NRC Research Press

ARTICLE

The Chic-Choc Mountains are the last southern refuge for Arctic lichens in eastern North America

Richard Troy McMullin, and Briann C. Dorin

Abstract: Endemic and disjunct populations of vascular plants and cryptogams occurring in the Chic-Choc Mountains on the Gaspé Peninsula in eastern Québec, Canada, have been attracting botanists for over a century. Although controversial, these ancient mountains have been hypothesized to have been nunataks during the Wisconsin glaciation in part because they contain vascular plants that are not known to colonize nearby mountains with similar environments that were not thought to be nunataks. To determine whether there are lichen species that have the same pattern as the vascular plants, we examined the North American distribution of all the approximately 600 lichens known from the Chic-Chocs. Fifteen Arctic-alpine species were found to reach the edge of their southeastern North American range in the Chic-Chocs. Six of these species are not known to occur again for over 1000 km to the north. These results provide an additional layer of biogeographic knowledge about the unusual flora of the Chic-Chocs and lend some support to the hypothesis that the Chic-Chocs might have been nunataks during the last glacial period. Any Arctic-alpine species occurring in the Chic-Chocs are good candidates for monitoring the effects of climate change, but the 15 lichen species that reach their southeastern limit in this range might be the most vulnerable.

Key words: biogeography, alpine, climate change, protected areas, nunataks.

Résumé : Les populations de plantes et de cryptogames vasculaires endémiques et isolées qu'on retrouve dans les monts Chic-Chocs en Gaspésie à l'est du Québec au Canada attirent les botanistes depuis plus d'un siècle. Quoique sujet à controverse, ces montagnes anciennes sont présumées avoir été des nunataks pendant la glaciation du Wisconsin, et ce, en partie, car elles contiennent des plantes vasculaires que l'on ne reconnait pas comme colonisant près des montagnes ayant des environnements semblables que l'on pensait ne être pas des nunataks. Afin de déterminer s'il y a des espèces de lichen qui ont la même tendance que les plantes vasculaires, nous avons examiné la distribution nord-américaine d'environ 600 lichens connus dans les Chic-Chocs. Quinze espèces arctiques ou alpines se sont avérées atteindre la limite de leur aire de répartition sud-est nord-américaine dans les Chic-Chocs. Six de ces espèces ne surviennent de nouveau qu'à 1000 km au nord. Ces résultats donnent un niveau de connaissance biogéographique supplémentaire au sujet de la flore particulière des Chic-Chocs et apportent un soutien à l'hypothèse que les Chic-Chocs ont pu être des nunataks pendant la dernière période glaciaire. Toutes les espèces arctiques ou alpines survenant dans les Chic-Chocs sont de bons candidats aux fins de la surveillance du changement climatique, mais les 15 espèces de lichen qui atteignent leur limite sud-est dans cette chaîne sont peut-être les plus vulnérables.

Mots-clés : biogéographie, zone alpine, changement climatique, zones protégées, nunataks.

Received 4 September 2015. Accepted 21 July 2016.

R.T. McMullin. Museum of Nature – Research and Collections, P.O. Box 3443, Stn. "D," Ottawa, ON K1P 6P4, Canada.
B.C. Dorin. Biodiversity Institute of Ontario Herbarium, University of Guelph, 50 Stone Road East, Guelph, ON N1G 2W1, Canada.
Corresponding author: Richard Troy McMullin (e-mail: tmcmullin@mus-nature.ca).

Introduction

Lichen communities are broadly shaped by bioclimatic regions such as Arctic-alpine, boreal, temperate, and tropical (Thomson 1984, 1997; Gowan and Brodo 1988; Brodo et al. 2001). In the Arctic-alpine region, lichen communities have important functional roles including nitrogen fixation, which is vital in these nitrogen-poor areas (Crittenden 1989; Longton 1997), contributing to the carbon cycle, with their biomass representing a substantial portion of the Arctic carbon sink (Lange et al. 1996), and as a primary food source for caribou (*Rangifer tarandus*), which rely on lichen in these sparsely vegetated (i.e., low biomass) environments (Holleman et al. 1979; Danell et al. 1994). Arctic-alpine lichens are also important for global lichen biodiversity and to the biodiversity of plant communities in these regions (Matveyeva and Chernov 2000).

Lichen abundance in the Arctic, however, is predicted to decline, while shrub vegetation increases due to climate warming (Semenova et al. 2015). The temperature in the Arctic has had a mean increase of ~0.1 °C annually over the last 30 years, nearly twice that of lower latitudes (Dormann and Woodin 2002; Anisimov et al. 2007; IPCC 2007; Kaufman et al. 2009). Vegetative responses to this changing climate include an advancing tree line and an increase in shrub density (Myers-Smith et al. 2011; Elmendorf et al. 2012; IPCC 2013). Arctic species have three possible population-level responses to these warming conditions: migration, adaptation, or extirpation (Davis et al. 2005; Hewitt and Nichols 2005; Gibson et al. 2009). Arctic lichens may not have new areas to migrate to or enough time to adapt to the rapidly warming conditions, but the open high-Arctic and Arctic-alpine regions are expected to be refugia (Cornelissen et al. 2001).

The Chic-Choc Mountains (Chic-Chocs) on the Gaspé Peninsula in eastern Québec exemplify refugia for Arctic-alpine species in eastern North America. The summits of the highest peaks are above the tree line and are colonized by disjunct Arctic-alpine lichen communities (Dodge 1926; Thomson 1984, 1997; Sirois et al. 1988), which are also found on the summits of other Appalachian mountains farther south such as Mt. Katahdin in Maine (Hinds et al. 2002; Miller et al. 2005; Fryday 2006; Hinds et al. 2009). However, there are Arctic-alpine species in the Chic-Chocs (Dodge 1926; Sirois et al. 1988) that do not occur on Katahdin (Hinds et al. 2009). Fernald (1925) suggested that this difference may be because the Chic-Chocs are nunataks and Katahdin is not.

The Chic-Chocs were hypothesized to be nunataks, or ice-free, during the maximum extent of the Wisconsin glaciation largely because of their disjunct and endemic vascular flora (Fernald 1925). Fernald (1925) considered the species on these mountains to be "far more ancient" than on nearby mountains in New England with similar environments, such as Katahdin, which he believed was covered during this glacial period. The "antiquity" of the species on these nunataks was further stressed by their failure to migrate to mountains like Katahdin after the Labrador ice sheet melted, suggesting that they are localised relics, some of which (25 species) are endemic (Fernald 1925). His hypothesis was also based on the lack of "drift and smoothed, striated, and grooved surfaces" in the Chic-Chocs that are typical of glaciation. Flint et al. (1942) also concluded that the plateaus of the Chic-Chocs were nunataks after a detailed search failed to produce definitive geological evidence of glaciation. Hétu and Gray (1985) suggested that the plateaus could have been exposed during the Wisconsin glaciation as well because they only found slight traces of glacial erosion and the age of these erosion events cannot be determined accurately because of the lack of correlative deposits. However, the nunatak hypothesis is controversial (Wynne-Edwards 1937; Marie-Victorin 1938; Griggs 1940; Scoggan 1950; Rousseau 1974; Olejczyk and Gray 2007). For example, Olejczyk and Gray (2007) postulated that the sparse striae and erratics on the plateaus may have been due to protection from the glaciers by an initial buildup of ice. Although it is uncertain if the Chic-Chocs were nunataks, they still contain numerous endemic and disjunct populations of vascular plants (Fernald 1925), lichens (Macoun 1902; Dodge 1926; Sirois et al. 1988; McMullin et al. 2014), and moss (Belland 1987*a*, 1987*b*, 2015), many of which typically occur in the Arctic and the western mountains of North America. The Chic-Chocs are a refuge for many species, but their suitability for continued colonization by some species could be affected by the changing climate, particularly Arctic species that are at the edge of their range.

The aim of our study was to determine the number of Arctic-alpine lichen species that reach their southern range limit in eastern North America in the Chic-Chocs. Our objectives were to (1) compile a list of all lichen species that have been reported from the Chic-Chocs, (2) determine the known North American distribution of each lichen species, and (3) identify the species with distributions limited to the Arctic and western mountains that reach the edge of their southeastern range in the Chic-Chocs. The results will provide a better understanding of the ecological importance of the Chic-Chocs and provide support for their continued protection. Species that follow this distribution pattern are also good candidates for monitoring the effects of climate change in the Chic-Chocs.

Study site

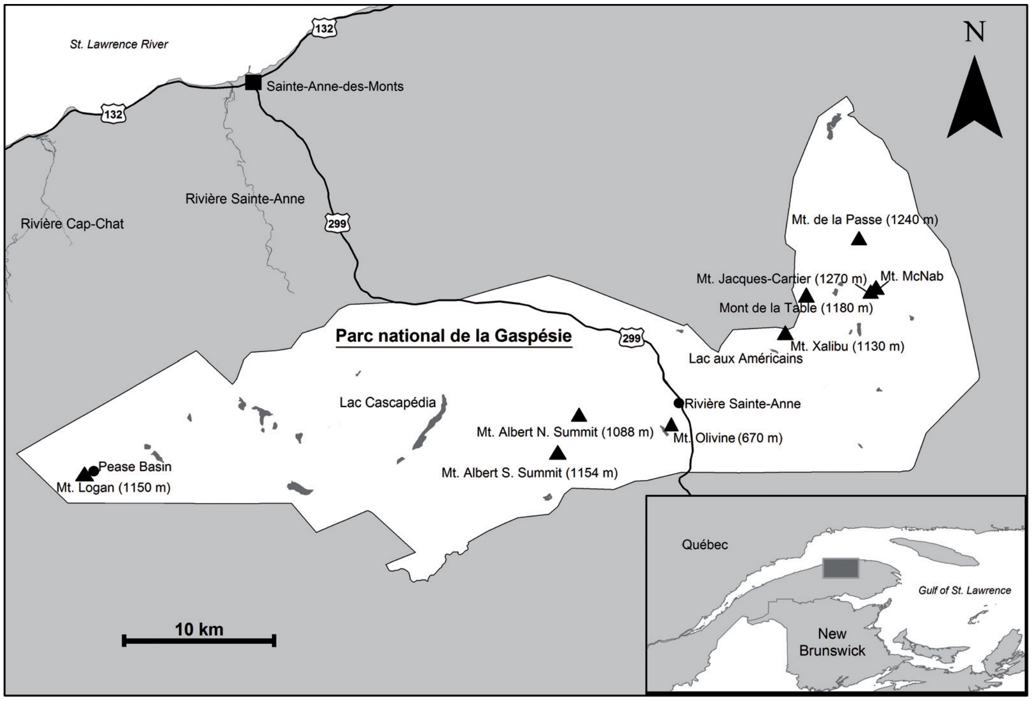
The Chic-Choc Mountains, previously the Shick Shock and Table Top Mountains (Fernald 1925), are located on the Gaspé Peninsula in eastern Québec (Fig. 1). They are part of the Notre Dame Mountains, which run from Vermont to the Gaspé Peninsula, and are also part of the Appalachian Mountains (Rune 1954; Commission de Toponymie 2015). The Gaspé Peninsula is bordered by the Saint Lawrence River to the north, the Gulf of the Saint Lawrence to the east/southeast, and Chaleur Bay to the south. The Chic-Chocs are located on the north-central region of the peninsula approximately 20–40 km south of the Saint Lawrence River (Fig. 1). The range runs parallel to the river for approximately 95 km (Commission de Toponymie 2015) and lies within 48.8274° and 49.1045° latitude and −65.8415° and −66.7059° longitude. A boreal forest ecosystem, dominated by mature *Abies balsamea*, *Picea glauca*, and *Picea mariana*, characterizes the Chic-Chocs, except for the highest peaks, which are above the tree line (approximately >1000 m) (Morin and Payette 1988; Sirois et al. 1988), and some low-elevation forests that were recently disturbed by spruce budworm, logging, and fire (Scoggan 1950; Rune 1954; Sirois and Grandtner 1992; Ouellet et al. 1996). The summits of the Chic-Chocs have eroded over the last 480 million years since their formation and many now have flat plateaus (Fernald 1925; Sirois et al. 1988; Matte 2001). The plateaus above the tree line have Arctic-alpine conditions dominated by herbaceous and lichen communities with many disjunct and endemic species (Fernald 1925; Scoggan 1950; Payette and Boudreau 1984; Sirois et al. 1988). Collections were made primarily on the summits of two mountains, Mont Albert and Mont Jacques-Cartier. The summit of Mont Albert is 1154 m, has the largest plateau in the Chic-Chocs (up to 9 km long and 6.5 km wide), and is primarily comprised of serpentine rock and, to a lesser degree, amphibolite (Sirois et al. 1988). Mont Jacques-Cartier is the highest mountain in the Chic-Chocs (1270 m), and in southern Québec, and also has an extensive plateau (up to 2.4 km long and 1 km wide). At the summit of Mont Jacques-Cartier, the average temperature in July is 10.6 °C and −15 °C in February and the average annual precipitation is 163.3 cm (Morin and Payette 1988).

Methods

Specimen collections and verifications

Approximately 1500 lichen specimens were collected throughout the Chic-Choc Mountains by the first author in 2007, 2012, and 2013. All known historical lichen collections from the Chic-Chocs that are deposited in public herbaria (i.e., Canadian Museum of Nature (CANL), Farlow at Harvard University (F), Laval University Herbarium (QFA), and the

Fig. 1. Location of lichen collection sites within the Chic-Choc Mountains and parc national de la Gaspésie in Quebéc, Canada. Lichen species collected at each location are listed in the Appendix.



New York Botanical Garden (NY)) were verified by the first author. Specimens were examined while on loan or during visits between 2007 and 2015.

Lichen identification

Specimens collected by the first author and historical herbarium specimens that were verified or revised were examined using stereo and compound microscopes and standard chemical spot tests with the following reagents: para-phenylenediamine in ethyl alcohol, nitric acid, sodium hypochlorite, 10% potassium hydroxide, and Lugol's iodine (Brodo et al. 2001). Chemistry was further examined using an ultraviolet light chamber. Specimens that could not be reliably identified by morphology, spot tests, or ultraviolet light were confirmed using thin-layer chromatography following Culberson and Kristinsson (1970) in solvents A and C. Specimens collected are housed at CANL in Ottawa and the Biodiversity Institute of Ontario Herbarium (OAC) at the University of Guelph.

Distribution data

Species distributions were determined using data from published literature and digitized collections data from 64 North American herbaria (CNALH 2015). Approximately 600 lichen species have been reported from the Chic-Choc Mountains (McMullin, in preparation), all of which were examined to determine whether they met the criteria for our study. Initial evaluations were done by creating point distribution maps with the digitized herbaria data. A literature review was then completed for all species that met our criteria (i.e., North American distributions only in the Arctic and western mountains that reach their southeastern limit in the Chic-Chocs). Our literature search began with the monographs for each genus and the published results from extensive studies on the lichens of

Mt. Katahdin in Maine, which is colonized by many disjunct populations of Arctic-alpine species (Hinds et al. 2002; Miller et al. 2005; Fryday 2006; Hinds et al. 2009). Maps were produced with ArcMap 10.2.2, with some modifications made in Photoshop CS5.

Results

Fifteen Arctic-alpine lichen species appear to reach their southern limit in eastern North America in the Chic-Chocs (Table 1; Fig. 2). Specimens included in this assessment were collected between 1906 and 2014 from 11 localities (Table 1; Fig. 1). There are modern collections of all species but one, *Amygdalaria elegantior*, which was last collected in 1923 (Table 1; Appendix). All specimens were collected from the alpine regions of the Chic-Chocs, except *Biatora subduplex*, which occurred at lower elevations (Table 1). Two of the 15 species have a fruticose growth form (*Cladonia trassii* and *Gowardia nigricans*), three are foliose (*Hypogymnia subobscura, Solorina crocea*, and *Vulpicida juniperina*), and the remaining 10 are crustose species (see Table 1).

Discussion

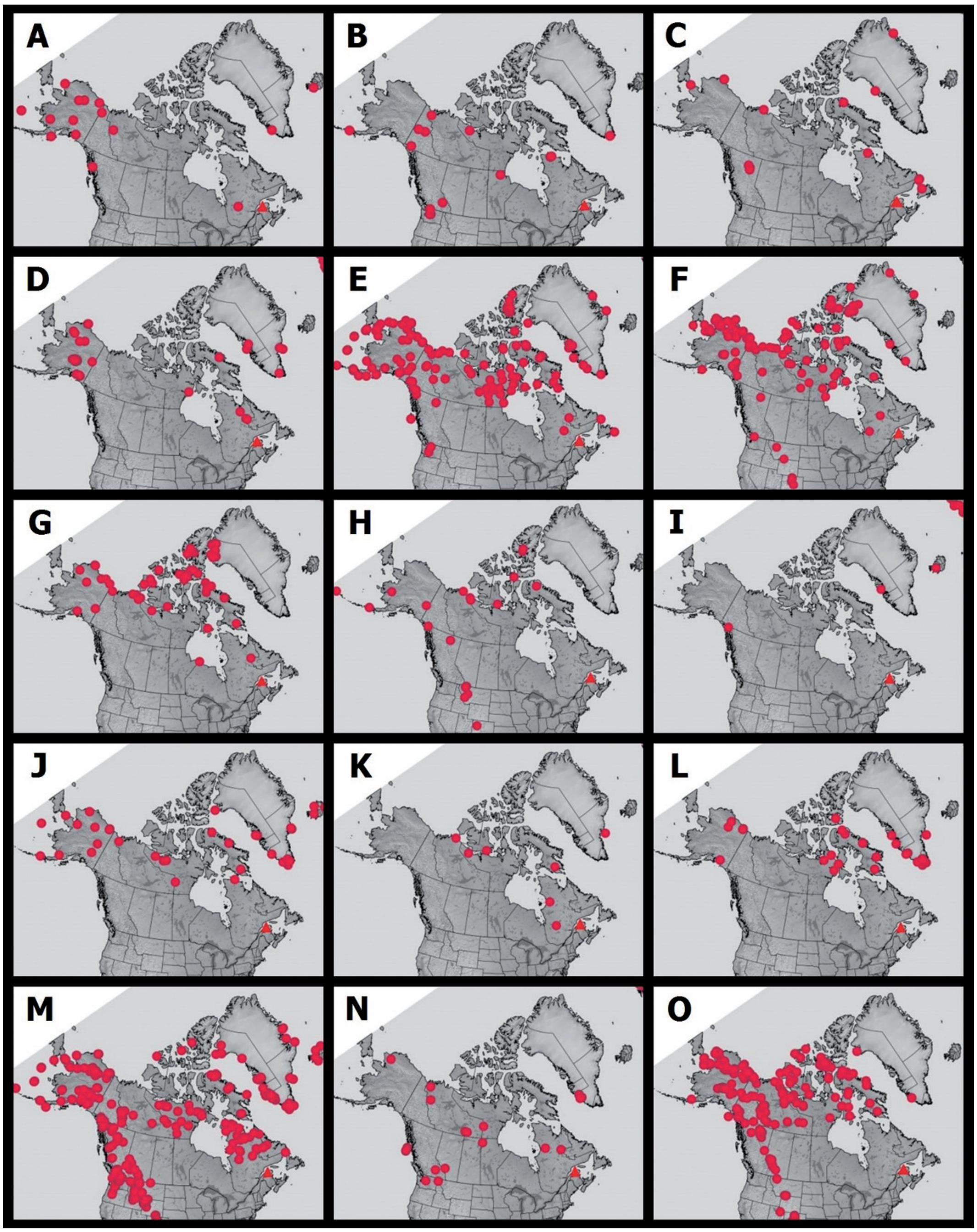
The Chic-Choc Mountains are the last southern refuge for at least 15 Arctic-alpine lichen species in eastern North America. We add an additional layer of biogeographic knowledge about the unusual flora of the Chic-Chocs, which have attracted the interest of lichenologist and other types of botanists for over a century (Macoun 1902; Fernald 1925; Torrey 1937;

Table 1. Location and collection year of 15 lichen species with a southeastern range limit in North America in the Chic-Choc Mountains of parc national de la Gaspésie, Québec.

Species	Location(s)	Year(s) collected
Amygdalaria elegantior (H. Magn.) Hertel & Brodo	PB (ML)	1923
Bellemerea subsorediza (Lynge) R. Sant.	UNM	2014
Biatora subduplex (Nyl.) Printzen	MO, SAR	2012
Cladonia trassii Ahti	MA	1981, 1982
Gowardia nigricans (Ach.) P. Halonen, L. Myllys, S. Velmala, & H. Hyvärinen	MA, MJ, ML	1882, 1968, 1969, 1971, 1973, 1981, 1982, 2012, 2013
Hypogymnia subobscura (Vain.) Poelt	MA, MJ	1971, 2012
Lecidea ramulosa Th. Fr.	MJ	2012
Lecidea umbonata (Hepp) Mudd	MA	1981
Miriquidica nigroleprosa (Vain.) Hertel & Rambold	MA, MJ	2012, 2014
Ochrolechia grimmiae Lynge	MA, MJ	1953, 2014
Rhizocarpon ferax H. Magn.	UNM	2014
Rhizocarpon rittokense (Hellbom) Th. Fr.	MA	1982
Solorina crocea (L.) Ach.	CR, MdP, MJ, MMN	1906, 1923, 1972, 2012, 2014
Varicellaria rhodocarpa (Körb.) Th. Fr.	LA, MJ, MO, MX	2012
Vulpicida juniperina (L.) J.-E. Mattsson & M. J. Lai	MA	1940, 1953, 1969, 1981, 1982, 2012, 2013

Note: Collection locations within the Chic-Chocs: Castle Ridge (CR), lac aux Américains (LA), Mont Albert (MA), Mont de la Passe (MdP), Mont Jacques-Cartier (MJ), Mont Logan (ML), Mont MacNab (MMN), Mont Olivine (MO), Mont Xalibu (MX), Pease Basin (PB), Saint Ann River along the base of Mont Albert or location unknown (SAR), and unnamed mountain south of Mont de la Table and east of lac Dugué (UNM). Nomenclature follows the 19th edition of the North American Lichen Checklist (Esslinger 2014). Species authors are cited following Brummitt and Powell (1992). Authors that are not listed by Brummit and Powell are cited following Esslinger (2014). See the Appendix for collectors, collector numbers, determiners, verifiers, the herbaria where specimens are deposited, and substrate(s) for each specimen.

Fig. 2. North American distribution of 15 Arctic-alpine lichen species that reach their southeastern range limit in the Chic-Choc Mountains, which are denoted by a triangle "▲". **A**, *Amygdalaria elegantior*; **B**, *Bellemerea subsorediza*; **C**, *Biatora subduplex*; **D**, *Cladonia trassii*; **E**, *Gowardia nigricans*; **F**, *Hypogymnia subobscura*; **G**, *Lecidea ramulosa*; **H**, *Lecidea umbonata*; **I**, *Miriquidica nigroleprosa*; **J**, *Ochrolechia grimmiae*; **K**, *Rhizocarpon ferax*; **L**, *Rhizocarpon rittokense*; **M**, *Solorina crocea*; **N**, *Varicellaria rhodocarpa*; **O**, *Vulpicida juniperina*.



Scoggan 1950; Sirois et al. 1988; Belland 2015). Many of these 15 lichens are not known to occur again for over 1000 km to the north (e.g., *Bellemerea subsorediza*, *Lecidea umbonata*, *Miriquidica nigroleprosa*, *Ochrolechia grimmiae*, *Rhizocarpon rittokense*, and *Vulpicida juniperina*). They also do not occur on neighbouring mountains with similar Arctic-alpine conditions (i.e., the Green Mountains, White Mountains, or Mt. Katahdin), which lends some support to the hypothesis that the Chic-Chocs might have been nunataks during the last glacial period (Fernald 1925). If the mountains in New England and those on the Gaspé Peninsula were both covered by the Labrador Ice Sheet, then an equal opportunity for recolonization would appear to exist after its retreat. Instead, at least 25 vascular plants and 15 lichen species are unique to the Chic-Chocs (Fernald 1925).

The lichen community on Mt. Katahdin is perhaps the best Appalachian comparison to the Chic Chocs. It has been extensively surveyed for lichens and contains a similar number of species, 549 versus approximately 600 in the Chic Chocs, and both include a rich Arctic-alpine community (Hinds et al. 2009). The 15 species that reach their southeastern limit in the Chic-Chocs are not known from Mt. Katahdin, but there are many species on Mt. Katahdin that are not known from the Chic-Chocs. For example, Hinds et al. (2009) reported 15 lichen species from Mt. Katahdin that are new to North America and five that are new to science. Therefore, differences in these lichen communities might not be due to the Chic-Chocs being nunataks and Mt. Katahdin being fully ice-covered during the Wisconsin glaciation. Instead, climatic differences might be the reason for these differences or dispersal limitations could have prevented some species from colonizing both areas (Ellis et al. 2007).

Most of the data used to determine the North American distribution of the approximately 600 lichen species known from the Chic-Chocs are from herbarium databases uploaded to the Consortium of North American Lichen Herbaria. Based on the large number of revised names required for older collections examined for our study, some identifications in herbaria databases may be inaccurate, especially historical determinations. Therefore, type II errors (false-negative) could occur if misidentifications were made of specimens occurring south of the Chic-Chocs of species that would otherwise increase the number of taxa that fit our criteria. Type I errors (false-positive) are unlikely to occur, although, because species that were misidentified as one of our 15 species would not change the distribution patterns we determined. Misidentifications are more likely to occur with microlichens (crustose) because their morphological differences are more subtle than macrolichens (foliose and fruticose) and there is less literature to aid identifications, particularly historically. Crustose lichens are also more likely to be over looked because of the inconspicuous nature of some species. Therefore, the most reliable distribution patterns determined are for the macrolichens.

One specimen of *Solorina crocea* was collected on Castle Ridge in the Chic-Chocs in 1906 (see Appendix), but that location name no longer appears to be in use. When Fernald (1925) visited Gaspé in the early 1900s, many of the mountains and other landscape features did not have names, so he named them. Some of those names persist today, but not Castle Ridge. Based on a hand-drawn map by J.F. Collins in 1906 in the Harvard Herbaria Library archives, this appears to be Mont les Cônes, approximately 5 km directly south of Mont Jacques-Cartier.

None of the lichen species listed in our study are federally or provincially protected, but their habitat in the Chic-Chocs is. The majority of the Chic-Chocs are protected by the Government of Québec as a provincial park, parc national de la Gaspésie, and three wilderness reserves: Réserve faunique de Matane, Réserve écologique Fernald, and Réserve faunique des Chic-Chocs. Climate change, therefore, might be the most immediate threat to the disjunct populations in the Chic-Chocs. Tree lines in other regions have been shown to be advancing in latitude (Grace et al. 2002) and elevation (Gehrig-Fasel et al. 2007) due to climate change. In the Chic Chocs, however, there has been no clear evidence of climate change over the last four decades (Fortin and Hétu 2014). Nevertheless, Hayhoe et al. (2006) have projected an average annual surface temperature increase of 2.9–5.3 °C in northeastern North America by 2070–2099. The Arctic-alpine plateaus in the Chic-Chocs occur <100 m from the tree line on many of the mountains. A slight temperature increase could alter the suitability of this habitat for many species. Therefore, any Arctic-alpine species in the Chic-Chocs are good candidates for monitoring the effects of climate change and the 15 lichens that reach their southeastern limit in this range may be the most vulnerable.

Acknowledgements

We gratefully acknowledge the staff at parc national de la Gaspésie for providing permits and identification space, field companions C. Smith, E. Point, J. Rankin, J. Glynn-Morris, H. Ross, and participants of the Crum and Tuckerman Workshops, herbarium staff at CANL, F, NY, and QFA for providing access to their collections and sending specimens on loan, Friends of the Farlow for financial support to visit F, and support from Steven Newmaster and the OAC.

References

Anisimov, O.A., Vaughan, D.G., Callaghan T.V., Furgal, C., Marchant, H., Prowse, T.D., Vilhjálmsson, H., and Walsh, J.E. 2007. Polar regions (Arctic and Antarctic). *In* Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate. 15th ed. pp. 653–685. Cambridge University Press, Cambridge, UK.

Belland, R.J. 1987*a*. The moss flora of the Gulf of St. Lawrence region: ecology and phytogeography. J. Hattori Bot. Lab. **62**: 205–267.

Belland, R.J. 1987*b*. The disjunct moss element of the Gulf of St. Lawrence region: glacial and postglacial dispersal and migrational histories. J. Hattori Bot. Lab. **63**: 1–76.

Belland, R.J. 2015. The arctic-alpine and montane mosses of the Gulf of St. Lawrence Region Part I: montane element. Evansia. **32**: 10–24. doi: 10.1639/079.032.0104.

Brodo, I.M., Sharnoff, S.D., and Sharnoff, S. 2001. Lichens of North America. Yale University Press, New Haven, Conn.

Brummitt, R.K., and Powell, C.E. 1992. Authors of plant names. Royal Botanical Gardens, Kew, Great Britain.

CNALH (Consortium of North American Lichen Herbaria). 2015. http://lichenportal.org/portal/index.php [accessed May 25, 2015].

Commission de Toponymie. 2015. Monts Chic-Chocs. Goverment of Québec. www.toponymie.gouv.qc.ca/ct/ToposWeb/fiche.aspx?no_seq=13165 [accessed August 28, 2015].

Cornelissen, J.H.C., Callaghan, T.V., Alatalo, J.M., Michelsen, A., Graglia, E., Hartley, A.E., Hik, D.S., Hobbie, S.E., Press, M.C., et al. 2001. Global change and Arctic ecosystems: is lichen decline a function of increases in vascular plant biomass? J. Ecol. **89**(6): 984–994. doi: 10.1111/j.1365-2745.2001.00625.x.

Crittenden, P.D. 1989. Nitrogen relations of mat-forming lichens. Nitrogen, phosphorus and sulphur utilization by fungi. Cambridge University Press, Cambridge, UK. pp. 243–268.

Culberson, C.F., and Kristinsson, H. 1970. A standardized method for the identification of lichen products. J. Chromatogr. **46**: 85–93. doi: 10.1016/S0021-9673(00)83967-9.

Danell, K., Utsi, M.P., Palo, T.R., and Eriksson, O. 1994. Food plant selection by reindeer during winter in relation to plant quality. Ecography. **17**(2): 153–158. doi: 10.1111/j.1600-0587.1994.tb00088.x.

Davis, M.B., Shaw, R.G., and Etterson, J.R. 2005. Evolutionary responses to changing climate. Ecology. **86**: 1704–1714. doi: 10.1890/03-0788.

Dodge, C.W. 1926. Lichens of the Gaspé Peninsula, Québec. Rhodora. **288**: 157–161.

Dormann, C.F., and Woodin, S.J. 2002. Climate change in the Arctic: using plant functional types in a meta-analysis of field experiments. Funct. Ecol. **16**(1): 4–17. doi: 10.1046/j.0269-8463.2001.00596.x.

Ellis, C.J., Coppins, B.J., Dawson, T.P., and Seaward, M.R. 2007. Response of British lichens to climate change scenarios: trends and uncertainties in the projected impact for contrasting biogeographic groups. Biol. Conserv. **140**(3): 217–235. doi: 10.1016/j.biocon.2007.08.016.

Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., Bjork, R.G., Boulanger-Lapointe, N., Cooper, E.J., Cornelissen, J.H.C., Day, T.A., Dorrepaal, E., et al. 2012. Plot-scale evidence of tundra vegetation change and links to recent summer warming. Nat. Clim. Chang. **2**: 453–457. doi: 10.1038/NCLIMATE1465.

Esslinger, T.L. 2014. A cumulative checklist for the lichen-forming, lichenicolous and allied fungi of the continental United States and Canada. North Dakota State University, Fargo, North Dakota. http://www.ndsu.edu/pubweb/~esslinge/chcklst/chcklst7.htm (first posted December 1, 1997, most recent version (#19) March 23, 2014).

Fernald, M.L. 1925. Persistence of plants in unglaciated areas of boreal America. Mem. Am. Acad. Arts Sci. **15**(3): 241–315. doi: 10.2307/25058128.

Flint, R.F., Demorest, M., and Washburn, A.L. 1942. Glaciation of Shickshock Mountains, Gaspé Peninsula. Geol. Soc. Am. Bull. **53**(8): 1211–1230. doi: 10.1130/GSAB-53-1211.

Fortin, G., and Hétu, B. 2014. Estimating winter trends in climatic variables in the Chic-Choc Mountains, Canada (1970–2009). Int. J. Climatol. **34**(10): 3078–3088. doi: 10.1002/joc.3895.

Fryday, A.M. 2006. New and interesting North America lichen records from the alpine and sub-alpine zones of Mt. Katahdin, Maine. Bryologist. **109**(4): 570–578. doi: 10.1639/0007-2745(2006)109[570:NAINAL]2.0.CO;2.

Gehrig-Fasel, J., Guisan, A., and Zimmermann, N.E. 2007. Tree line shifts in the Swiss Alps: climate change or land abandonment? J. Veg. Sci. **18**(4): 571–582. doi: 10.1111/j.1654-1103.2007.tb02571.x.

Gibson, S.Y., Van Der Marel, R.C., and Starzomski, B.M. 2009. Climate change and conservation of leading-edge peripheral populations. Conserv. Biol. **23**: 1369–1373. doi: 10.1111/j.1523-1739.2009.01375.x.

Gowan, S.P., and Brodo, I.M. 1988. The lichens of Fundy national Park, New Brunswick, Canada. Bryologist. **91**: 255–325. doi: 10.2307/3242770.

Grace, J., Berninger, F., and Nagy, L. 2002. Impacts of climate change on the tree line. Ann. Bot. **90**(4): 537–544. doi: 10.1093/aob/mcf222.

Griggs, R.F. 1940. The ecology of rare plants. Bull. Torrey Bot. Club. **67**: 575–594. doi: 10.2307/2481578.

Hayhoe, K., Wake, C.P., Huntington, T.G., Luo, L., Schwartz, M.D., Sheffield, J., Wood, E., Anderson, B., Bradbury, J., et al. 2006. Past and future changes in climate and hydrological indicators in the US Northeast. Clim. Dyn. **28**: 381–407. doi: 10.1007/s00382-006-0187-8.

Hétu, B., and Gray, J.T. 1985. Le modelé glaciaire du centre de la Gaspésie septentrionale, Québec. Géogr. Phys. Quatern. **39**(1): 47–66. doi: 10.7202/032584ar.

Hewitt, G.M., and Nichols, R.A. 2005. Genetic and evolutionary impacts of climate change. Climate Change and Biodiversity. Yale University Press, New Haven, Conn. pp. 176–192.

Hinds, J.W., Fryday, A.M., and Dibble, A.C. 2002. Three additions to the lichen flora of North America from Mt. Katahdin, Maine. Evansia. **19**(4): 137–141.

Hinds, J.W., Fryday, A.M., and Dibble, A.C. 2009. Lichens and bryophytes of the alpine and subalpine zones on Katahdin, Maine, II: Lichens. Bryologist. **112**(4): 673–703. doi: 10.1639/0007-2745-112.4.673.

Holleman, D.F., Luick, J.R., and White, R.G. 1979. Lichen intake estimates for reindeer and caribou during winter. J. Wildl. Manage. **43**: 192–201. doi: 10.2307/3800651.

IPCC. 2007. Climate change 2007: the physical science basis. Agenda. Cambridge University Press, Cambridge, UK.

IPCC. 2013. Climate change 2013: the physical science basis. Agenda. Cambridge University Press, Cambridge, UK. 1535.

Kaufman, D.S., Schneider, D.P., McKay, M.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., et al. 2009. Recent warming reverses long-term Arctic cooling. Science. **325**: 236–1239. doi: 10.1126/science.1173983.

Lange, O.L., Hahn, S.C., Müller, G., Meyer, A., and Tenhunen, J.D. 1996. Upland tundra in the foothills of the Brooks Range, Alaska: influence of light, water content and temperature on CO_2 exchange of characteristic lichen species. Flora. **89**: 67–83. doi: 10.2307/1551972.

Longton, R.E. 1997. The role of bryophytes and lichens in polar ecosystems. Special Publ. Br. Ecol. Soc. **13**: 69–96.

Macoun, J. 1902. Catalogue of Canadian plants. Part VII. Lichens and hepaticae. Government Printing Bureau, Ottawa, Ont.

Marie-Victorin, F. 1938. Phytogeographical problems in eastern Canada. Am. Midl. Nat. **19**: 489–558. doi: 10.2307/2420466.

Matte, P. 2001. The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review. Terra Nova. **13**: 122–128. doi: 10.1046/j.1365-3121.2001.00327.x.

Matveyeva, N., and Chernov, Y. 2000. Biodiversity of terrestrial ecosystems. *In* The Arctic: environment, people, policy. *Edited by* M. Nuttall and T.V. Callaghan. Harwood Academic Publishers, Amsterdam, The Netherlands. pp. 233–274.

McMullin, R.T., Lendemer, J.C., Harris, R.C., Roy, C., Gagnon, J., and Clayden, S.R. 2014. Discovery of *Hypogymnia pulverata* on the Gaspésie Peninsula in eastern Canada. Opusc. Philolichenum. **13**: 91–95.

Miller, N.G., Fryday, A.M., and Hinds, J.W. 2005. Bryophytes and lichens of a calcium-rich spring seep isolated on the granitic terrain of Mt. Katahdin, Maine, U.S.A. Rhodora. **107**: 339–358. doi: 10.3119/05-7.1.

Morin, H., and Payette, S. 1988. Buried seed populations in the montane, subalpine, and alpine belts of Mont Jacques-Cartier, Québec. Can. J. Bot. **66**: 101–107. doi: 10.1139/b88-015.

Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Macias-Fauria, M., Sass-Klaassen, U., et al. 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environ. Res. Lett. **6**: 045509. doi: 10.1088/1748 9326/6/4/045509.

Olejczyk, P., and Gray, J.T. 2007. The relative influence of Laurentide and local ice sheets during the last glacial maximum in the eastern Chic-Chocs Range, northern Gaspé Peninsula, Quebec. Can. J. Earth Sci. **44**(11): 1603–1625. doi: 10.1139/e07-039.

Ouellet, J.P., Ferron, J., and Sirois, L. 1996. Space and habitat use by the threatened Gaspé caribou in southeastern Québec. Can. J. Zool. **74**: 1922–1933. doi: 10.1139/z96-217.

Payette, S., and Boudreau, F. 1984. Évolution post-glaciaire des hauts sommets alpins et subalpins de la Gaspésie. Can. J. Earth Sci. **21**: 319–335. doi: 10.1139/e84-034.

Rousseau, C. 1974. Géographie floristique du Québec/Labrado. Les Presses de L'Université Laval, Quebec City, Que.

Rune, O. 1954. Notes on the flora of the Gaspé peninsula. Sven. Bot. Tidskr. **48**: 117–138.

Scoggan, H.J. 1950. The Flora of Bic and the Gaspe Peninsula, Quebec. National Museum of Canada, Bulletin No. 115, Biological Series No. 39. 399.

Semenova, T.A., Morgado, L.N., Welker, J.M., Walker, M.D., Smets, E., and Geml, J.O. 2015. Long-term experimental warming alters community composition of ascomycetes in Alaskan moist and dry Arctic tundra. Mol. Ecol. **24**: 424–437. doi: 10.1111/mec.13045.

Sirois, L., and Grandtner, M.M. 1992. A phyto-ecological investigation of the Mount Albert serpentine plateau. *In* The ecology of areas with serpentinized rocks. Springer, The Netherlands. Vol. 17. pp. 115–133. doi: 10.1007/978-94-011-3722-5_5.

Sirois, L., Lutzoni, F., and Grandtner, M.M. 1988. Les lichens sur serpentine et amphibolite du plateau du mont Albert, Gaspésie, Québec. Can. J. Bot. **66**(5): 851–862. doi: 10.1139/b88-124.

Thomson, J.W. 1984. American Arctic lichens 1. The macrolichens. Columbia University Press, New York.

Thomson, J.W. 1997. American Arctic lichens 2. The microlichens. The University of Wisconsin Press, Madison, Wis.

Torrey, R.H. 1937. Botanizing in the Shickshock Mountains of Gaspé, Quebéc. Torreya. **37**: 73–79.

Wynne-Edwards, V.C. 1937. Isolated arctic-alpine floras in eastern North America: a discussion of their glacial and recent history. Trans. R. Soc. Can. **3**(31): 258–288.

Appendix

The 15 lichen species that reach their southeastern range limit in North America in the Chic-Chocs are listed below alphabetically by genus and species. The following information is provided for each species: substrate(s), collection location(s) within the Chic-Chocs, collection year(s), collector(s), collection number(s), determiner(s) and verifier(s) if applicable, and herbarium/herbaria the specimens have been deposited in. The following acronyms are listed below for collection locations: Castle Ridge (CR), lac aux Américains (LA), location unknown (LU), Mont Albert (MA), Mont Dunraven (MD), Mont de la Passe (MdP), Mont Jacques-Cartier (MJ), Mont Logan (ML), Mont MacNab (MMN), Mont Olivine (MO), Mont Xalibu (MX), Pease Basin (PB), Saint Ann River along the base of Mont Albert or location unknown (SAR), and unnamed mountain south of Mont de la Table and east of lac Dugué (UNM). Herbaria acronyms listed below are Canadian Museum of Nature (CANL), Farlow Herbarium at Harvard University (F), Louis-Marie Herbarium at Laval University (QFA), New Brunswick Provincial Museum (NBM), New York Botanical Garden (NY), University of Guelph Herbarium (OAC), and University of Maine Herbarium (MAINE).

Amygdalaria elegantior (H.Magn.) Hertel & Brodo – Saxicolous. PB: 1923 – J. Collins & C. Dodge 2665 (det. I. Brodo & T. McMullin) (F).

Bellemerea subsorediza (Lynge) R. Sant. – Saxicolous. UNM: 2014 – *J. Gagnon s.n.* (det. R. Harris) (QFA).

Biatora subduplex (Nyl.) Printzen **–** Lignicolous (*Picea*) & saxicolous. MO: 2012 – *W. Buck 59602* (NY). SAR: 2012 – *F. Anderson s.n.* (QFA).

Cladonia trassii Ahti – Saxicolous & terricolous. MA: 1981 – L. Sirois & F. Lutzoni 10570-L1 (1/1), 10595-L8 (1/2) (det. R. Mimeault), 10616-L1a(1/1) (QFA); 1982 – L. Sirois & R. Mimeault 10638-L6(1/1), 10683-L3M (det. G. Lavoie), 10695-L3(1/1) (QFA).

Gowardia nigricans (Ach.) Halonen – Corticolous (*Picea*, *Picea mariana*), lignicolous (snag), saxicolous (granitic), & terricolous. LU: 1882 – *J. Macoun 512* (CANL); 1973 – *F. Boudreau s.n.* (det. J. Ouzilleau) (QFA). MA: 1968 – *D. Miller s.n.* (CANL); 1971 – *I. Brodo 18537* (CANL); 1981 – *L. Sirois & F. Lutzoni 10565-L14(1/1), 10589-L9(1/1)* (det. G. Lavoie), *10612-L3(2/3)* (det. P. Y. Wong) (ver. C. Roy) (QFA), *L. Sirois & R. Mimeault 10631-L10-L11* (det. F. Lutzoni) (QFA); 1982 – *L. Sirois & R. Mimeault 10631-L20(1/1)* (det. G. Lavoie), *10684-L1, 10684-L4* (det. G. Lavoie.) (ver. F. Lutzoni) (QFA). MA>T: 2012 – *T. McMullin 9485* (OAC). MJ: 2012 – *J. Lendemer 32561* (NY), *R. Harris 57617* (NY), *W. Buck 59628* (NY). MJ>T: 2012 – *J. Hinds 3741.00* (MAINE). **MJ>T:** 2012 – *D. Waters 0946* (personal herbarium), *S. Clayden 23287* (NBM). ML: 1969 – *R. Gauthier 1904* (det. I. Brodo & P. Y. Wong) (QFA). ML>T: 2013 – *T. McMullin 13757* (OAC).

Hypogymnia subobscura (Vain.) Poelt – Terricolous. MA: 1971 – *H. Muhle 995* (QFA). MJ: 2012 **–** *J. Lendemer 32566* (NY).

Lecidea ramulosa Th. Fr. – Terricolous. MJ>T: 2012 – *J. Hinds 5706.00* (MAINE).

Lecidea umbonata Henssen. MA: 1981 – L. Sirois & F. Lutzoni 10559-L10(2/3) (QFA).

Miriquidica nigroleprosa (Vain.) Hertel & Rambold – Saxicolous. MA: 2014 – *J. Gagnon s.n.* (det. R. Harris) (QFA). MJ: 2012 – *J. Lendemer 32560, 32608* (NY).

Ochrolechia grimmiae Lynge – Bryicolous. MA: 1953 – *Y. Desmarais L-9* (ver. T. McMullin) (QFA). MJ: 2014 – *J. Gagnon s.n.* (det. R. Harris) (QFA).

Rhizocarpon ferax H. Magn. – Saxicolous. **UNM:** 2014 – *J. Gagnon s.n.* (det. R. Harris) (QFA).

Rhizocarpon rittokense (Hellbom) Th. Fr. – Saxicolous. MA: 1982 – *L. Sirois & M. Mimeault 10631-L12 à L17* (det. F. Lutzoni) (ver. T. McMullin) (QFA).

Solorina crocea (L.) Ach – Terricolous. **CR:** 1906 – *J. Collins 4502a* (ver. T. McMullin) (F). LU: 1972 – *F. Boudreau s.n* (det. J. Ouzilleau) (ver. T. McMullin) (QFA). MdP: 2014 – *J. Gagnon s.n.* (det. R. Harris) (QFA). **MJ:** 2012 – *D. Ladd 32362* (personal herbarium), *J. Lendemer 32585* (NY). MJ>T: 1923 – *M. Fernald, C. Dodge & L. Smith 2690* (ver. T. McMullin) (F); 1972 – *F. Boudreau s.n.* (ver. T. McMullin) (QFA); 2012 – *J. Hinds*

3738.00 (MAINE), *S. Clayden 23265* (NBM), *T. McMullin 13926, 13927* (OAC). MMN: 1923 – *M. Fernald, C. Dodge & L. Smith 2295* (ver. T. McMullin), *2690* (ver. T. McMullin) (F).

Varicellaria rhodocarpa (Körb.) Th. Fr. – Corticolous (Abies, Betula, Picea), lignicolous (stump). LA: 2012 – E. Lay 12-0196 (NY), R. Harris 57694, 57705 (NY). MJ: 2012 – J. Lendemer 32598 (NY), R. Harris 57604 (NY). MJ<T: 2012 – J. Lendemer 32617 (NY). MJ>T: 2012 – D. Waters 0937 (personal herbarium). MO: 2012 – J. Lendemer 32518 (NY), R. Harris 57548 (NY). **MX:** 2012 – J. Lendemer 32747 (NY).

Vulpicida juniperina (L.) J.-E. Mattsson & M. J. Lai – Saxicolous (with moss), terricolous. MA: 1940 – *E. Lepage 2094* (det. T. McMullin) (QFA); 1953 – *Y. Desmarais L-6* (ver. T. McMullin) (QFA); 1969 – *R. Gauthier 2045* (det. I. Brodo & P. Y. Wong) (QFA); 1981 – *L. Sirois & F. Lutzoni 10571-L7c, 10629-L150(1/3)* (QFA); 1982 – *L. Sirois 10705-L6* (QFA), *L. Sirois & Renaud Mimeault 10642-L6, 10643-L2* (QFA). **MA>T:** 2012 – *J. Hinds 5748.00* (MAINE); 2013 – *T. McMullin 9518, 9519, 9520* (OAC).