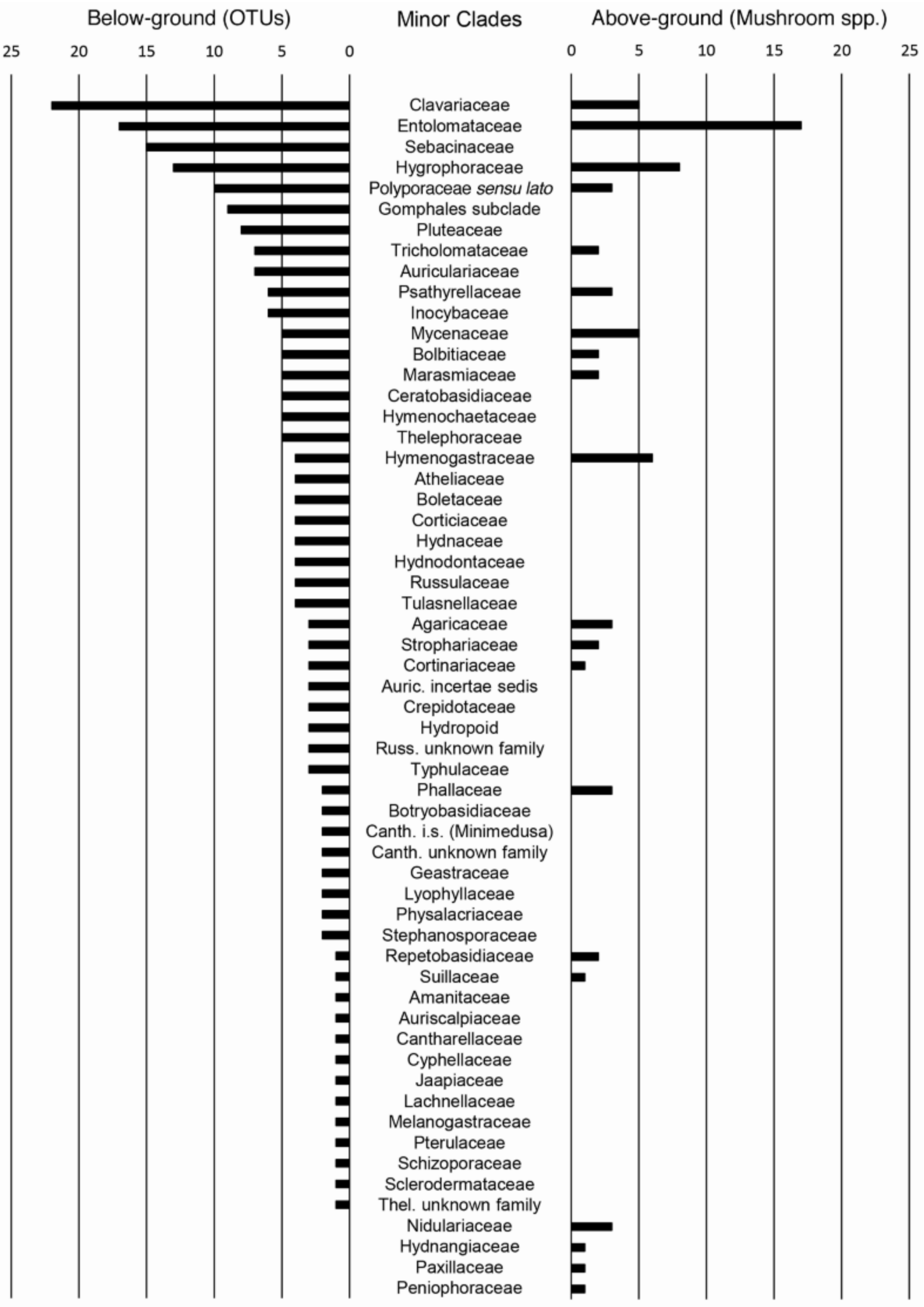

FIGURE 2. Richness of operational taxonomic units (OTUs) and species within minor clades (ca. family level), comparing results of soil rDNA NGS ("below-ground") with fruiting body ("above-ground") surveys. Richness here is a function of the composition of all sites, taxonomic diversity in each clade, and detection ability of each technique.

of extraneous sampling data reduced the number of Agaricomycete OTUs from 281 to 238 OTUs which were used in the analyses following. Six OTUs remained unknown, because query results represented diverse taxa and OTU phylogram branches showed low bootstrap values. These OTUs were included in species-level analyses but were not counted as a unique minor or major clade. Excluding the clades for the unknowns (one minor and one major), diversity spanned 55 minor clades and 19 major clades (Supplementary Data Sheet C; Hay *et al.* 2018).

The OTUs from soil rDNA sampling with highest relative read abundances were *Minimedusa polyspora* (Hotson) Weresub & P.M. LeClair and Ceratobasidiaceae sp. 1 that do not produce fruiting bodies visible to the naked eye, and *Hygrocybe conica* ("witch's hat") group sp. 3 and *Mutinus elegans* (Mont.) Fisch. ("elegant stinkhorn") that do (Table 3). The OTUs occurring across the most sites were *M. polyspora*, Fomitopsidaceae sp., *Entoloma* sp. 3, Gomphales sp. 3, and Lyophyllaceae sp. 2 (Table 3; Supplementary Data Sheet D; Hay *et al.* 2018). The most OTU rich minor clades (ca. families) were the Clavariaceae, Entolomataceae, Sebacinaceae, Hygrophoraceae, and Polyporaceae *sensu lato*, with 22 to 10 OTUs each (Figure 2).

Collective results and comparison between above- and below-ground techniques

Across both sampling techniques, the most species and OTU rich clades found were the Clavariaceae, Hygrophoraceae, and Entolomataceae (Figure 2). Many minor clades were only found using the below-ground technique (soil rDNA NGS), not by above-ground sampling (fruiting body surveys), whereas relatively few were unique to above-ground sampling. Most minor clades unique to the below-ground sampling technique seldom or never produce conspicuous fruiting bodies (e.g., Sebacinaceae) or may represent uncommon species that were overlooked during sampling. Minor clades unique to the above-ground sampling technique are either mycorrhizal incidentals (Hydnangiaceae and Paxillaceae) or saprobes apparently limited to colonization of litter above the soil surface (Nidulariaceae and Peniophoraceae). Other taxa not exclusive to one technique were still found disproportionately by one or the other. For example, in the Clavariaceae 22 OTUs were found below- and only five above-ground. In contrast 17 OTUs or species of Entolomataceae were found in each of above- and below-ground techniques.

TABLE 3. The 15 most abundant soil rDNA operational taxonomic units (OTUs), as measured by average relative abundance (average relative abundance of OTU in each sample i.e., site visit, averaged across all samples).

OTU	Average relative abundance	Sites
Minimedusa polyspora	0.0978	12
Ceratobasidiaceae sp. 1	0.0393	4
Hygrocybe conica group sp. 3	0.0387	4
Mutinus elegans	0.0385	4
Gomphales sp. 3	0.0333	10
Hygrocybe conica group sp. 2	0.0318	7
Russulales sp. 1	0.0313	5
Sebacinaceae sp. 2	0.0248	5
Tricholomataceae sp. 3	0.0227	6
Mycena epipterygia sp. 1	0.0223	6
Entoloma sp. 3	0.0201	10
Fomitopsidaceae sp.	0.0185	10
Hymenogastraceae sp.	0.0181	8
Hypochnicium sp.	0.0179	4
Hypholoma sp.	0.0163	3

Shared species and degrees of overlap at different taxonomic scales

There were eight species detected by both the above and below-ground techniques that had identical sequences ("shared species"; Table 4). Some of these shared species were found by both methods at the same site (e.g., *C. undulata*), by only one technique or the other across different sites (e.g., *Clavaria* cf. *fragilis* Holmsk. ["white spindles"]), or a combination of these two scenarios (e.g., *V. curtisii*). Several species seem to correspond between techniques (Tables 2 and 3), but are unconfirmed: *Mycena epipterygia* (Scop.) Gray sp. 1 OTU with the abundant *Mycena* sp. (*sensu lato*, white) fruiting bodies for which sequencing failed, the Hymenogastraceae sp. OTU with *Hebeloma* spp. fruiting bodies, and species with identical names between both tables: the *H. conica* group spp., *M. elegans*, and species of *Entoloma*.

The degree of overlap between fruiting body and soil rDNA sampling depends on the taxonomic scale in consideration, as seen in Venn diagrams (Figure 3). At the finest scale of genetic species only eight species were

TABLE 4. Detection of shared species (identical sequences) across sites via fruiting body surveys (above-ground – A), rDNA soil sampling (below-ground – B), or both (AB). Site abbreviations as in Table 1.

Species	HA	HB	OA	OB	HC	HD	WA	WB	WD	WE	DM	BF
Arrhenia cf. *acerosa*	A									A	B	
Clavaria cf. *acuta*			B	B	B			A	B			
Clavaria cf. *fragilis*		B							A			
Cotylidia undulata											AB	
Entoloma incanum		B	B	B					AB	A		
Entoloma cf. *tubaeforme*	AB	A								A		
Hygrocybe conica group	B	B	B	B		B	B	A		AB		
Vascellum curtisii	B			B			A		AB	AB		

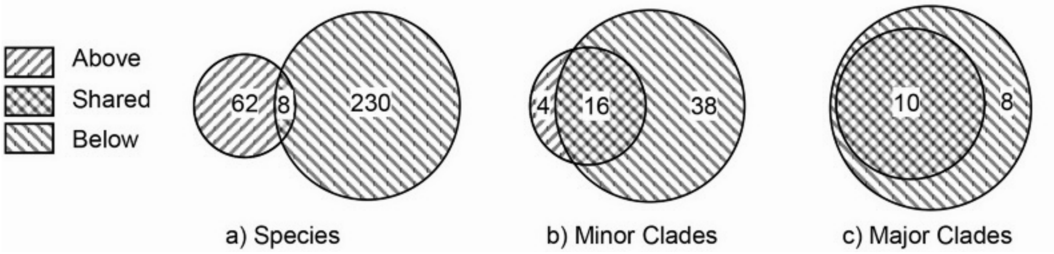

FIGURE 3. Area-proportional Venn diagrams comparing below-ground (soil rDNA high throughput sequencing) and above-ground (fruiting body survey) richness at three taxonomic scales: a. genetic species (identical sequences of operational taxonomic units with fruiting body sequences), b. minor clades (ca. family), and c. major clades (ca. order).

shared, representing 11% of above-ground and 3% below-ground diversity (Figure 3a). At the minor clade level (ca. family) 16 minor clades were shared, representing 76% of above-ground minor clades and 30% of those below-ground (Figure 3b). At the major clade level (ca. order) all 10 major clades found above-ground were also found below-ground, representing 56% of below-ground major clades (Figure 3c). This shows that even at a coarse taxonomic scale (major clades), fruiting body surveys failed to detect the full range of diversity in the soil-inhabiting Agaricomycetes.

Discussion

A grassland mycota

Combining our above-ground survey data with selected grassland studies from around the world (Wilkins and Patrick 1939; Warcup 1951, 1959; Warcup and Talbot 1962, 1963, 1965; Wicklow and Angel 1974; Gumińska 1976; Arnolds 1981; Mycological Society of Toronto 2005a,b; Hay 2013; Detheridge *et al.* 2018) we were able to compile a grassland mycota and identify where tallgrass prairies fit in this context. Almost 500 species of Agaricomycetes were reported among the eight groups of studies examined (including ours). One fifth of species were reported in two or more groups of studies. The most common species were *Agaricus campestris* L. ("meadow mushroom"), *Hygrocybe conica* (Schaeff.) P. Kumm. ("witch's hat"), *H. miniata* (Fr.) P. Kumm. ("vermillion waxcap"), *Cuphophyllus virgineus* (Wulfen) Kovalenko ("snowy waxcap"), *E. sericeum*, and *Lycoperdon perlatum* Pers. ("gem-studded puffball"). The most commonly reported genera were *Agaricus*, *Bovista*, *Coprinopsis*, *Hygrocybe*, *Lycoperdon*, and *Parasola*, and the genus with the most reported species was, by far, *Entoloma* (64 species). All these species and genera were found in our study except for *L. perlatum.* Although we initally identified several puffball specimens as *L. perlatum*, we corrected our identification to *V. curtisii* after microscopic spore inspection. *Entoloma* was also our most speciose genus at 15 species.

We found at least six gasteroid species and they were not limited to sites with any specific conditions or to any one region. Common genera from our study and others in our review include small puffballs from *Bovista*, *Lycoperdon*, and *Vascellum*; large puffballs represented by *Calvatia* spp. and *Mycenastrum corium* (Guers.) Desv. ("leathery puffball"; Mycological Society of Toronto 2005b); and the stinkhorns *Phallus* or *Mutinus*. Gasteroid and secotioid species are typical in hot dry environments (e.g., Gabel and Gabel 2011; Tomaszewska *et al.* 2015). The secotioid species *Chlorophyllum agaricoides* (Czern.) Vellinga ("puffball agaric"), *Battarrea phalloides* (Dicks.) Pers. ("scaley-stalked puffball"), and others were found in arid Saskatchewan mixedgrass prairie (Hay 2013), but no secotioid taxa were encountered in our surveys. We suspect that Ontario tallgrass prairies, but perhaps not all tallgrass prairies, are too moist for them.

Most grassland surveys, including our own, encountered species associated with living or dead trees and shrubs. Wood decomposers may appear when deadfall is available or on litter with enough lignin content (e.g., *Galerina* spp. from Arnolds [1981]; *Trametes* and *Peniophora* spp. from the present study and by Warcup and Talbot [1963]; *Tubaria* spp. from multiple studies). However, wood decomposing fungi have been found in subsurface soil (Goos 1960; Lynch and Thorn 2006), so our Polyporaceae *sensu lato* OTUs may represent a natural component of tallgrass prairie soils. The rarely reported (and perhaps of conservation importance) *Polyporus cryptopus* Ellis & Barthol. ("prairie polypore") is an exception to its genus, attached to grass roots rather than wood, and is unique to North American grasslands. There are several collections from the central USA states (e.g., Cripps 2011) and fewer from the Canadian prairies (Saskatchewan: Hay 2013; Ontario: previously collected from WIFN Site #4 – RGT 090616/sn, UWO). It has been suggested to be a synonym of the Eurasian species now known as *Picipes rhizophilus* (Pat.) J.L. Zhou & B.K. Cui (Zhou *et al.* 2016) but studies of type material of both are required for confirmation. Ectomycorrhizal species (associated with the roots of living trees or shrubs) are also reported in grassland surveys, usually only when trees are nearby. This includes species of *Hebeloma*, *Cortinarius*, *Russula*, and *Suillus* from the present study, and *Hebeloma* spp. reported in other studies (Wilkins and Patrick 1939; Arnolds 1982). However, some ectomycorrhizal fungi partner with small perennial plants such as *Lechea mucronata* Raf. [Cistaceae], recorded as *Lechea villosa* Ell. from a grassland site in the same county as our sandy sites (DeMaere prairie and Mary & Peter's prairie; Malloch and Thorn 1985). The Sebacinaceae are best known for being included in mycorrhizal partnerships with a wide diversity of plants (Weiss *et al.* 2004) but may also be endophytes (Weiss *et al.* 2011) or of unresolved ecologies (Tedersoo *et al.* 2010). Many Sebacinaceae OTUs were detected in the below-ground portion of our study and a similar study from agricultural soils in Michigan, USA (Wong 2012). Above-ground fruiting bodies are rarely reported, probably due to their inconspicuous corticioid nature, although species of *Sebacina* were cultured in studies by Warcup and Talbot (1962, 1965). Many endophytic and parasitic taxa produce inconspicuous fruiting bodies and so are more easily detected by culturing or sequencing, as demonstrated with the Sebacinaceae in our study and review.

Decomposers of above-ground plant litter are commonly reported from fruiting body surveys when methods include litter searches. The most commonly reported genera are *Parasola* and *Mycena* spp. (though some of the species may grow from the soil, not litter), and appearing in fewer studies *Cyathus*, *Nidula*, and *Marasmiellus* spp. Our study found all of these taxa, showing the importance of including careful litter examination when conducting complete surveys. Coprophilous species are often conspicuous from sites actively managed by large grazing mammals (e.g., sheep in Wilkins and Patrick [1939]; cattle in Wicklow and Angel [1974]; American Bison [*Bison bison*] in Hay [2013]), but most grasslands receive some dung from wildlife (e.g., Pronghorn Antelope [*Antilocapra americana*], rabbits, and voles). Commonly reported taxa from our review were *Coprinopsis* spp. (especially *Coprinopsis nivea* (Pers.) Redhead, Vilgalys & Moncalvo ["snowy inkcap mushroom"]), *Panaeolus* spp. (esp. *Panaeolus papilionaceus* (Bull.) Quél. ["petticoat mottlegill"]), *Protostropharia semiglobata* (Batsch) Redhead, Moncalvo & Vilgalys ("dung roundhead"), and *Deconica coprophila* (Bull.) P. Karst. ("dung-loving Psilocybe"). Our study included no sites with large grazing mammals and no fruiting bodies were observed on any small dung examined, so all the coprophilous fungi listed here were noticeably absent from our study.

Terrestrial saprobic species in grasslands cover a wide array of taxonomic groups. *Agaricus campestris* was present across more studies than any other species, with other agaricoid members of the Agaricaceae reported moderately frequently (genera *Chlorophllum, Macrolepiota,* and *Lepiota*) and other *Agaricus* spp. less fequently. From other families, *Marasmius oreades* (Bolton) Fr. ("fairy ring mushroom") and *Clitocybe* spp. were commonly reported, *Melanoleuca* spp. moderately, and *Volvariella* sp. and *Volvopluteus gloiocephalus* (DC.) Vizzini, Contu & Justo ("rose-gilled grisette") less frequently. Aside from *A. campestris* and *Clitocybe dealbata* (Sowerby) Gillet ("ivory funnel") found at one of our sites, we did not find any of these taxa in our tallgrass prairie surveys. Many other terrestrial saprobic taxa are considered nutrient-loving due to their abundance in sites supplemented with dung or artificial fertilizers, specifically species of the Psathyrellaceae (genera: *Coprinellus, Coprinopsis, Panaeolus, Parasola, Psathyrella*), Strophariaceae (genera: *Agrocybe, Deconica, Stropharia*), and genera from other families: *Conocybe*, *Marasmius*, and *Psilocybe* (Arnolds 1988, 1989b; Mycological Society of Toronto 2005b). We encountered few of these nutrient-loving species in our tallgrass prairie surveys (*Coprinopsis lagopus* (Fr.) Redhead, Vilgalys & Moncalvo ["harefoot inkcap"], *Parasola* cf. *conopilus* (Fr.) Örstadius & E. Larss. ["conical brittlestem"], and *Stropharia coronilla* (Bull.) ["garland Stropharia"]), suggesting Ontario tallgrass prairies are naturally relatively nutrient-poor.

We found more Clavariaceae, *Hygrocybe*, and *Entoloma* (CHE) species in Ontario tallgrass prairies than the other terrestrial surveys of North American grasslands (Mycological Society of Toronto 2005a,b; Hay 2013). In contrast to the terrestrial saprobic and nutrient-loving taxa, these fungi prefer nutrient-poor grasslands, such as the unimproved waxcap grasslands of Europe (Arnolds 1989a; Rotheroe *et al.* 1996; Detheridge *et al.* 2018). Most non-lignicolous Clavariaceae species are believed to be biotrophic (Birkebak *et al.* 2013) and grassland *Hygrocybe* species are biotrophic with grasses (Griffith *et al.* 2014). In addition, these two taxa have correlated diversity across grassland sites, but not with *Entoloma* (Newton *et al.* 2003). Most species of *Entoloma* are believed to be saprobic (Noordeloos 2004) with few known parasitic (Agerer and Waller 1993; Czederpiltz *et al.* 2001) or mycorrhizal (Kobayashi and Yamada 2003; Rinaldi *et al.* 2008) exceptions. We suggest grassland *Entoloma* species may also be biotrophic in some way, because even *Entoloma* species growing on dead wood are not readily cultured (R.G.T. pers. obs.). Detheridge *et al.* (2018) consider the CHE taxa biotrophic and group them as one of five fungal ecological functional groups. The abundance of these taxa suggests similar ecological dynamics are at play between tallgrass prairies and European waxcap grasslands, in contrast to drier, nutrient-rich, or agriculturally improved grasslands. Besides the CHE taxa, we found *Arrhenia* cf. *acerosa* (Fr.) Kühner ("moss oysterling"), which is associated with ground-dwelling mosses (usually in open grassy areas of woods but apparently also in grasslands, e.g., forest meadows; Gumińska 1976). Investigations are under way to determine if lowland specimens of *A.* cf. *acerosa* are distinct from arctoalpine ones originally described by Fries (1821; Voitk 2017).

Waxcap grassland surveys focus on surveying from five taxonomic groups to assess grassland quality: Clavariaceae (C) ("coral fungi"), *Hygrocybe* (H) ("waxcaps"), *Entoloma* (E) ("pinkgills"), Geoglossaceae (G ["earth tongues"], Ascomycota; not included in our survey), and *Dermoloma* (D; not detected in our survey; Rotheroe *et al.* 1996). Ratios between taxa have been examined to compare community composition among grasslands (Newton *et al.* 2003) though the initial use of this system was to highlight sites with high conservation value by uniformly sampling across sites on a national or international scale (Rotheroe *et al.* 1996). In a comparison of recent surveys of Welsh grasslands, Griffith *et al.* (2013) found the number of species within each taxonomic group to be 19 C, 35 H, and 46 E. Across all our sites in total we found 4 C, 6 H, and 14 E. Our study is less extensive by sampling area and effort, but a roughly similar ratio was found and many species from our study were also detected in theirs: two Clavariaceae (*Clavaria* cf. *acuta* Sowerby ["pointed fairy club"], *C.* cf. *fragilis*), all six of our *Hygrocybe* and *Cuphophyllus* species, and over a third of our *Entoloma* species (*Entoloma* cf. *griseocyaneum* (Fr.) P. Kumm. ["felted pinkgill"], *Entoloma incanum* (Fr.) Hesler ["mouse-scented mushroom"], *Entoloma sericellum* (Fr.) P. Kumm. ["cream pinkgill"], *E. sericeum*, and *Entoloma undatum* (Fr.) M.M. Moser ["wavy Entoloma"]). Other waxcap grassland surveys produced differing CHE ratios, especially having more *Hygrocybe* and fewer *Entoloma* species (Rotheroe *et al.* 1996; Rotheroe 2001).

Mycological red lists have been produced for many European countries. Comparing our survey with a preliminary red list from sand dunes and grasslands in the Netherlands (Arnolds 1989a) yields insights into which taxa occur in grasslands across continents and may belong on red lists for North America. In common between Ontario and the Netherlands were *Cuphophyllus pratensis* (Fr.) Bon ("meadow waxcap"), *C. virgineus*, *Cyathus stercoreus* (Schwein.) De Toni ("dung-loving bird's nest"), *E. incanum*, *Entoloma* cf. *excentricum* Bres. ("excentric pinkgill"), *Entoloma mougeotii* Fr. ex P. Kumm., *H. conica* (group), *Hygrocybe glutinipes* Bon. ("glutinous waxcap"), *Hygrocybe flavescens* (Kauffman) Singer ("golden waxcap"), *Phallus hadriani* Vent. ("dune stinkhorn"), and *Ramariopsis subtilis* (Pers.) R.H. Petersen ("slender coral"). Greater and more focussed survey efforts for these species should be conducted in North America to determine if their populations are declining as they are in the Netherlands, perhaps due to similar pressures (particularly grassland habitat loss). Our fruiting body surveys detected no species of *Conocybe*, *Dermoloma, Lepiota*, *Lepista*, *Psathyrella*, *Psilocybe*, *Tulostoma*, or *Volvariella*, all found in Netherlands grasslands, although some related sequences were detected below-ground (OTUs of the Agaricaceae, Bolbitiaceae, Pluteaceae, Psathyrellaceae, and unknown minor clades; Supplementary Data Sheet C; Hay *et al.* 2018). Differences may be reconciled with the Netherlands studies having sampled over a longer period and across more sites, perhaps representing a greater variety of habitats than our tallgrass prairie sites. More research is needed in North America to determine which taxa occur in tallgrass versus other prairies, such as *Tulostoma* and *Volvariella* that have only been found in mixedgrass prairie (Hay 2013).

Several species in our survey are new or interesting records. *Entoloma tubaeforme* T.H. Li, E. Battistin, W.Q. Deng & M. Gelardi has only been recorded from under Australian Pine (*Casuarina equisetifolia* L.) in China. Although we did not conduct microscopy prior to destroying our specimen for sequencing, our specimen and theirs appear macromorphologically identical and our sequence and theirs are distinct from other *Entoloma* spp. when placed on a curated phylogram (Battistin *et al*. 2014; our phylogram not shown). Few records exist in MyCoPortal for *Hebeloma dunense* L. Corb. & R. Heim ("dune poisonpie"); it has been recorded from sand dunes in Oregon, DBG-F-016550 and deciduous forest in Quebec, HRL1069. Our *Hebeloma vaccinum* Romagnesi ("willow poisonpie") specimen is the first record of this species from Canada. We found abundant *C. undulata* in only one of our sites, on open sand amongst moss. It is rarely mentioned in the literature (see *Stereum tenerrimum* Berk. & Rav. and *Stereum exiguum* (Peck) Burt as cited in Reid 1965; Kout and Zíbarová 2013), though there are several records on MyCoPortal from across North America. Ours is only the second sequence available on GenBank and one of a few specimens from Canada.

Psathyrella ammophila (Durieu & Lév.) P.D. Orton ("dune brittlestem") was another species limited to our sandy soil sites. This species is known from sand dunes and especially in relationship with beachgrass roots (*Ammophila* spp.; Watling and Rotheroe 1989) or, in this case, apparently species of other prairie grasses (*Ammophila* spp. were not present in our sites). Both *C. undulata* and *P. ammophila* were absent from the Netherlands grassland and dune preliminary red lists of Arnolds (1989a), but may be of conservation interest in North America. *Polyporus cryptopus* was not found in our surveys, but if it is rare and declining it would be an ideal candidate species for conservation of grassland fungi in North America given its ease of identification.

Although it is difficult to compare NGS studies with different objectives, methods (including primers used), taxonomic scope and scale, some commonalities and differences are apparent. Minor clades Clavariaceae and Hygrophoraceae, which showed high OTU richness in Ontario prairies, were represented among the most abundant genera of Oklahoma tallgrass prairie samples (*Camarophyllopsis* and *Cuphophyllus,* as *Camarophyllus*; Penton *et al.* 2013). No conclusions as to the richness or abundance of these two families can be drawn from a study of Kansas tallgrass prairie (Jumpponen *et al.* 2010) except that genus *Hygrocybe* was detected and no genera of the Clavariaceae are listed. In Kansas, the Atheliales was the third most abundant order, holding 21% of Basidiomycota sequences, whereas in our study the Atheliaceae (=Atheliales; Jülich 1981) had low total relative abundance (less than 1%; Supplementary Data Sheet D; Hay *et al.* 2018). Unique to our study were the Entolomataceae and Sebacinaceae (second and third most OTU rich minor clades) that were not detected in Kansas and Oklahoma prairies (Jumpponen *et al.* 2010; Penton *et al.* 2013). Similarly, a recent NGS study in grasslands of Wales, United Kingdom found many Clavariaceae and Hygrophoraceae but many fewer Entolomataceae and Sebacinaceae than in our study (Detheridge *et al.* 2018; Gareth Griffith pers. comm. 7 August 2018). It is unclear whether methodological factors (e.g., primers used) or site factors are behind these coarse-scale disparities. Our use of primers to the D1 region of the large ribosomal subunit, instead of part or all of the internal transcribed spacer region, may have reduced the bias towards Ascomycota, with their often shorter (and thus more readily PCR-amplified) ITS region (Asemaninejad *et al.* 2016). A comparison of raw sequence files from each study processed side-by-side would yield more detailed and authoritative comparisons. However, each geographic region should be sampled using the same methods and primers, ideally with multiple primers that might compensate for PCR bias, lack of resolution, or gaps in the reference database of any one primer set (Seifert *et al.* 2007; Asemaninejad *et al.* 2016; De Filippis *et al.* 2017). More NGS studies in North American grasslands could determine fungal composition and how it is shaped by soil condition, vegetative community, grassland management regime, and climate (c.f., Detheridge *et al.* 2018).

Comparing above- and below-ground survey techniques

Several studies of fungal communities have compared fruiting body surveys and below-ground molecular techniques (Table 5). Different sampling environments and methods probably explain discrepencies. Fruiting body sampling period varied from one (our study) to four years (Smith *et al.* 2007) with more or fewer site visits, and below-ground techniques were either cloning (Smith *et al.* 2007; Porter *et al.* 2008) or NGS (Ovaskainen *et al.* 2013; our study), with varying numbers of soil or wood samples collected. Earlier studies of ectomycorrhizal fungi comparing fruiting body surveys with root tip mycorrhizae often compared above- and below-ground results and found little correspondence (reviewed by Horton and Bruns 2001). Smith *et al.* (2007) attribute apparent lack of overlap with sampling difficulties and methodology. They showed that greater correspondence can be found by conducting fruiting body sampling visits over multiple years, making equal effort to find all fruiting body forms (epigeous, hypogeous, and resupinate species). However, even with Smith *et al.*'s (2007) greater sampling effort, more than half of their species were not found by both techniques. Taxa with inconspicuous corticioid fruiting bodies such as Sebacinaceae and Atheliaceae that we failed to detect above-ground were also missed by the thorough fruiting body surveys of Porter *et al.* (2008). Smith *et al.* (2007) were able to detect fruiting bodies of four species of the order Sebacinales, but this is only a fraction of the 15 Sebacinaceae OTUs found in our study.

In other cases, minor clades were not completely exclusive to one method or the other but were disproportionately represented. For example, richness of Clavariaceae was better revealed through below-ground sampling in our study. As suggested by Smith *et al.* (2007), it could be that inconspicuous corticioid or hypogeous species were overlooked due to infrequent fruiting, or species were cryptic (e.g., Clavariaceae: *C. acuta* and *C. fragilis* are both white fairy clubs that were initially recorded as one morphospecies but which we later identified through sequencing). It has been proposed that imbalanced representation of abundance across above- and below-ground techniques may represent different life history strategies: allocate energy into spore release via above-ground fruiting bodies or compete vegetatively below-ground (Gardes and Bruns 1996; Horton and Bruns 2001). Ovaskainen *et al.* (2013) found that among wood-decomposing fungi, there is no tradeoff; species with many fruiting bodies also have more mycelium. These authors outlined several different types of species-specific life-history strategies. Our limited above-ground sampling was not suited to identify life-history tradeoffs.

At coarse taxonomic scales, Porter *et al.* (2008) found that species-rich orders were detected using either above- or below-ground techniques but some, less species-rich orders, were missed by either technique on its own. In contrast, we found that at the major clade level (ca. order) NGS was able to detect all above-ground taxa whereas fruiting body sampling still missed many below-ground taxa. However, most species-rich taxa were still found by either technique at the minor clade (ca. family) level. In general, we found that in a grassland ecosystem, NGS produced more thorough assessments of fungal composition more efficiently than fruiting body surveys. The opposite conclusion is drawn in studies of fungi in treed ecosystems, at least with the molecular methods used for below-ground surveys of the time (Porter *et al.* 2008; Tóth and Barta 2010). Fungi in more arid ecosystems fruit infrequently, so below-ground molecular techniques are probably more practical (noted in Gardes and Bruns 1996). In our study and all others comparing above- and below-ground techniques, using multiple techniques helped discover a more complete view of the ecosystem's fungal composition, but consideration of the ecosystem, taxa of interest, and study objectives can determine which technique(s) would be most appropriate.

Limitations in methods

Sequencing of DNA from soil samples has been criticized for including inactive fungal material when only

TABLE 5. Statistical review of our and three other studies that collected data above-ground (fruiting body surveys) and below-ground (molecular surveys from soil or wood samples) to compare numbers of shared species (species detected by both above-ground and below-ground methods).

Study	Our study	Ovaskainen *et al.* (2013)	Porter *et al.* (2008)	Smith *et al.* (2007)
Environment	tallgrass prairies	Norway spruce (*Picea abies* (L.) H. Karst.) logs	Hemlock (*Tsuga canadensis* (L.) Carrière) dominated forest	xeric oak (*Quercus*) woodland
Shared above-ground (shared / total above)	11%	30%	11%	42%
Shared below-ground (shared / total below)	3%	23%	25%	45%
Shared (species count)	8	30	13	39
Above (species count)	70	99	119	92
Below(species count)	238	133	53	86

active fungal material should be included (Klein 2015). Our soil washing procedure helped to address this by washing away spores (inactive fungal material) and retaining only plant debris, fungal hyphae, rhizomorphs, and sclerotia (Thorn *et al.* 1996; Lynch and Thorn 2006). One drawback was that our two most abundant below-ground species are probably overrepresented: *M. polyspora* produces bulbils 0.1–0.2 mm in diameter (Weresub and LeClair 1971) and members of the Ceratobasidaceae (potentially our Ceratobasidiaceae sp. 1) produce sclerotia 0.25–0.50 mm in diameter (Kumar *et al.* 2002). These would have been selectively retained on our soil-washing sieves.

Although reference sequence datasets are constantly growing, data gaps still exist. The gaps may represent known fungi yet to be sequenced or fungi that are undescribed, perhaps due to lack of conspicuous fruiting body production or an inability to culture. Queries of OTUs from some of our minor clades unique to the below-ground sampling technique (e.g., Gomphales subclade, Pluteaceae, Cantharellales unknown family, and Russulales unknown family) did not return any confident GenBank matches. Our Pluteaceae minor clade may correspond with a "sister clade to *Volvariella*" (Lynch and Thorn 2006; Bahnmann 2009) and "Pluteoid clade" (Wong 2012) that continues to lack reference sequences from closely related taxa.

Given the short read lengths obtained with Illumina platforms of NGS, annotating OTUs to species-level is difficult and uncertain, and probably is the main reason that comparisons with fruiting body surveys are not usually attempted (Ovaskainen *et al.* 2013). We expect there are a greater number of shared species than the eight we found with identical sequences between our techniques. Our ability to detect more shared species was limited due to some unsuccessful fruiting body sequencing and the requirement of short sequences for NGS (making intra-specific gene variation difficult to account for). The expected true number of shared species can be extrapolated to 15, assuming all fruiting body species we encountered were successfully sequenced. Degrees of gene variation are more difficult to account for and vary depending on the taxon and gene region in question. Some taxa lacked sufficient variation in the D1 LSU region to distinguish species (e.g., our Polyporaceae *sensu lato* OTUs) whereas other taxa seemed to be variable enough to produce a split between morphological and genetic species (e.g., *M. elegans* which was found by both techniques but not with identical sequences).

Confident identification and sequencing of fruiting bodies was sometimes limited by availability of material from the field for sequencing and microscopy work. For example, small whitish *Mycena* (*sensu lato*) were abundant and recurring in our study, but often occurred singly, providing limited material for microscopy and molecular work. A few distinct *Mycena sensu stricto* species and *Atheniella* cf. *flavoalba* (Fr.) Redhead, Moncalvo, Vilgalys, Desjardin, B.A. Perry ("ivory bonnet") were distinguished with microscopy and sequencing. Our unidentified *Mycena* sp. (*sensu lato*, white) could belong to *Mycena* (*sensu stricto*), *Hemimycena*, *Delicatula*, or *Atheniella*, which may appear superficially similar but actually cross three families. Two below-ground OTUs (*M. epipterygia* sp. 1 and *Mycena* sp. 2) were particularly abundant and may correspond with above-ground, unsequenced *Mycena* species. *Mycena epipterygia* and *A. flavoalba* were found in European grassland surveys (Wilkins and Patrick 1939; Gumińska 1976; Arnolds 1981). Such difficult taxa benefit from studies that include more frequent surveying than ours to increase chances of finding abundant fruitings, as well as ample time dedicated to careful and extended microscopy and consulting the taxonomic literature.

Conclusions

Our surveys of above- and below-ground fungal taxa showed that most Ontario tallgrass prairie Agaricomycete species belonged to the Clavariaceae, Entolomataceae, Sebacinaceae, Hygrophoraceae, and Polyporaceae *sensu lato*. Inconspicuous taxa such as the Sebacinaceae and Polyporaceae were only revealed with NGS technology. Similarly to previous studies, we found little correspondence between our above- and below-ground techniques at finer taxonomic scales and greater overlap at coarser scales, but NGS uncovered many taxa that fruiting body surveys missed. Thus, we stress the importance of methodological details in comparing techniques. NGS is a practical technique to determine grassland fungal community composition, but fruiting body surveys remain an important supplement and should not be neglected. In our relatively short fruiting body survey, and using recent advancements in technology (NGS, newly developed primers, and a more comprehensive GenBank reference sequence database), we took the first steps into defining Agaricomycete communities in Ontario tallgrass prairies. More research is needed to discover and better understand the fungal communities of grasslands across North America.

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Supplementary Material:

Spreadsheets containing metadata and data are available from *The Canadian Field-Naturalist* and from the Dryad Digital Repository: https://doi.org/10.5061/dryad.sm0kk00.

Sheet A. Above-ground (mushroom) species, authority, and associated minor (ca. family) and major (ca. order) clade placement.

Sheet B. Above-ground (mushroom) data as individuals across site visits.

Sheet C. Below-ground (soil sample rDNA) OTU (Operational Taxonomic Unit) taxonomic annotations, and associated minor (ca. family) and major (ca. order) clade placement.

Sheet D. Below-ground (soil sample rDNA) data as OTU (Operational Taxonomic Unit) reads per site visit.

Sheet E. Raw data for all specimens (above-ground, i.e., mushrooms) collected or otherwise recorded as observations in this study.

Book Reviews

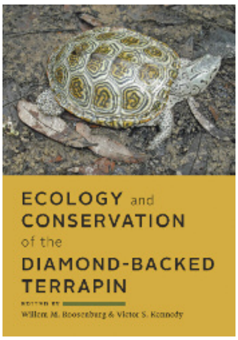
Book Review Editor's Note: *The Canadian Field-Naturalist* is a peer-reviewed scientific journal publishing papers on ecology, behaviour, taxonomy, conservation, and other topics relevant to Canadian natural history. In line with this mandate, we review books with a Canadian connection, including those on any species (native or non-native) that inhabits Canada, as well as books covering topics of global relevance, including climate change, biodiversity, species extinction, habitat loss, evolution, and field research experiences.

Currency Codes: CAD Canadian Dollars, USD US Dollars, EUR Euros, AUD Australian Dollars, GBP British Pound.

HERPETOLOGY

Ecology and Conservation of the Diamond-backed Terrapin

Edited by W.M. Roosenburg and V.S. Kennedy. 2019. Johns Hopkins University Press. 296 pages, 79.95 USD, Cloth or E-book.



Diamond-backed Terrapin (*Malaclemys terrapin*) lives in estuaries in the United States from Massachusetts to Texas. Most species of turtles are associated with freshwater and a few are found in the oceans (sea turtles), but the Diamond-backed Terrapin is the only turtle species to permanently reside in brackish water, the narrow interface between the full saltwater of the ocean and the freshwater of the inland lakes and rivers. It is closely related to the map turtles, and the species share characteristics such as females being substantially larger than males, and feeding on molluscs and other hard-shelled invertebrates.

During the 19th and early part of the 20th century, Diamond-backed Terrapins were widely collected for food. By 1880, it is estimated that more than 200 000 individuals were caught each year. Philadelphia, New York City, and Baltimore were some of the larger markets, but Diamond-backed Terrapins were also shipped live to England, France, and Germany. Prices were as high as $125 a dozen by the early 1900s, but by 1938, prices had dropped to $36 a dozen because of declining demand. Nonetheless, the commercial harvest of Diamond-backed Terrapins caused the collapse of many populations.

This book collects together review papers on various topics related to the biology and conservation of this wide-ranging species. The book begins with an introduction by J. Whitfield Gibbons, a veteran turtle researcher. Part I, Biology and Ecology, includes 11 papers on field techniques, evolutionary history, taxonomy, genetics, geographic variation, reproductive behaviour, hatchling behaviour, osmoregulation, temperature-dependent sex determination, habitat use, and environmental toxicology. Part II, Fisheries and Conservation Challenges, includes seven papers on commercial harvest, habitat loss and road mortality, motorboats, bycatch from the crab harvest, environmental education, habitat restoration and head-starting, and concludes with a paper on the future of the Diamond-backed Terrapin. The papers were written by researchers (mainly from universities and government agencies) with experience with Diamond-backed Terrapins from across the range of the species.

The collected papers provide a broad and rich overview on the biology of this turtle. The concluding paper on the future of Diamond-backed Terrapins demonstrates the importance of collaborative work carried out over many years to accomplish conservation goals. And many threats, such as Diamond-backed Terrapins getting caught and drowning in abandoned crab pots set out to catch crabs, are still significant threats after years of work. Viable solutions have been suggested, such as the use of biodegradable panels which would mean that lost or abandoned crab pots would not continue to be death traps for years to come, but work on reducing the mortality from this threat is making only slow progress.

Although all of these papers specifically target Diamond-backed Terrapin, the contents of these papers are broadly applicable to other turtle species. In particular, the sections on threats (e.g., habitat loss, road mortality, and motorboats) and on environmental education are relevant to Canadian freshwater turtles. For example, injuries from boat propellers are a widespread threat for many turtles. Diamond-backed Terrapin research has found that individuals in the water dive deeper when a boat approaches, but only by about 30 cm, which is not enough to avoid being potentially hit by the propeller. In many cases, then, the specific details around Diamond-back Terrapin threats or issues are relevant to other turtle species, making this a highly recommended book for anyone working in turtle biology or conservation.

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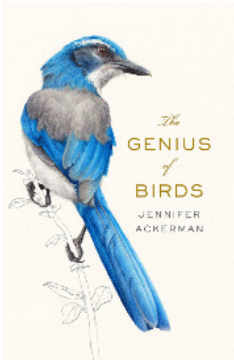
ORNITHOLOGY

The Genius of Birds

By Jennifer Ackerman. 2016. Penguin Random House. 340 pages, 23.00 CAD, Paper.



From its striking cover to its detailed index, Jennifer Ackerman delivers a well-crafted popular science book to satisfy enthusiastic birders and armchair naturalists alike. The book is divided into eight chapters plus an Introduction, each with amusing titles such as "Four – Twitter: Social Savvy" and "Three – Boffins: Technical Wizardry". Each chapter features a delightful illustration by John Burgoyne picking up on one of the stories or central themes of the chapter; these are excellent additions to the text and follow through on the promise of the Western Scrub Jay cover art by Eunike Nugroho.

As you might expect, much of the content is reasonably cerebral—the short subsections belie their content, and for most folks this will not be a book for drowsy before-bedtime reading. Fortunately, Jennifer Ackerman writes with a rich style that makes cognitive neuroscience research appealing and accessible. Through direct quotes and anecdotes curated from researcher interviews coupled with her own extensive research, the author explores various forms of avian intelligence—problem solving, navigational, musical, and more.

This is a book full of surprises and unknowns, including cutting edge research as well as unanswered questions about common and rare species alike. Not limited to probing accounts of experimental research, *The Genius of Birds* is full of cocktail conversation starters. I learned that pigeons are better at intuiting the Monty Hall Dilemma than I am, for example. And that some birds have a keen sense of smell, and may use it to navigate. This is not to say that this volume is just a litany of facts, nor that it strays from its central theme. The book is specialized in its focus: bird learning and intelligence are front and centre. The last chapter is the only one that delves into the 'big issues' of biodiversity declines, habitat loss, and climate change in a significant way.

The book is also exquisitely researched and has the largest reference list I've seen in a popular science book, with a whopping 54 pages of notes in reduced font size. If you would like more information on a particular topic and have journal subscription privileges, you will not be disappointed. If you forget where in the 266 content pages you read an interesting tidbit, there is also a detailed index so you can retrace your steps.

If you start the first page of *The Genius of Birds* thinking that birds are simple automatons incapable of logic or reasoning, you are in for a shock. If you came in already believing that birds are intelligent beings, you will turn the last page astounded by just how true that really is. I recommend this book to anyone looking for an in-depth read on bird intelligence, who wants to understand more about our feathered friends, and perhaps as a gift to friends and family members who don't understand why birdwatching is such a popular pastime.

HEATHER A. CRAY
Waterloo, ON, Canada

Best Places to Bird in Ontario

By Kenneth Burrell and Michael Burrell. 2019. Greystone Books. 278 pages, 24.95 CAD, Paper.

A book on where to find birds is a truly valuable tool. It has been a long time since Clive Goodwin's indispensable *A Bird-Finding Guide to Ontario* (University of Toronto Press, 1982 and revised 1995) and much has changed since then. So periodically someone needs to write a new version to incorporate the changes in the land and the concepts in biology.

The Burrell brothers have now produced *Best Places to Bird in Ontario* to bring us current information. They have chosen 30 of their favourite places to highlight the best Ontario has to offer. Each place is described by a general introduction that familiarises the reader with the local environment. There are instructions on how to get there, whether by road, rail, or aeroplane. (These tend to be a little Toronto-centric.)

There is a well described birding strategy. The authors propose a starting point, a route, and the key places to check for special species. These plans are carefully thought through and appear to be logical (or perhaps I think the same way as the Burrells). I have followed a similar route to that suggested through Point Pelee and the surrounding area many times, seeing many of the species mentioned at the location highlights.

Each area is accompanied by a location map. Like most recent publications these are clear and easy to read and follow. The Burrells have added locations that are particularly relevant to birdwatchers. Only birders will understand the significance of Pelee's "Serengeti" tree or Rose Lane on Canoe Lake Road or the sewage lagoons at Moosonee. This makes these the most useful birding maps I have seen.

Writers of this type of book must reflect a good level of enthusiasm. They need to paint a rosy picture of each site; after all they are their favourites. Is the zeal in this book warranted? It depends on the site. I have been going to Presqu'ile Provincial Park (PIPP) for years. In the spring it has a flood of waterfowl and the fall is shorebird season. Even on a bad day you should get a good count of these birds, and a good day can be wonderful. For a place like Algonquin Provincial Park (APP) it is very different. Recently I reviewed the last 10 day trips my regular birding group took to APP. We go every year to look for 10 boreal species. We have a 24% success rate seeing those species and average of 2.2 species of the 10 per trip. As one of those species is always Canada Jay these results are not impressive. The difference is PIPP is filled with visible migrants, whereas APP has a group of elusive forest dwellers. The APP birds are always there and seen every week by somebody, but usually on different days of the week.

Pelee is a different case. The authors think this is the best birding spot in Ontario and I strongly agree. There are more different species seen and even a few hours in spring will get you an impressive list. My own view is a bit prejudiced because I first went to Pelee in the 1960s. Then the park was visited by two dozen birders a day (we all knew each other) and there were higher numbers of individual birds than today. In spring, trees near the point would be loaded with birds and the fall would bring streams of migrants. I used to band raptors (and sleep) at the base of the tip near the hot dog stand. Yes, sadly, it was different, but the Burrells are still correct in their praise. I am planning a spring trip to the USA, so I pulled a guide to New England. The Burrell's book is significantly superior to this, admittedly older, book.

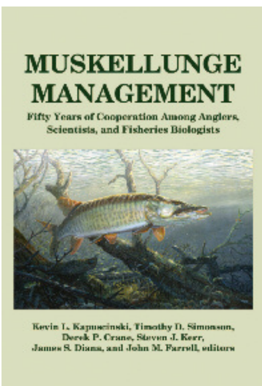
This guide will be of great value to new birders and visitors alike. More experienced people will likely know most of the chosen places. But if they have not been to the more distant spots, like Rainy River or Moosonee, then it is still worth the purchase. I will not be abandoning Goodwin's guide entirely as it covers many more areas than the 30 selected for this guide. Should I be going to one of the favoured 30, however, I will use the new book with enthusiasm.

Roy John
Ottawa, ON, Canada

Zoology

Muskellunge Management: Fifty Years of Cooperation Among Anglers, Scientists, and Fisheries Biologists

Edited by Kevin Kapuscinski, Timothy Simonson, Derek Crane, Steven Kerr, James Diana, and John Farrell. 2017. American Fisheries Society. 675 pages, 79.00 USD, Cloth.



Muskellunge (*Esox maskinongy*) is a freshwater apex predatory fish whose native range revolves around the Great Lakes region of North America. Because this species is long-lived and can grow to an exceptional size (approximately 160 cm), it has attracted continuing attention throughout recent history from an indigenous subsistence harvest, recreational anglers, and commercial netting operations. Inhabiting waters close to human population centres and the accompanying agricultural/industrial development, it has been impacted by water pollution, habitat degradation, and invasive species, as well as overfishing and harvesting.

In support, modern Muskellunge fisheries management encompasses all the administrative actions, procedures, and regulations developed and implemented, usually by a government agency, to restore, maintain, or enhance the biological and economic potential of the fish species in a body of water.

During the last 50 years, anglers in pursuit of Muskellunge have banded together to form muskie clubs specific to this species and promote public education, conservation, scientific research, fish data collection, and artificial propagation where necessary. In cooperation with the American Fisheries Society, academic researchers, fishery biologists, and clubs like Muskies Inc. and Muskies Canada, this textbook sized compendium of almost 700 pages reflects the proceedings of the Hugh Becker Memorial Muskie Symposium which was held in Minnesota during 2016. Containing many scientific papers, extended abstracts, and regional reports, *Muskellunge Management* demonstrates thematically 50 years of cooperation among anglers, scientists, and fisheries management concerns.

This book is primarily aimed at the fisheries management community across North America as well as scientists and researchers interested in this animal. Its state-of-the-art papers are organized into eight sections: 50 years of cooperative efforts, biology, habitat, population dynamics, genetics, population assessments, regional management approaches, and stocking and propagation. Essentially, these form a broad spectrum of papers on many aspects and issues related to Muskellunge.

As an example of the partnerships section, Muskies Canada, working with natural resource agencies, is seeking to ensure sustainable wild Muskellunge populations through habitat protection, restoration, and enhanced regulation. In contrast, in the United States, much more emphasis is placed on artificial propagation/stocking and also range extension across its continental geography. To support some of the Canadian objectives, muskie anglers are encouraged to enter angling information online, including waterbody location, data on fish captured, and amount of fishing effort. With this yearly data collection, large scale changes to fish size and abundance can be monitored by management agencies. For the curious, in 2018 within Ontario over 1400 captures were recorded by participants. On average it took about 16 hours of angling effort to record one capture of a Muskellunge.

In 1984 during a previous Muskellunge symposium, genetic research was identified as a priority future requirement. In this issue, a sizeable number of papers highlight the significant genetic diversity among native populations of this single species across its range. The genetic data appears to substantiate the reality of three distinct regional lineages derived from a single Mississippian glacial refugium population. Each lineage can be broken down to multiple subgroups impacted by local geography, spawning fidelity, proximity to each other, and habitat connectivity. For example, around the City of Ottawa, native Ottawa River Muskellunge above and below the city form different subgroups and the Muskellunge of the Rideau River tributary form a third genetic subgroup. The Chaudière and Rideau falls within the City contribute to these genetic differences. This can be compared to the Trent Severn system of the Kawartha lakes where the Muskellunge show little to no genetic substructure over a comparably more extensive geography.

Several papers detail the attempt to restore a self-supporting population of Muskellunge in Ontario's Lake Simcoe. The species was essentially extirpated in the lake during the early part of the last century, mostly through commercial harvest and habitat loss. Over the last 14 years, millions of dollars, and multiple partners, more than 10 000 young-of-the-year Muskellunge have been stocked into Lake Simcoe. This project has wrapped up and now it is up to the animal. Biologists estimated that it will take another 15 years of monitoring to determine if this project will result in a successful restoration—a new self-sustaining population.

Interestingly enough, other articles call attention to an opposite ecological dilemma happening to the east. As the story goes, Muskellunge were introduced by Quebec provincial authorities, in efforts to increase sportfishing opportunity, to a headwater lake. Over time the Muskellunge emigrated and set up populations along the St. John River watershed throughout Maine and New Brunswick to points downstream of the City of Fredericton. Currently these fish are considered an invasive species subject to active efforts of elimination by government management agencies despite their increasing popularity as a sportfish.

For many decades the upper St. Lawrence River has long been considered mythical as harbouring some of the largest growing specimens of this animal on the continent. Despite many recent management efforts, researchers indicate it is suffering a continuing population decline triggered at least in part by fairly recent invasive species, such as the outbreak of viral hemorrhagic septicaemia causing adult die offs and staggering numbers of the Eurasian Round Goby which act as an egg predator limiting recruitment. Recommendations include management plans to enhance young-of-the-year recruitment with actions to restore high quality spawning and nursery habitat.

Within this substantial volume, much more subject matter touches on many issues, including non-lethal tissue sampling, weight estimates, tournament impacts, response to catch and release, nursery habitat, population assessment, regional management perspectives, and many others. Based on the partnership of an increasing number of concerned and dedicated non-profit muskie clubs, resource managers are forging biologically sound research and management efforts. The book *Muskellunge Management* provides a solid foundation for a potentially bright future.

HEDRIK WACHELKA
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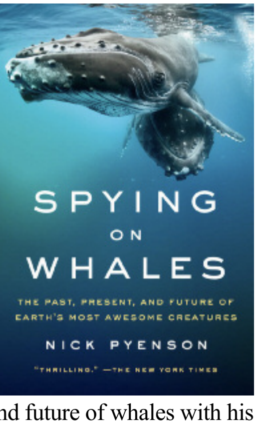
Spying on Whales

By Nick Pyenson. 2018. Viking. 336 pages, 27.00 USD, Cloth, 17.50 USD, Audiobook, 13.99 USD, E-book.



Spying on Whales is a book full of interesting facts about the biology and ecology of whales. The author, Nick Pyenson, is the curator of fossil marine mammals at the Smithsonian Institution's National Museum of Natural History, and has been studying whales for many years. The book is structured in a unique but intriguing style: the author interweaves a narrative of the past, present, and future of whales with his own field excursions to study whales. As a paleontologist, the author often studies the fossilized bones of whales, but he also compares this to contemporary samples taken from whaling stations, and he presents the information in a compelling way by relating his discoveries to the form and function of whales. Throughout the book, he describes some of the basic biology of whales, such as how and why Blue Whales evolved their gigantic sizes, and how Fin Whales and other rorqual whales withstand the shear force of opening their mouth while lunge feeding. Within this narrative, the author describes the mysteries of whale evolution, teasing apart the history of how current behemoths of the ocean evolved from relatively small terrestrial mammals. He also discusses the future of whales, and how they might adapt to changes brought on by climate change and human activity.

As an ecologist who studies whales, I found this book to be quite compelling, but that may be due to my own biases. Any naturalist interested in marine mammals should find this book intriguing. It is written in clear language, and although the author does present some details of the science behind the narrative that he tells, he doesn't get too bogged down in the details, and most readers without an education in science should still find the book accessible and interesting. One warning for any squeamish readers: the author does spend some time discussing field trips to past and current whaling stations, and describes how whales are processed in gruesome detail. He fully justifies his own use of whales killed by whaling operations for his research—he reasons that it is completely ethical and is a good use of dead whales that were going to be killed regardless of his research. Even still, the whole enterprise of commercial whaling might be too much for some readers.

I found a somewhat troubling error in the book that bothered me about Bowhead Whales in the Bering-Chukchi-Beaufort (BCB) stock, a population near and dear to me because I study it. The author states that the explorer Sir John Franklin likely saw Bowhead Whales from this population while on board the *Erebus* near King William Island, which is in the central Canadian Arctic Archipelago. This is extremely unlikely, however, as the BCB stock summers in the eastern Beaufort Sea, Amundsen Gulf, and Viscount Melville Sound and, to the best of my knowledge, whales from this stock have never been documented near King William Island. Franklin would likely have seen plenty of Bowhead Whales from the eastern Canada-west Greenland (ECWG) stock when he and his crew travelled from England to Baffin Bay, and then deeper into the Canadian Arctic Archipelago from the east. The ECWG stock spends its time in the eastern Canadian Arctic around Baffin Island, and ranges much more closely to King William Island than the BCB population does. However, the current range of the ECWG stock doesn't even overlap with King William Island, so perhaps Franklin didn't observe any Bowhead Whales while he was near King William Island. Given that Franklin's expedition was more than 150 years ago and species distributions can change through time, it is possible that these Bowhead Whale populations lived in slightly different areas during that time. However, it is unlikely that the distributions of either population would have shifted toward King William Island because summer sea ice concentration should have been even higher in the 1800s than it is now, and patterns in sea ice dictate where Bowhead Whales spend their winters and summers, as well as the timing of their migrations. Both populations currently spend their winters quite far away from King William Island, and increased summer sea ice concentration would make it more difficult for whales from either population to migrate to King William Island.

Overall, *Spying on Whales* was a pleasure to read, and provided me with plenty of tidbits about whale biology and evolutionary history that I was not aware of before reading this book. I highly recommend this book to any naturalists interested in evolution, whales, or paleontology.

WILLIAM D. HALLIDAY

Wildlife Conservation Society Canada, Whitehorse, YT, and Department of Biology, University of Victoria, Victoria, BC, Canada

NEW TITLES

Prepared by Barry Cottam

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BOTANY

Detecting and Responding to Alien Plant Incursions. Ecology, Biodiversity, and Conservation. By John R. Wilson, F. Dane Panetta, and Cory Lindgren. 2016. Cambridge University Press. 282 pages, 116.00 USD, Cloth, 57.99 USD, Paper, 46.00 USD, E-book.

Fungipedia: A Brief Compendium of Mushroom Lore. By Lawrence Millman. 2019. Princeton University Press. 208 pages, 16.95 USD, Cloth or E-book.

The Nature of Plants: An Introduction to How Plants Work. By Craig N. Huegel. 2019. University Press of Florida. 288 pages, 24.95 USD, Paper.

Plant Evolutionary Developmental Biology: The Evolvability of the Phenotype. By Alessandro Minelli. Photographs by Maria Pia Mannucci. 2018. Cambridge University Press. 468 pages, 84.99 USD, Cloth, 68.00 USD, E-book.

Sedges of The Northern Forest – A Photographic Guide. By Jerry Jenkins. 2019. Cornell University Press. 96 pages, 16.95 USD, Paper.

Sedges of the Northern Forest – Quick Guide. By Jerry Jenkins. 2019. Cornell University Press. 4 pages, 11.95 USD, Fold-out Chart.

ENTOMOLOGY

Dragonflies and Damselflies: A Natural History. By Dennis Paulson. 2019. Princeton University Press. 224 pages, 29.95 USD, Cloth or E-book.

*__Field Guide to the Flower Flies of Northeastern North America.__ By Jeffrey H. Skevington, Michelle M. Locke, Andrew D. Young, Kevin Moran, William J. Crins, and Stephen A. Marshall. 2019. Princeton University Press. 512 pages, 3 000 images, and 414 maps, 27.95 USD, Flexibound Paper.

The Lives of Bees: The Untold Story of the Honey Bee in the Wild. By Thomas D. Seeley. 2019. Princeton University Press. 432 pages and 110 illustrations, 29.95 USD, Cloth or E-book.

The Solitary Bees: Biology, Evolution, Conservation. By Bryan N. Danforth, Robert L. Minckley, and John L. Neff. 2019. Princeton University Press. 464 pages, 45.00 USD, Cloth or E-book.

Protecting Pollinators: How to Save the Creatures that Feed Our World. By Jodi Helmer. 2019. Island Press. 232 pages, 28.00 CAD, Paper or E-book.

Wings in the Light: Wild Butterflies in North America. By David Lee Myers. Foreword by Robert Michael Pyle. 2019. Yale University Press. 288 pages and 430 colour illustrations, 35.00 USD, Cloth.

HERPETOLOGY

Australia's Dangerous Snakes: Identification, Biology and Envenoming. By Peter Mirtschin, Arne R. Rasmussen, and Scott A. Weinstein. 2017. CSIRO Publishing. 432 pages, 120.00 AUS, Cloth. Also available as an E-book.

Behavior of Lizards: Evolutionary and Mechanistic Perspectives. By Vincent Bels and Anthony Russell. 2019. CRC Press. 410 pages, 159.95 CAD, Cloth. Also available as an E-book.

Reptiles: A Very Short Introduction. By T.S. Kemp. 2019. Oxford University Press. 160 pages, 8.99 GBP, Paper.

ICHTHYOLOGY

Fish Ecology, Evolution, and Exploitation: A New Theoretical Synthesis. By Ken H. Andersen. 2019. Princeton University Press. 280 pages, 120.00 USD, Cloth, 40.00 USD, Paper.

Ocean Outbreak: Confronting the Rising Tide of Marine Disease. By Drew Harvell. 2019. University of California Press. 224 pages, 26.95 USD, Cloth or E-book.

Overrun: Dispatches from the Asian Carp Crisis. By Andrew Reeves. 2019. ECW Press. 384 pages, 22.95 CAD, Paper, 16.99 CAD, E-Book.

A Sea of Glass: Searching for the Blaschkas' Fragile Legacy in an Ocean at Risk. By Drew Harvell. Foreword by Harry W. Greene. 2019. University of California Press. 256 pages, 24.95 USD, Paper.

Vanishing Fish: Shifting Baselines and the Future of Global Fisheries. By Daniel Pauly. Foreword by Jennifer Jacquet. 2019. Greystone Books. 304 pages, 34.95 CAD, Cloth.

The Walking Whales: From Land to Water in Eight Million Years. By J.G.M. "Hans" Thewissen. 2019. University of California Press. 256 pages, 34.95 USD, Cloth or E-book, 29.95 USD, Paper.

ORNITHOLOGY

***Birds of Eastern Canada. Second Edition. Revised and Expanded.** Consultant editor, David M. Bird. 2019. DK Canada. 399 pages, 27.99 CAD, Plasticized Paper.

***Birds of Western Canada. Second Edition. Revised and Expanded.** Consultant editor, David M. Bird. 2019. DK Canada. 399 pages, 27.99 CAD, Plasticized Paper.

Gulls. Collins New Naturalist No. 139. By John C. Coulson. 2019. HarperCollins. 496 pages, 135.99 CAD, Cloth.

***The Handbook of Bird Families.** By Jonathan Elphick. 2018. Firefly Books. 416 pages, 35.00 CAD, Paper.

***Ospreys: The Revival of a Global Raptor.** Alan F. Poole. 2019. Johns Hopkins University Press. 220 pages and 122 colour photographs, 39.95 USD, Cloth or E-book.

Whooping Cranes: Biology and Conservation. Biodiversity of the World: Conservation from Genes to Landscapes Series. Edited by John French, Sarah Converse, and Jane Austin. 2018. Elsevier – Academic Press. 538 pages, 99.95 USD, Cloth or E-book.

ZOOLOGY

Avoiding Attack: The Evolutionary Ecology of Crypsis, Aposematism, and Mimicry. Second Edition. By Graeme D. Ruxton, William L. Allen, Thomas N. Sherratt, and Michael P. Speed. 2018. Oxford University Press. 304 pages, 100.00 USD/CAD, Cloth, 49.95 USD/CAD, Paper. Also available as an E-book.

Bats: An Illustrated Guide to All Species. By Marianne Taylor. Photographs by Merlin Tuttle. 2019. Smithsonian Books. 400 pages, 29.95 USD, Cloth.

Fires of Life: Endothermy in Birds and Mammals. By Barry Gordon Lovegrove. Foreword by Roger S. Seymour. 2019. Yale University Press. 384 pages, 40.00 USD, Cloth.

How to Walk on Water and Climb up Walls: Animal Movement and the Robots of the Future. By David L. Hu. 2018. Princeton University Press. 240 pages, 24.95 USD, Cloth or E-book.

Nature's Giants: The Biology and Evolution of the World's Largest Lifeforms. By Graeme D. Ruxton. Foreword by Norman Owen-Smith. 2019. Yale University Press. 224 pages and 350 colour illustrations, 35.00 USD, Cloth.

OTHER

All the Boats on the Ocean: How Government Subsidies Led to Global Overfishing. By Carmel Finley. 2017. University of Chicago Press. 224 pages, 45.00 USD, Cloth. Also available as an E-book.

Animal Beauty: On the Evolution of Biological Aesthetics. By Christiane Nüsslein-Volhard. Translated by Jonathan Howard. 2019. MIT Press. 128 pages and 47 colour illustrations, 14.95 USD, Cloth.

The Anthropocene as a Geological Time Unit: A Guide to the Scientific Evidence and Current Debate. Edited by Jan Zalasiewicz, Colin N. Waters, Mark Williams, and Colin Summerhayes. 2019. Cambridge University Press. 382 pages, 62.99 USD, Cloth.

Biodiversity and Climate Change: Transforming the Biosphere. Edited by Thomas E. Lovejoy and Lee Hannah. Foreword by Edward O. Wilson. 2019. Yale University Press. 416 pages, 40.00 USD, Paper.

Complexity: The Evolution of Earth's Biodiversity and the Future of Humanity. By William C. Burger. 2016. Prometheus Books. 380 pages, 26.00 USD, Cloth, 11.99 USD, E-book.

Corridor Ecology, Second Edition: Linking Landscapes for Biodiversity Conservation and Climate Adaptation. By Jodi A. Hilty, Annika T.H. Keeley, William Z. Lidicker Jr., and Adina M. Merenlender. 2019. Island Press. 368 pages, 40.00 CAD, Paper or E-book.

***Darwin Comes to Town: How the Urban Jungle Drives Evolution.** By Menno Schilthuizen. 2018. Picador. 304 pages, 27.00 USD, Cloth, 18.00 USD, Paper, 9.99 USD, E-book.

Earth Emotions: New Words for a New World. By Glenn A. Albrecht. 2019. Cornell University Press. 256 pages, 19.95 USD, Paper.

Emerald Labyrinth: A Scientist's Adventures in the Jungles of the Congo. By Eli Greenbaum. 2017. ForeEdge. 336 pages, 22.95 USD, Paper, 14.99 USD, E-book.

Finding Resilience: Change and Uncertainty in Nature and Society. By Brian Walker. 2019. CSIRO Publishing. 168 pages, 59.99 AUS, Paper.

Great Lakes Rocks: 4 Billion Years of Geologic History in the Great Lakes Region. By Stephen E. Kesler. 2019. University of Michigan Press. 360 pages, 80.00 USD, Cloth, 29.95 USD, Paper.

***How to Give Up Plastic: A Guide to Changing the World, One Plastic Bottle at a Time.** By Will McCallum. 2018. Penguin Life. 224 pages, 27.99 CAD, Cloth.

A Naturalist at Large: The Best Essays of Bernd Heinrich. By Bernd Heinrich. 2018. Houghton Mifflin Harcourt Publishers. 304 pages, 26.00 USD, Cloth.

The Nature of Canada. Edited by Colin M. Coates and Graeme Wynn. 2019. UBC Press, On Point Press. 320 pages, 29.95 CAD, Paper.

†**The New Beachcomber's Guide to the Pacific Northwest: Alaska to Oregon, 2019 Edition.** By J. Duane Sept. 2019. Harbour Publishing. 432 pages and 400 colour photos, 32.95 CAD, Paper.

Nature Rx: Improving College-Student Mental Health. By Donald A. Rakow and Gregory T. Eells. 2019. Cornell University Press, Comstock Publishing Associates. 108 pages, 14.95 USD, Paper.

Nightingales in Berlin: Searching for The Perfect Sound. By David Rothenberg. 2019. University of Chicago Press. 184 pages, 26.00 USD, Cloth, 18.00 USD, E-book.

Oceans in Decline. By Sergio Rossi. 2019. Springer International Publishing. 369 pages, 29.99 CAD, Paper, 19.99 CAD, E-book.

Plastic Soup: An Atlas of Ocean Pollution. By Michiel Roscam Abbing. 2019. 136 pages, 27.00 CAD, Paper or E-book.

Poached: Inside the Dark World of Wildlife Trafficking. By Rachel Love Nuwer. 2018. Da Capo Press. 384 pages, 36.50 CAD, Cloth.

Rebirding: Rewilding Britain and Its Birds. By Benedict Macdonald. Foreword by Stephen Moss. 2019. Pelagic Publishing. 300 pages, 34.24 CAD, Cloth.

Restoring Farm Woodlands for Wildlife. By David Lindenmayer, Damian Michael, Mason Crane, Daniel Florance, and Emma Burns. 2018. CSIRO Publishing. 136 pages, 39.99 AUS, Paper or ePDF.

Rewilding. By Nathalie Pettorelli, Sarah M. Durant, and Johan T. du Toit. 2019. Cambridge University Press. 460 pages, 143.95 CAD, Cloth, 56.95 CAD, Paper.

Sarapiquí Chronicle: A Naturalist in Costa Rica. Revised and Expanded Edition. By Alan M. Young. 2017. University of New Mexico Press. 350 pages, 29.95 USD, Paper.

Soil Fauna Assemblages: Global to Local Scales. Ecology, Biodiversity and Conservation Series. By Uffe N. Nielsen. 2019. Cambridge University Press. 378 pages, 102.95 CAD, Cloth, 51.95 CAD, Paper, 36.00 CAD, E-book.

The Songs of Trees: Stories from Nature's Great Connectors. By David George Haskell. 2018. Penguin Books. 304 pages, 28.00 USD, Cloth, 17.00 USD, Paper, 12.99 USD, E-book.

***Surviving Global Warming: Why Eliminating Greenhouse Gases Isn't Enough.** Roger A. Sedjo. 2019. Prometheus Books. 245 pages, 25.50 CAD, Cloth.

***The Uninhabitable Earth: Life After Warming.** By David Wallace-Wells. 2019. Allen Lane. 320 pages, 36.00 CAD, Cloth, 16.99 CAD, E-book.

There Is No Planet B: A Handbook for the Make or Break Years. By Mike Berners-Lee. 2019. Cambridge University Press. 302 pages, 12.95 USD, Paper.

Wildlife Gardening: For Everyone and Everything. By Kate Bradbury. 2019. Bloomsbury Wildlife. 176 pages and 300 colour photographs, 14.99 GBP, Paper. Also available as an E-book.

The Wood for the Trees: One Man's Long View of Nature. By Richard Fortey. 2017. Knopf / Vintage. 336 pages, 18.00 USD, Paper, 12.99 USD, E-book.

A Year on the Wild Side. By Briony Penn. 2019. Touchwood Editions. 400 pages, 26.00 CAD, Paper.

News and Comment

Upcoming Meetings and Workshops

Plant Canada 2019

Plant Canada 2019 to be held 7–10 July 2019 at the University of Guelph, Guelph, Ontario. The theme of the conference is: ‘Communicating innovation in plant science’. Registration is currently open. More information is available at http://www.cspb-scbv.ca/PlantCanada2019/index.shtml.

Mothapalooza

Mothapalooza to be held 12–14 July 2019 at the Shawnee Lodge & Conference Center, West Portsmouth, Ohio. The 2019 Conference Moth is the Sooty-winged Chalcoela (*Chalcoela iphitalis*). More information is available at http://www.mothapalooza.org/.

Northeast Partners in Amphibian and Reptile Conservation Annual Meeting

The Northeast Partners in Amphibian and Reptile Conservation (NEPARC) Annual Meeting to be held 17–19 July 2019 at Stockton University, Galloway, New Jersey. The theme of the conference is: ‘20 Years of NEPARC – Back to New Jersey’. Registration is currently open. More information is available at http://northeastparc.org/next-meeting-info/.

Behavior 2019

The joint meeting of the 56th Annual Conference of the Animal Behavior Society and the 36th International Ethological Conference to be held 23–27 July 2019 at the University of Illinois, Chicago, Illinois. Registration is currently open. More information is available at http://www.animalbehaviorsociety.org/2019/.

Botany 2019

Botany 2019 to be held 27–31 July 2019 at Starr Pass, Tucson, Arizona. Registration is currently open. More information is available at https://2019.botanyconference.org/.

Symposium on the Conservation and Biology of Tortoises and Freshwater Turtles

The 17th annual Symposium on the Conservation and Biology of Tortoises and Freshwater Turtles, co-hosted by the Turtle Survival Alliance and the IUCN Tortoise and Freshwater Turtle Specialist Group, to be held 4–8 August 2019 at the Loews Ventana Canyon Resort, Tucson, Arizona. Registration is currently open. More information is available at https://turtlesurvival.org/2019symposium/.

2019 Mycological Society of America Meeting

The 2019 meeting of the Mycological Society of America to be held 10–14 August 2019 at the University of Minnesota, Minneapolis, Minnesota. The theme of the conference is: ‘Diversity in All Dimensions’. Registration is currently open. More information is available at https://msafungi.org/2019-annual-meeting/.

Ecological Society of America and United States Society for Ecological Economics Joint Meeting

The 104th annual meeting of the Ecological Society of America in partnership with the United States Society for Ecological Economics to be held 11–16 August 2019 at the Kentucky International Convention Center, Louisville, Kentucky. The theme of the conference is: ‘Bridging Communities & Ecosystems: Inclusion as an Ecological Imperative’. Registration is currently open. More information is available at https://esa.org/louisville/.

Canadian Society for Ecology & Evolution, Entomological Society of Canada, and Acadian Entomological Society Joint Meeting

The joint meeting of the Canadian Society for Ecology & Evolution, Entomological Society of Canada, and Acadian Entomological Society to be held 18–21 August 2019 at the Fredericton Convention Centre, Fredericton, New Brunswick. Registration is currently open. More information is available at http://csee-esc2019.ca/index.html.

2019 International Conference on Ecology & Transportation

The 10th biennial International Conference on Ecology & Transportation, hosted by the California Department of Transportation and California Department of Fish and Wildlife, to be held 22–26 August 2019 at the Hyatt Regency Hotel, Sacramento, California. Registration is currently open. More information is available at https://icoet.net/.

Society of Canadian Ornithologists – Societe des ornithologistes du Canada

The 36th meeting of the Society of Canadian Ornithologists – Societe des ornithologistes du Canada to be held 27–30 August 2019 at the Hôtel Chateau Laurier, Québec City, Quebec. Registration is currently open. More information is available at http://sco-soc-quebec2019.org/.

iNaturalist Canada passes the 1 000 000 observation mark

The value of citizen scientists—and their collaborations with, for want of a better term, "professional" scientists—is becoming increasingly recognized (e.g., Silvertown 2009; Dickinson *et al*. 2012). This is evident in the pages of *The Canadian Field-Naturalist*, including the current issue. For example, in Bowden *et al*. (2018) the combined efforts of citizen scientists, naturalists, and scientists led to an astounding increase in the list of spiders known to occur on Prince Edward Island. They were able to to more than quadruple the number of known spider species, from 44 to 198 species! And Mullins *et al*. (2018) were able to leverage public engagement in the Ontario BioBlitz Program, an annual citizen science event, to collect and identify lichen and allied fungus species within the Greater Toronto Area. These data allowed them to increase the list of known lichens and allied fungi species within the region to 180 species.

I chose to highlight one citizen science endeavour—iNaturalist Canada—in this issue because, as of 19 April 2019, it has surpassed the 1 000 000 observation mark. At the time of writing (4 May 2019), this number had already grown to 1 038 803 observations, representing observations of 18 678 species (iNaturalist Canada 2019).

iNaturalist is a place where environmental non-government organizations (ENGOs), academics, government, and citizen scientists come together to work towards an increasing understanding of wildlife in Canada. It was developed by two ENGOs—the Canadian Wildlife Federation and NatureServeCanada—in collaboration with the federal government (Parks Canada) and the Royal Ontario Museum. These Canadian organizations also collaborated with iNaturalist.org (housed in the California Academy of Sciences). These agencies worked together to launch (and maintain) the website and associated app used in data collection. In addition to these agencies, the success of iNaturalist Canada depends on the contributions of citizen and professional scientists, with (as of 4 May 2019) 25 569 observers (who collect and upload wildlife observations, e.g., photographs) and 10 912 identifiers (who aid in identification of wildlife in photographs; iNaturalist Canada 2019). The cellphone app—which is available in English and French, and downloadable through Google Play or the Apple App Store—makes it easy to contribute to data collection. And the webpage https://inaturalist.ca/ makes it easy for anyone to benefit from this resource, even if one just wants to enjoy photographs of Canadian wildlife.

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